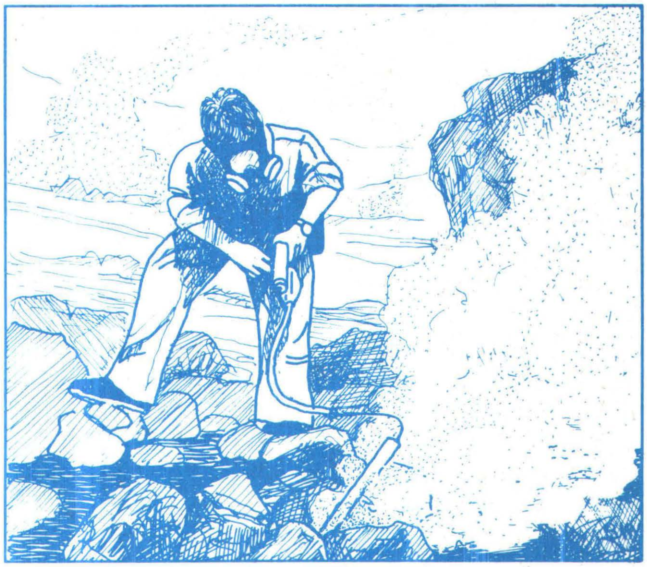
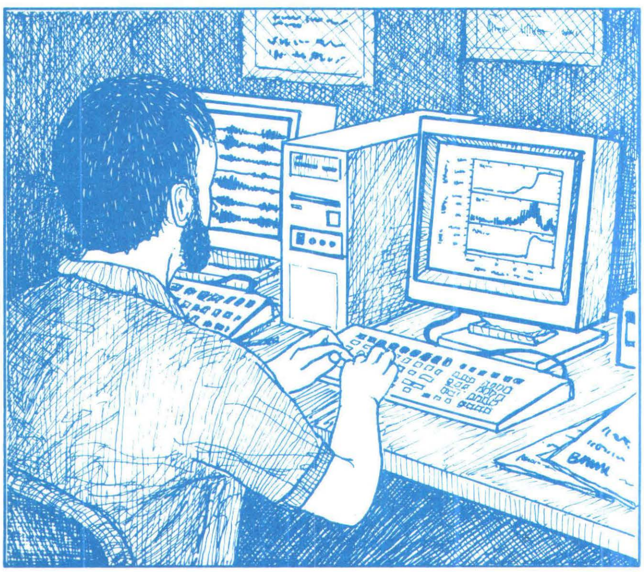
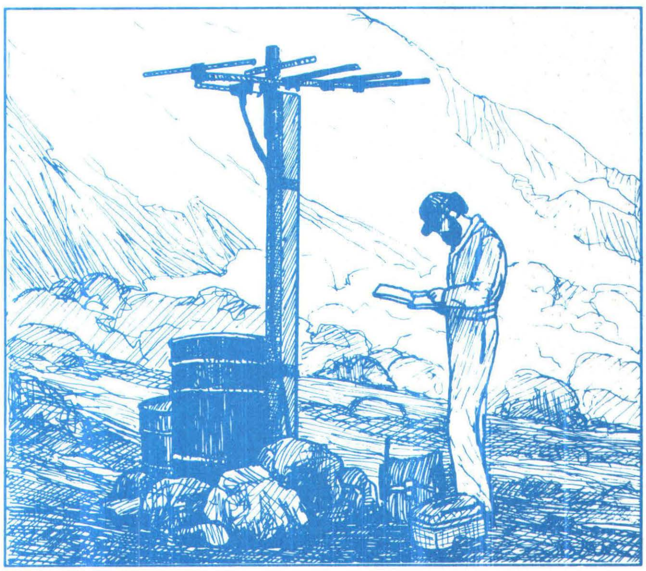
Monitoring Volcanoes: Techniques and Strategies Used by the Staff of the Cascades Volcano Observatory, 1980–90







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JOHN W. EWERT and DONALD A. SWANSON, Editors

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CONTENTS

Monitoring Volcanoes: Techniques and Strategies Used by the Staff of the Cascades Volcano Observatory, 1980–1990

INTRODUCTION

By John W. Ewert *and* Donald A. Swanson, *Editors*

This bulletin marks the tenth anniversary of the May 18, 1980, eruption of Mount St. Helens by describing many of the monitoring techniques used since then to track the volcano's ongoing activity. All the chapters in this volume were written by technicians and scientists who are now or were at some time in the past 10 years members of the Cascades Volcano Observatory (CVO), which was established in Vancouver, Washington, in the summer of 1980 in response to the eruption of nearby Mount St. Helens. The chapters in the bulletin describe the techniques and strategies employed by CVO's staff to collect data used to monitor volcanic activity and predict eruptive activity of Mount St. Helens, as well as other volcanoes in the United States, Latin America, and New Zealand. The chapters focus on the methods for acquiring and managing data, not on the interpretations resulting from the data. We anticipate that the audience of the bulletin will be those scientists and technicians, particularly in developing countries, who themselves are, or will be, monitoring volcanoes. The bulletin is not intended to be a comprehensive text on volcano monitoring but instead a distillation of how CVO's staff responded both to the need to monitor an active composite volcano and to the dynamic technological developments during the 1980's. Further reading in volcano-monitoring techniques can be found in UNESCO (1972), Civetta and others (1974), Tazieff and Sabroux (1983), and Tilling (1989).

Much of the seismic monitoring of Mount St. Helens during the decade was conducted by S. D. Malone and associates in the University of Washington's Geophysics Program, not by CVO staff members. Techniques used by Malone's group are described in unpublished *in-house* manuals (Malone and Zollweg, 1985; Malone, 1989) available upon request from Malone (Geophysics Program AK-50, University of Washington, Seattle, WA 98195). The methods used by Malone's group are appropriate for large seismic networks that employ mainframe computers to acquire and process data. Examples of how these techniques are applied to interpret volcanic activity are papers by Malone and others (1981), Malone (1983), Malone and others (1983), Hofstetter and Malone (1986), and Swanson and others (1985).

Several of the methods used to monitor volcanoes have changed greatly since 1980 as a result of technological advances. Most important of these is the revolution in the field of electronics, particularly microcomputers. Smaller, more powerful electronic distance meters (EDM's), low-power digital telemetry, PC-based seismic-data acquisition and analysis systems, and laptop-computer controllers and interfaces are just some of the results of this revolution that have allowed us to improve established monitoring techniques or develop new ones.

When Mount St. Helens began showing signs of unrest in March 1980, most of the U.S. Geological Survey personnel dispatched to the volcano had previous experience monitoring Kilauea while stationed at the Hawaiian Volcano Observatory (HVO). Although most of the monitoring techniques used in 1980 were developed and (or) used at HVO, it became apparent that the different eruptive style of composite volcanoes in general, and of Mount St. Helens in particular, required modification of some of these monitoring practices. The chapters in this bulletin illustrate the degree to which modification was required.

The chapters fall into several logical groupings: telemetry, acquisition of seismic data, data management, ground deformation, geochemistry, and imaging. The first three groupings represent the areas in which the most marked technological progress has been made. Rapidly changing conditions prior to eruptive activity require that data be available to volcanologists in as close to real time as possible, in order to make reasonable assessments of the future and to aid in hazard-mitigation efforts. To be most effective, the data must be available in a format in which the different measured parameters can be easily compared and rapidly analyzed.

The real-time seismic-amplitude monitor (RSAM) (Murray and Endo, chapter 1 of this bulletin) allows seismic data to be quantified and utilized at the time such data are most needed—when the seismic activity at a volcano is saturating all other seismic-data acquisition and analysis systems. Inexpensive, low-power, radio-telemetry systems (Murray, chapter 2; Lockhart and others, chapter 3) allow almost any sensor to send back data from the volcano in near real time. The microcomputer-based volcano-monitoring system using the program BOB (Murray, chapter 4) permits all data gathered by a monitoring team to be recorded, processed, and displayed on a common time base. Development of this system, together with that of the PC-AT and Sun workstation seismic systems (Endo and Smith, chapter 5), more than anything else represents the most dramatic new contribution to volcano-monitoring methods and techniques made by the CVO group. These PC-based systems are powerful, portable, and very inexpensive compared to what was only marginally available at the beginning of the 1980's.

Fully half of the chapters cover techniques for monitoring ground deformation, using both telemetered and nontelemetered methods. This emphasis in part reflects the success of the CVO staff in predicting eruptive activity at Mount St. Helens using these methods (Swanson and others, 1983, 1985). Four of the chapters deal directly with monitoring at Mount St. Helens itself and provide suggestions for field procedures gained from a decade of first-hand experience: those by Iwatsubo and Swanson (chapter 6), Dzurisin (chapter 7), Iwatsubo, Topinka, and Swanson (chapter 8), and Iwatsubo, Ewert, and Murray (chapter 9). Two of the chapters cover aspects of EDM techniques and strategies employed by CVO personnel at volcanoes other than Mount St. Helens (Iwatsubo and Swanson, chapter 10; Doukas and Ewert, chapter 11). The rest of the chapters on deformation cover various aspects of leveling, including geodetic leveling (Dzurisin, chapter 12; Yamashita and Kaiser, chapter 13), single-setup leveling using classical (Yamashita, chapter 14) and trigonometric (Ewert, chapter 15) methods, and lake leveling (Kleinman and Otway, chapter 16) that draws from experience gained in the United States and New Zealand.

In the chapters on leveling we introduce the term *single-setup leveling* to replace the widely used but inexpressive and slang term *dry tilt*. The new term also replaces *tilt leveling*, which mixes a method (leveling) with a goal (to determine tilt). Single-setup leveling implies that the techniques of leveling are used with only one instrument setup—an implication that aptly describes the method. We hope that this more expressive term is used in the future by other workers.

The two chapters on geochemistry describe a technique for continuous monitoring of springs and lakes (McGee and others, chapter 17) and give an overview of an integrated approach to geochemical monitoring (Sutton and others, chapter 18). The geochemistry chapters reflect the perceived need of CVO's geochemists to obtain data in close to real time. Continuous geochemical monitoring of a variety of chemical species will no doubt provide important monitoring data that can be integrated with other monitoring data in the years to come.

The chapters on imaging describe the slow-scan-television surveillance system used to view the crater from 8.5 km away (Furukawa and others, chapter 19) and the photodocumentation efforts (Topinka, chapter 20) used to trace the development of the eruption and the evolution of the crater, dome, and adjacent landscape. The bulletin's final chapter (21), by Swanson, points out the value of on-site observations and measurements in monitoring volcanoes, stresses that such techniques constitute important components of any monitoring program, and puts forth the view that monitoring should be done in as simple a way as is practical.

The progress in monitoring techniques displayed in this bulletin is notable on several counts. Available technology has been adapted to monitor active volcanoes by a very small group of dedicated and innovative people. Most of the development of new procedures, and the modification of old ones, was conducted with the guiding philosophy of keeping the techniques as inexpensive as practical using easily accessible technology. This philosophy results in systems that are both suitable for, and within the budgetary reach of, developing nations that have a need to evaluate, monitor, and mitigate volcanic hazards. In addition, personal, hard-won, trial-and-error experience gained from ten years of monitoring Mount St. Helens and other volcanoes contributes significantly to the improved procedures.

Most of the chapters were written by the technical personnel of CVO, who were largely responsible for the development and testing of the monitoring technologies. The new and improved capabilities resulted from the stimulating, give-and-take environment fostered by an observatory setting in which scientific and technical staff interact and learn with each other on a daily basis. This sort of environment encourages people to ask themselves "how can we do this better" and gives them the opportunity and freedom to try to do better. We believe that the chapters in this bulletin demonstrate the wisdom of promoting and maintaining such an environment.

Nothing is permanent except change. All of the techniques described in the bulletin can and will be improved with time. Certainly modifications will need to be made on a case-by-case basis for each volcano that requires monitoring. The chapters in the bulletin should provide well-grounded starting points for such improvements. We particularly hope that scientists and technicians in developing countries—our primary audience—will find the bulletin useful and will be able to adapt the methodologies to their particular problems.

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1. A Real-Time Seismic-Amplitude Measurement System (RSAM)

By Thomas L. Murray *and* Elliot T. Endo

Abstract

Although several real-time earthquake detection and recorder systems exist, few address the problem of continuously measuring the amplitude of seismic signals during volcano-crisis conditions, when individual events are difficult to recognize. We developed a real-time seismic-amplitude measurement system (RSAM) that uses an inexpensive eight-bit analog-to-digital converter controlled by a laptop computer to provide 1-minute-averaged, absolute-amplitude information for eight seismic stations near Mount St. Helens. The absolute voltage level for each station is digitized at 60 samples/second, averaged, and immediately transmitted to a host computer for analysis. The RSAM provides a convenient-to-access, continuous time history of seismic activity at the volcano. RSAM systems calculating 10-minute amplitude averages have been installed at the Cascades, Alaska, and Hawaiian Volcano Observatories. The RSAM has been a useful tool in predicting eruptive activity at Mount St. Helens and Redoubt Volcano, Alaska.

INTRODUCTION

During a volcanic crisis, seismicity commonly reaches a level at which distinguishing individual seismic events is difficult. Analog seismic records provide some information, but rapid analysis is not always possible without substantially disturbing the continuity of recording. Although several real-time earthquake detection and recorder systems exist, most fail to provide quantitative information during periods of high seismicity that are commonly seen prior to a volcanic eruption. Yet it is during such conditions that quantitative seismic information needs to be processed most rapidly. To fill this need, we developed a simple and inexpensive real-time seismic-amplitude measurement system (RSAM).

The RSAM measures the absolute amplitude of as many as eight seismic signals. The sampling rate is roughly 60 samples/second per signal. From these data, two measurements are computed for each incoming signal.

1. The 1-minute average amplitude (absolute voltage) for each incoming signal is computed by summing the measurements made in the minute and dividing by the number of measurements. We have found that storing and analyzing 1-minute data for periods greater than a few days is cumbersome, owing to the sheer volume of data (1,440 measurements/day per signal). If a 10-minute average is computed using the the 1-minute averages, data are stored and analyzed more easily. At the Hawaiian Volcano Observatory (HVO) and Alaskan Volcano Observatory (AVO), 10-minute averages are used for analysis. There appears to be no loss of pertinent information using the 10-minute averages compared to the 1-minute average.

2. The number of events for each incoming signal occurring in a 10-minute period are counted by comparing successive 2-second average amplitudes. When the following conditions are met, the event counter for that input is incremented.

IF $A(n)$ is greater than THRESHOLD
and
IF $A(n)$ is greater than RATIO times $A(n\text{-}2)$

where $A(n)$, n=1,2,3... are the successive 2-second averages. THRESHOLD defines the minimum amplitude for an event and RATIO defines how much greater than background the amplitude must be to be considered an event. The default value for THRESHOLD is 5.0 RSAM units and for RATIO is 2.0.

Since no effort is made by the RSAM to discriminate seismic events from landslides, rockfalls, and other surface noise, the measurement is referred to as an "RSAM event," not a seismic event or earthquake.

The data are transferred at 10-minute intervals to a host computer, where they are immediately available for analysis (Murray, chapter 4). In this manner, seismicity can be quantitatively monitored in near-real time (within 10 minutes of acquisition), even during periods of intense tremor.

Energy release can also be monitored in near-real time. By squaring the average amplitude, a number proportional to the electrical energy generated by the movement of the geophone is computed. More study is required to determine the exact relationship between this electrical energy and seismic energy.

Although the method seems almost too simple to be effective, the RSAM proved useful predicting the May 1985, May 1986 (fig. 1.1), and October 1986 dome-building episodes at Mount St. Helens and the major January 2, 1990, eruption of Redoubt Volcano, Alaska (fig. 1.2). The RSAM data from stations close to the lava dome (Yellow Rock and St. Helens West) began to rise above background noise some 48 hours before the time of extrusion of a new lobe (fig. 1.1). The amplitudes continued increasing and peaked near the probable time of extrusion (exact time of extrusion is not known). The spikes and high amplitudes following extrusion were due to surface activity resulting from the emplacement of a new lobe.

The energy release curve prior to the January 2, 1990, eruption of Redoubt Volcano, Alaska, is shown in figure 1.2. The steepening of the curve beginning on January 1 was instrumental in the prediction of the eruption (J. Power, oral commun., 1990).

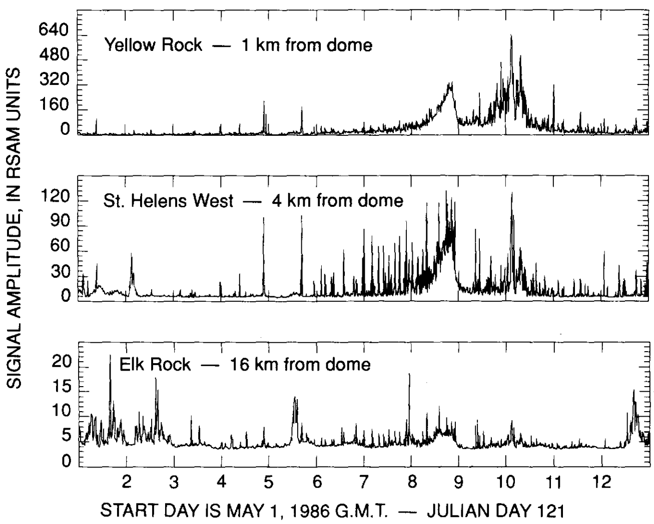

Figure 1.1. Fifteen-minute average amplitudes for three seismic stations during the May 1986 Mount St. Helens dome-growth episode. Stations Yellow Rock and St. Helens West began showing increased activity 2 or 3 days before the extrusion of the new lobe on or around May 9 and showed dramatic increases the day prior to the extrusion. The signal amplitude at Elk Rock during the episode did not increase much above background and is smaller in amplitude than wind noise recorded on May 1, 2, 5, and 12. This shows the importance of using the RSAM in conjunction with analog records.

The simplicity of the RSAM can aid in communicating levels of seismicity to public officials, who may be unfamiliar with the standard jargon used by seismologists. An RSAM time-series plot can, in many cases, show relative seismic activity more effectively than can graphs showing earthquake depths and magnitudes, or the number of long-period versus short-period earthquakes (Fairbanks Daily News-Miner, 1989).

The RSAM is not meant to replace a conventional seismic system. Instead, it complements a conventional system, giving real-time information on tremor-amplitude levels while earthquake locations and magnitudes are being computed by other systems. During times of little or moderate activity, the RSAM may be only marginally useful and especially susceptible to contamination by wind or other surface noise. During these times the RSAM should be used in conjunction with analog seismic records. But during times of tremor or intense earthquake activity, when conventional seismic systems fail to keep pace with activity and analog records become a blur, the RSAM can become the primary monitor of seismicity.

The RSAM can be used as a standalone unit, but we highly recommend that it be configured to transfer data to a more powerful host computer at 10-minute intervals. The host computer archives the data and enables them to be integrated with other volcano-monitoring information for near-real-time analysis (Murray, chapter 4).

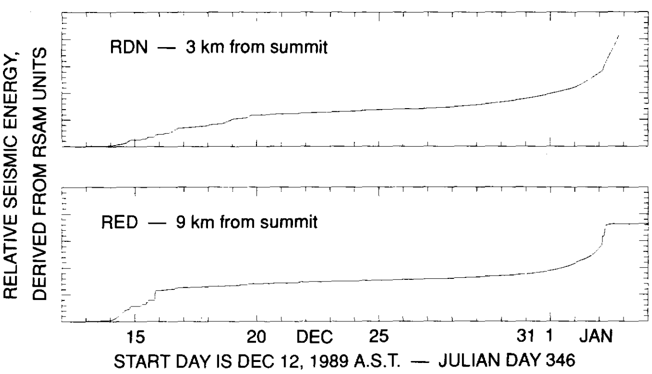

Figure 1.2. Cumulative RSAM energy release for stations RDN and RED for the January 2, 1990, eruption of Redoubt Volcano, Alaska. RSAM energy is calculated by squaring the average amplitude. Because the relation between RSAM energy and seismic energy is not yet known, the shape of the curve, not the actual amount of energy, provided the information used in predicting the eruption.

GENERAL DESCRIPTION

The real-time seismic-amplitude measurement system consists of a Tandy (Radio Shack) Model 100 laptop computer (or Model 102, which is essentially the same except for the system bus socket) and an in-house-designed data-acquisition board. The entire unit fits easily in a space 25.4 cm by 33 cm by 5.0 cm. Low power consumption (90 mA at 12 V) allows the unit to be powered by a car battery and solar panel if necessary.

The data acquisition board (fig. 1.3) buffers the eight seismic input signals and puts them through 0.1-Hz high-pass filters to eliminate any DC offsets. The multiplexer selects the desired signal for sampling. The signal is then full-wave rectified to convert any negative component to a positive voltage. The signals are digitized with an eight-bit analog-to-digital converter. Communication between the acquisition board and the computer is through the computer's system bus, freeing the computer's other ports for connection to other peripherals.

Generally, data from the RSAM are shown in RSAM units. RSAM units are the average value of the output of the eight-bit analog-to-digital converter, multiplied by 10 so as to be an integer. In a system set up for discriminators with a ±2.5-volt output, one RSAM unit is roughly 1 millivolt. For more precise measurements, each unit should be individually calibrated.

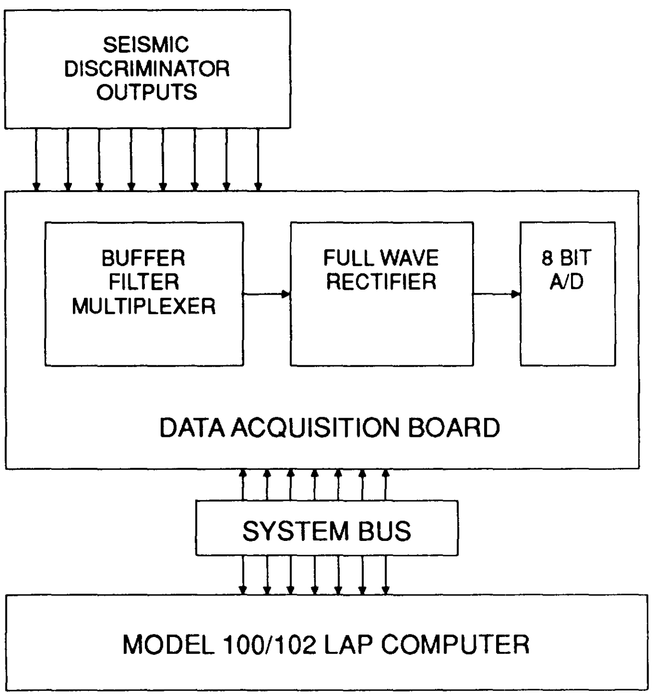

Figure 1.3. RSAM hardware block diagram.

Data Acquisition and Processing

The computer calculates the average signal amplitude once a minute for each input by simply dividing the sum of each input's digitized samples by the number of samples. Taking the average over a 1-minute period allows the cessation of data acquisition for short periods in order to process the data. This greatly simplifies programming, because data acquisition and processing do not have to be performed concurrently. The data processing requires roughly 0.5 second for every 2 seconds of data acquisition at 60 samples/second. Most of the processing time is due to the event detection routine.

At the beginning of each minute, a call to the data-acquisition subprogram causes the computer to digitize 125 samples for each seismic input at a rate of approximately 60 samples/second/input and return the sums of the digitized values. The returned sums are added to running totals for the entire minute. At this point the data are checked to determine if an RSAM event has occurred. Another call is then made to the data-acquisition subprogram, and the cycle continues throughout the minute. At the end of the minute, the average amplitudes are computed by dividing the running totals by the number of samples. The process then starts again for the next minute's data (fig. 1.4). Depending on the specific site setup, the averages can be sent to a more powerful computer via an RS-232C link for analysis, stored in memory for later access, or merely sent out to a printer. The Model 100/102, though only a 32 kilobyte, 8085-based computer, still allows for numerous options.

A full listing of the standard program used by the RSAM is in Murray and Endo (1989).

DATA ACQUISITION HARDWARE

The RSAM data-acquisition board can be divided into three sections: (1) power supply, (2) system-bus interface, and (3) signal conditioner/converter. The circuit schematic is shown in figures 1.5 and 1.6, and the parts are listed in table 1.1.

Power Supply

The power supply (U5 through U8) converts the 12-volt input (J2) to ±12 volts to power the analog section of the circuit, ±5 volts for the multiplexer, and +6 volts to power the computer via J3. This allows the entire unit to be powered by a 12-volt battery. Current draw is under 100 milliamps.

System-Bus Interface

The system-bus interface (U1 thru U4) performs the address decoding for the programmable interface adapter (PIA), U1, and the analog-to-digital converter (A/D), U9. A 40-conductor ribbon cable between J1 and the Model 100/102's system bus socket connects the board to the computer. Input-output (I/O) addresses 0–127 of the Model 100/102 are available for external uses such as this acquisition board. Switch S1 selects the address block (32–63, 64–95, or 96–127) in which the PIA will reside. The three blocks allow as many as three of the boards to be hooked to a single Model 100/102 (although at present adding the second or third board has not been implemented). S2 sets the I/O address for the A/D. Although S2 can be set to any address under 128, we recommend that it be set to one in the 0–31 block, leaving the higher addresses for the PIA's.

Note that only three of the PIA's 22 digital I/O lines are used to control the multiplexer. The remaining lines are available for circuit enhancements.

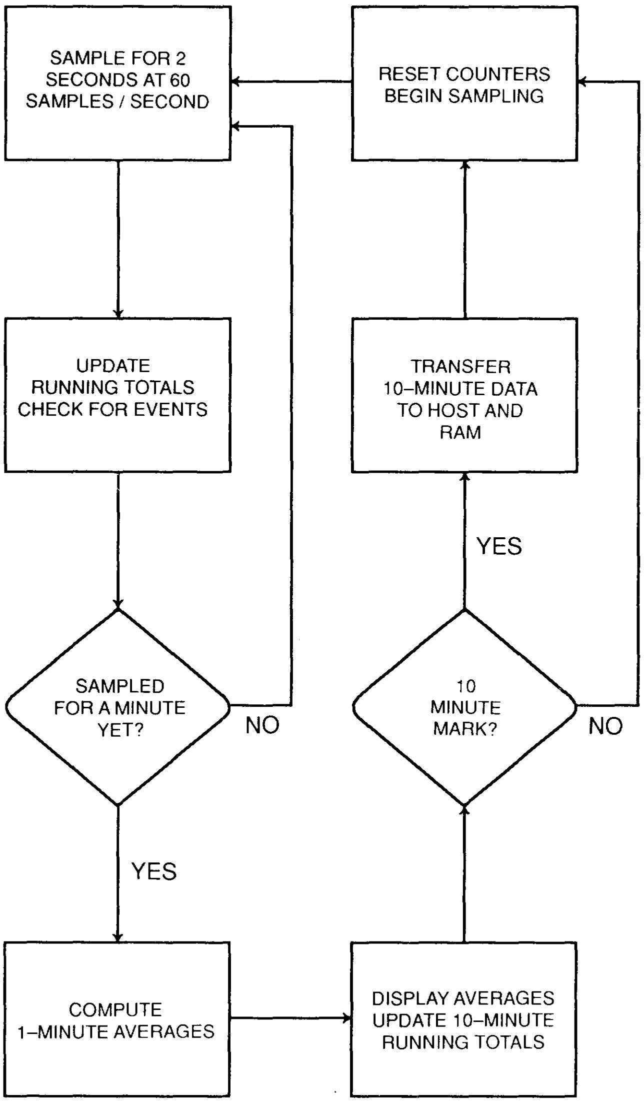

Figure 1.4. RSAM software flow chart.

Table 1.1. Parts list for data acquisition board.

Part	Value	Description
C1-C2	10mF	Electrolytic, 16 V
C3-C4	100mF	Electrolytic, 16 V
C5-C6	10mF	Electrolytic, 16 V
C7	150pF	Ceramic disk
C8-C12	0.1mF	Mallory CK05BX104K
C13	33mF	Kemet T352-F336K-010AS
C22-C35	33mF	Kemet T352-F336K-010AS
C37-C38	0.1mF	Mallory CK05BX104K
RN1	100K	Bourns 4610x-101 100K
R2	10k	Pot
R3	2.7k	5%, 1/4 W
R4	10K	5%, 1/4 W
R22-R43	100K	5%, 1/4 W (8 resistors total)
R82-R86	10K	5%, 1/4 W (5 resistors total)
D1		LM 385-1.2 for ±2.5 V inputs
		LM 336-2.5 for ±5.0 V inputs
D2-D3		1N914
D4		1N5818
D5-D6		1N914
D10-D11		1N914
U1		National Semiconductor NSC810
U2		74HC138
U3		CD4011B
U4		74HC688
U5		ICL7662
U6		78L05CP
U7		LM7806CK
U8		ICL7662
U9		ADC0803LCN
U10-U17		TL022
U18		CD4051B
U19		LM358

Signal Conditioner/Converter

The analog seismic signals enter the board via J5. All the signal lows are shorted to ground. These signals

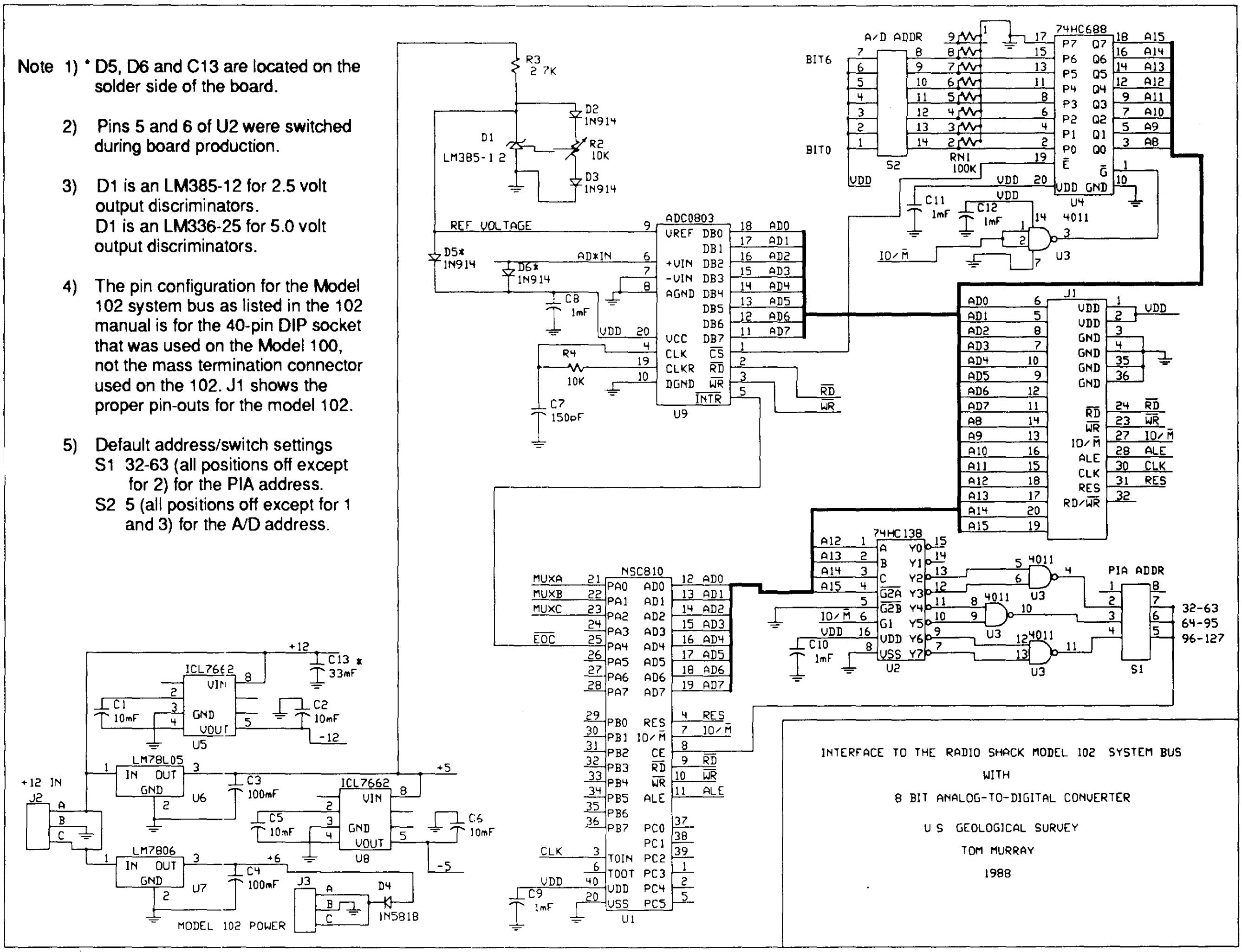

Figure 1.5. Circuit diagram for power supplies, analog-to-digital converter, and Model 100/102 system-bus interface of data-acquisition board.

should be tapped from either the outputs of the discriminators or the inputs to the analog drum recorders.

U10-U17 buffer each of the eight signals and send them through 0.1 Hz high-pass filters to remove any DC offsets. Bits 0-2 of port A of the PIA control which input the multiplexer (U18) switches to the A/D (U9) for digitizing. Since the A/D will accept only positive voltages, the signal must be full-wave rectified (U19) before it is digitized.

D1 supplies the reference voltage for the A/D. The full-scale input voltage for the A/D is twice the reference voltage. For signals with a range of ±2.5 volts, a 1.22-volt reference (LM385-1.22) is used. For signals with a range of ±5.0 volts, a 2.5-volt reference (LM336-2.5) is used. Note that R2 can be used to set the LM336-2.5 to precisely +2.500 volts, but no such adjustment is possible with the LM385-1.22.

CONCLUSION

The RSAM is not meant to replace analog seismic recorders or conventional seismic data-acquisition systems. Its inability to distinguish cultural noise from volcanic seismicity precludes using it without some method to visually inspect the analog seismic records. It is also of only marginal value during times of low seismicity. However, as seismicity increases during a volcanic crisis, the RSAM's value increases. The higher the level of seismicity, the more potentially important the RSAM becomes. Depending on the nature and level of seismicity, the RSAM may provide the only near-real-time quantitative measure of seismic activity. The RSAM has repeatedly demonstrated its utility in monitoring and predicting eruptions and has become an essential monitoring tool at the Cascades and Alaska Volcano Observatories.

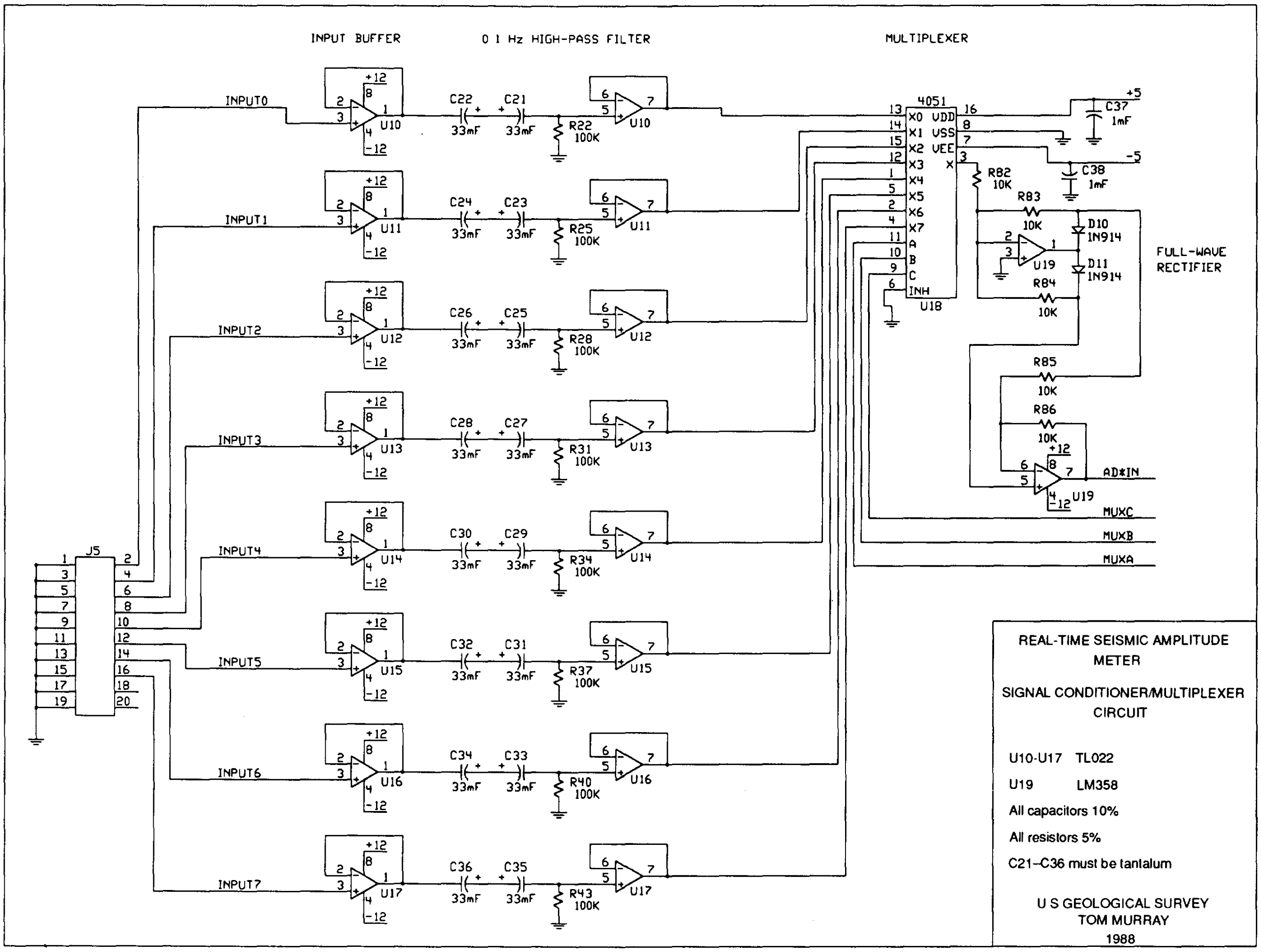

Figure 1.6. Circuit diagram for signal-conditioner/ multiplexer of data-acquisitiion board.

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Fairbanks Daily News-Miner, 1989, Travelers wait as Redoubt rumbles anew: December 19, p. 5.

Murray, T.L., and Endo, E.T., 1989, A real-time seismic amplitude measurement system (RSAM): U.S. Geological Survey Open-File Report 89-684, 26 p.

2. A Low-Data-Rate Digital Telemetry System

By Thomas L. Murray

ABSTRACT

Telemetering data from electronic devices that sense ground tilt, temperature, strain, gas concentration, and other phenomena can provide valuable information regarding current or impending volcanic activity. To facilitate such monitoring, I developed a low-data-rate digital telemetry system that transmits data at 10-minute intervals over VHF/UHF radio links to a central receiving site. Analog voltages are digitized with a 12-bit-plus-sign analog-to-digital converter in the field. The data are transmitted in Bell 103 format so that most computers with a Bell 103 compatible modem attached to their serial port can receive, process, and store the data. A 9-gallon steel drum houses the entire transmitter including radio, antenna, and sufficient batteries to power the unit for a year. Design considerations imposed by Mount St. Helens resulted in a robust, low-cost, low-power system with wide applicability at other volcanoes.

INTRODUCTION

Measuring ground tilt, gas concentrations, temperature, and other phenomena at 10-minute intervals can be useful in assessing volcanic activity (Dzurisin and others, 1983; McGee and others, 1987). Telemetering such measurements to a central receiving site provides near-real-time information on the status of a volcano when personal observation or on-site data collection is impractical due to high hazards or inclement weather. The system decribed here is a low-data-rate system in which measurements are made and transmitted at intervals greater than or equal to 1 minute. Its operation resembles that described by Roger and others (1977). Individual field transmitters accept up to 16 analog inputs. These inputs are digitized, and the data are transmitted by radio to a central receiving site at preselected intervals, usually every 10 minutes. Transmissions typically take less than 10 seconds, allowing the transmitter to be in a low-power sleep state most of the time. This procedure not only conserves power but also allows numerous transmitters to share the same radio and audio frequency. Each transmitter in turn activates itself, transmits its data, and goes back to sleep. Other transmitters can then transmit their data. The transmissions are received by a common radio receiver and relayed through the modem port of a battery-powered laptop computer for decoding and data storage.

The system was first used at the Cascades Volcano Observatory (CVO) in 1984. Since then, systems have been installed in Colombia, Ecuador, Guatemala, and Alaska. Data from tiltmeters, temperature sensors, magnetometers, strainmeters, gas sensors, and water-quality sensors have been transmitted through the system.

The data are usually transmitted back to a receiver located in an established volcano observatory, but this does not have to be the case. A four-transmitter network established in 1987 at Yellowstone Lake, Wyoming, transmits data to a Radio Shack Model 100 computer housed in a shed behind the nearby Lake Ranger Station. The data are transferred weekly to CVO through the phone system. Though a faulty fuse at the receiver caused some loss of data in the first year, the system has been operating since without a problem.

The following is a general description of the transmitter. I describe the operation of the transmitter in more detail in Murray (1988).

DESIGN CONSIDERATIONS

Telemetering data from the crater of Mount St. Helens presents several problems that constrain the design of the transmitter. The sites are located on and around the lava dome, which is situated in a horseshoe-shaped crater opening to the north. Some of the monitoring sites are situated on small ledges on the flanks of the dome. The sites can be buried by as much as 3 m of snow during the winter, making them inaccesible for up to 6 months of the year. Radio power, physical size, and power consumption were the primary considerations in designing the system, and each is discussed below.

Radio Power

Because of the horseshoe shape of the crater, a transmitter on the south flank of the dome does not have line-of-sight radio contact with the repeaters located to the north. This geometry requires the radio signal to be sufficiently powerful to reflect off the crater wall and out to the north. High-gain antennas are impractical owing to site considerations, so high-power (4 watt) radios are used instead of the 100–250 mW radios used at many telemetered seismic stations.

Physical Size

The stations on the flanks of the lava dome are commonly located on narrow ledges situated at the tops of talus slopes. These ledges can be as small as 0.3 m^2. Although the talus is sufficiently stable to stand upon when installing or servicing a site, it does not provide a stable platform for the transmitter. Hence, the entire transmitter package (electronics, battery, and antenna) must be small enough to fit on the ledges.

Power Consumption

Many of the sites on the dome are completely inaccesible from December to June owing to winter snowfall. Primary batteries must be used at these sites, since ashfall, wind-blown silt, and topography make solar panels impractical. Access to these sites is by helicopter (expensive) or by foot (time-consuming), so it is desirable that the transmitters operate a full year without replacing the batteries. The limited space on the ledges limits the size and number of batteries that can be used, in turn constraining the power consumption.

SYSTEM FEATURES

Using the above considerations as guidelines, I designed a digital transmitter with the following features:

1. Low power consumption. The average power consumption for the digital transmitter, when it is transmitting four measurements at 300 baud every 10 minutes, is under 300 μA at 12 volts. The power consumption of the radio is much larger. A 4-watt radio draws as much as 900 mA at 12 volts while transmitting; its average power consumption for the above example is 6.2 mA at 12 volts. The total power requirement for the site (excluding that required for the sensors) for a year is just under 60 amp-hours. Two 20-amp-hour 6-volt alkaline batteries connected in series can power the digital transmitter for 1 year. The radio requires four 40-amp-hour 7.5-volt alkaline batteries connected in series-parallel to power it for a year.

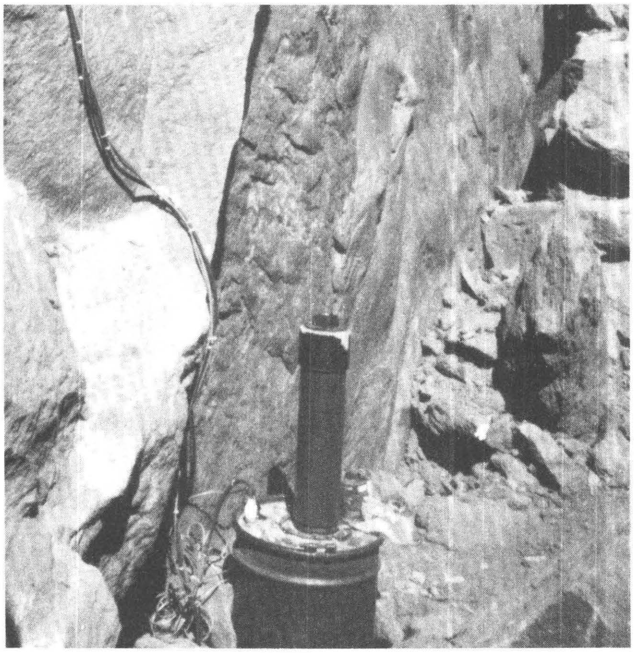
2. Transmitting data at 300 baud in standard Bell 103 format. The transmitter utilizes a single-chip modem (Motorola MC14412FP) to transmit data over radio links in Bell 103 format. This allows nearly any computer with a 300-baud Bell 103 compatible modem to receive the data. No custom circuitry other than the cable is required between the radio and the modem. The Bell 103 format also allows the transmissions to be summed with seismic signals and share radio links, though at the expense of two seismic audio bands (either 1,020 and 1,360 Hz or 2,040 and 2,380 Hz). When summed with the seismic signals, a filter may be required at the receiver if the modem filter does not discriminate the signal well enough.

3. Sharing a single radio and audio frequency. The short amount of time required to transmit the data also allows multiple transmitters to share a single audio and radio frequency. The situation is analogous to having numerous field crews communicating with each other using the same voice radio frequency. Each crew's radio is in transmit mode for only the duration of the message, or 2 seconds. At the end of the message, the radio transmitter is turned off, allowing another crew to transmit a message. Just as when two people try to transmit a message at the same time, transmissions may interfere with each other. Like the system described by Roger and others (1977), the system described here does not try to prevent these "collisions" but instead transmits data at semi-random intervals often enough that occasional collisions can be tolerated. The transmit interval is randomized by using inexpensive, relatively inaccurate oscillators. The transmission interval, though nominally set for 10 minutes, actually varies from 8 to 12 minutes. Transmission collisions between stations do occur, but owing to the variability in the transmit–interval, the next transmissions from two "colliding" stations are unlikely to overlap, and both transmissions will be successfully received.

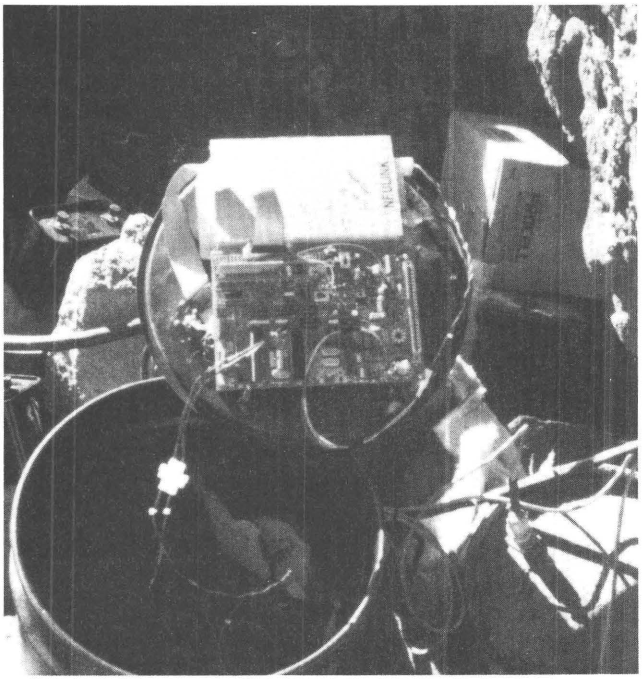
4. Utilizing 4-watt radio transmitters. The time required to transmit the data (2 seconds) is short relative to the time between transmissions (10 min), hence radios whose output power is 4 watts or more can be used without excessive power consumption. These radios can generally eliminate the need for the yagi antennas required by radios typically used at seismic stations, whose output powers are low (100–250 mW) owing to their 100 percent duty cycle. Eliminating the yagis reduces cost, bulk, weather-related problems, and visibility.

5. Transmitting data twice to determine its validity. Each measurement is transmitted in a six-byte message.

The first two bytes contain the data, and the third contains the channel (measurement) identifier (channel ID) indicating which sensor's datum is being transmitted.



A



B

Figure 2.1. *A*, Transmitter, radio, and batteries housed in a metal drum. Antenna is mounted on lid and is protected from snow and ice by a plastic pipe. *B*, Radio (top) and transmitter (bottom) mounted on the inside of the lid.

The fourth and fifth bytes are bytes one and two repeated. The sixth byte is the channel ID repeated. A message is considered valid only when the first three bytes are the same as the last three.

6. Putting the transmitter, radio, antenna, and batteries in a single package. At Mount St. Helens, the transmitters are housed in 9-gallon metal drums (fig. 2.1). The transmitter board and radio are mounted on the inside of the lid with alkaline batteries placed in the bottom of the drum. The drum has sufficient space to house enough batteries to power the system for 1 year at a 10-minute transmit interval. A quarter-wave whip antenna is attached to the top of the lid. The metal lid provides an excellent ground plane for the antenna. Plastic pipe 10 cm in diameter is attached to the lid to protect the antenna from snow and ice.

7. All logic in hardware, not software. The transmitter's logic is hardware based, not microprocessor based. Switches are used to set the transmit interval, channel IDs, and so on. Delays are determined by resistor-capacitor (RC) time constants. The field transmitters take samples at set intervals and transmit the data. Any changes to this operation, such as averaging data or transmitting data more often if certain values reach a threshold, cannot be done without modifying the board. Such modification is not easy, whereas with microprocessor-based systems, the changes could be easily implemented in software. Logic based in hardware has some advantages, however. Most of the integrated circuits are manufactured by several companies and are readily available in most countries. Also, troubleshooting does not require a high-speed oscilloscope or logic analyzer. A relatively slow (200 kHz) oscilloscope, a volt-ohm meter, and a frequency counter (MHz) are all that are usually required.

8. Field troubleshooting. A Radio Shack Model 100/102 battery-powered laptop computer with an integral Bell 103 modem serves as a portable field receiver. The Model 100/102 allows viewing of the data being transmitted in the field. The data's validity can checked before leaving the site.

9. Low cost. The cost of parts for a complete transmitter excluding radio is currently under $550. The cost of a radio transmitter ranges between $200 and $500.

THEORY OF OPERATION

The transmitter consists of 10 blocks (fig. 2.2):

1. Clock
2. System power supply
3. Transmission-control logic
4. Analog multiplexer

5. Analog-to-digital converter (A/D)
6. Channel ID counter
7. Number-of-channels-transmitted counter
8. Universal asychronous receiver transmitter (UART)
9. Modem
10. Radio

To conserve power, the transmitter is normally in a low-power sleep state; power is applied only to the clock and, if used, IC U14 (one of two choices for the analog multiplexer; see below). At switch-selectable intervals, the clock enables the system power supply, and the transmitter-control logic begins the data-transmission sequence. Counters indicating the initial analog input to be selected for digitizing and the channel ID are set to the proper values. The selected analog input is then digitized.

The radio transmitter, which was off to prevent radio frequency interference during the A/D conversion, is now enabled. The digitized data and its channel ID are converted in turn by the UART from 8-bit parallel data to 8-bit serial data. The serial data stream is converted by the modem to audio tones, which are transmitted by the radio. The radio transmitter is disabled at the completion of the transmission. The number-of-channels-transmitted counter, the analog-input-select counter, and the channel ID counter are incremented by one. If all of the scheduled channels have been transmitted, the system power supply is disabled and the digital transmitter returns to its sleep state. If, however, another channel is to be transmitted, the next analog input is digitized and the data transmitted as before. The data-transmission sequence continues until the designated number of channels has been transmitted.

CIRCUIT DESCRIPTION

The circuit schematic for the transmitter is shown in figure 2.3 and the parts list is given in Table 2.1.

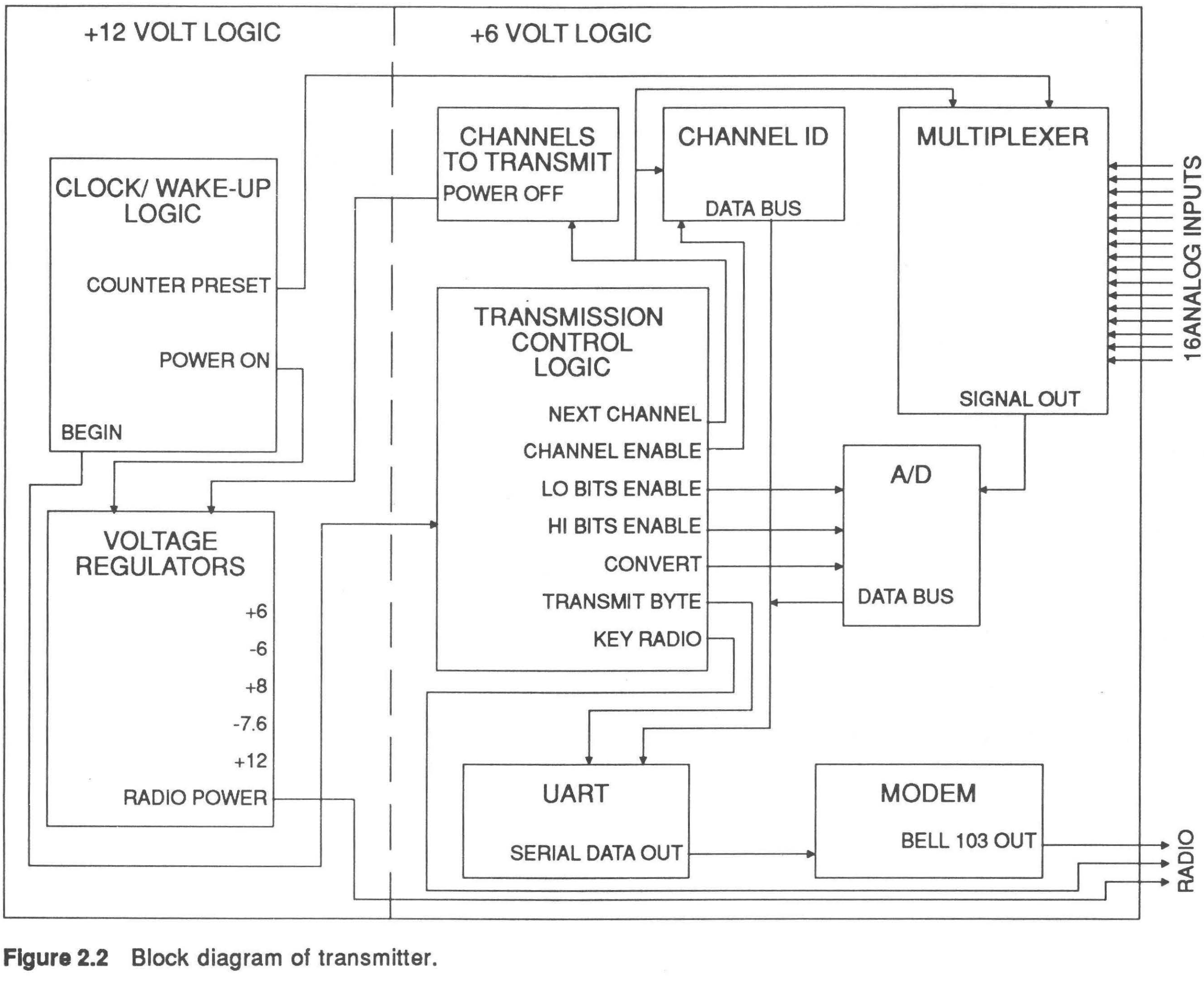


Figure 2.2 Block diagram of transmitter.

Table 2.1. Parts list for digital transmitter circuit board.
[Pin-for-pin equivalent components from manufacturers other than those listed may be substituted]

Part No.	Part	Value	Comments
C1	ceramic disk	.1 µF	
C2	ceramic disk	.01 µF	
C3	not used		
C4	electrolytic	10 µF	
C5	not used		
C6	ceramic disk	.1 µF	
C7	ceramic disk	.01 µF	
C8–C11	electrolytic	10 µF	
C12	electrolytic	15µf	
C13	ceramic disk	47µF	
C14	electrolytic	10 µF	
C15	ceramic disk	.01µF	
C16	polypropylene	.1µF	Electrocube 935B1B105K
C17	ceramic disk	.01 µF	
C18	polypropylene	.22 µF	Electrocube 935B1B224K
C19	polypropylene	.47 µF	Electrocube 935B1b474K
C20	ceramic disk	.01 µF	
C21	not used		
C22	ceramic disk	.47 µF	
C23-24	ceramic disk	.001 µF	
C25	tantalum	1 µF	
C26-27	ceramic disk	56 pF	Needed if U29 is a IM4702IPE
C28	ceramic disk	.01 µF	
C29	ceramic disk	.01 µF	
C30	electrolytic	10 µF	
C31-C32	electrolytic	22 µF	
C33	ceramic disk	.01 µF	
R1	resistor	750K	1/4 watt 5% carbon
R2	resistor	100K	1/4 watt 5% carbon
R3	resistor	200K	1/4 watt 5% carbon
R4	not used		
R5-R7	resistor	100K	1/4 watt 5% carbon
R8	not used		
R9	resistor	100 K	1/4 watt 5% carbon
R10	resistor	3M	1/4 watt 5% carbon
R11	resistor	1M	1/4 watt 5% carbon
R12	resistor	20	1/4 watt 5% carbon
R13	resistor	360K	1/4 watt 5% carbon
R14	resistor	100K	1/4 watt 5% carbon
R15	resistor	20	1/4 watt 5% carbon
R16	resistor	510	1/4 watt 5% carbon
R17	resistor	100	1/4 watt 5% carbon
R18	shorted		
R19	not used		
R20	resistor	1M	1/4 watt 5% carbon
R21-R33	resistor	100K	1/4 watt 5% carbon
R34	resistor	150K	1/4 watt 5% carbon
R35	resistor	100K	1/4 watt 5% carbon
R36	resistor	1M	1/4 watt 1% RN60C
R37	resistor	250K	1/4 watt 5% carbon
R38	resistor	2.4K	1/4 watt 5% carbon
R39	resistor	100K	1/4 watt 5% carbon
R40	resistor	1M	1/4 watt 5% carbon
R41	resistor	150K	1/4 watt 5% carbon
R42	resistor	100K	1/4 watt 5% carbon
R43	shorted		
R44	not used		
R45-R53	resistor	100K	1/4 watt 5% carbon
R54	not used		1/4 watt 5% carbon
R55	resistor	100K	1/4 watt 5% carbon
R56	resistor	10M	1/4 watt 5% carbon
R57	resistor	15M	1/4 watt 5% carbon
R58-R59	resistor		1/4 watt 5% carbon
R60-R61	resistor		Selects VCO output range
R62-R64	potentiometer		Spectrol 64W103
R65	potentiometer		Spectrol 64W104
R66	potentiometer		Spectrol 64W103
R67	resistor	100K	1/4 watt 5% carbon
R68	resistor	100	1/4 watt 5% carbon
R69	resistor	100K	1/4 watt 5% carbon
R70	resistor	20K	1/4 watt 5% carbon
R71	resistor	100K	1/4 watt 5% carbon
D1-4	diode	IN914	

Table 2.1. Parts list for digital transmitter circuit board.—*Continued*
[Pin-for-pin equivalent components from manufacturers other than those listed may be substituted]

Part No.	Part	Value	Comments
D5	tranzorb		General Semiconductor #1.5KE18CA
D6	diode		Motorola IN5400 (3 amp)
D7-D14	IN914		
Z0-Z15	tranzorb		General Semiconductor #1.5KE7.5CA (optional)
Q1	MOSFET		Siliconix VP0300L
Q2-Q3	MOSFET		Motorola IRF511
S1	switch	10 position	
S2-S3	switch	DPDY	Sprague QSP 1410
S4-S5	switch	8 pole DIP	C&K BD08
S6	switch	4 pole DIP	C&K BD04
S7	switch	8 pole DIP	C&K BD08
s8-s9	switch	4 pole DIP	C&K BD04
Y1	crystal	3.5795 MHz	US Crystal
Y2	crystal	2.4576 MHz	US Crystal
Y3	crystal	1.0 MHz	US Cryata;
T1	transformer	600 ohm primary/secondary impedance	
U1	integrated circuit	CD4047BE	National
U2	integrated circuit	CD4020BE	National
U3	integrated circuit	CD4043BE	National
U4	integrated circuit	CD40106BE	National
U5	integrated circuit	CD4050BCN	National
U6	integrated circuit	MC14504BCP	Motorola
U7	integrated circuit	ICL7663CPA	Intersil
U8	integrated circuit	ICL7660CPA	Intersil
U9	integrated circuit	ICL7663CPA	Intersil
U10	integrated circuit	ICL7660CPA	Intersil
U11	integrated circuit	MC14017BCP	Motorola
U12	integrated circuit	MC14017BCP	Motorola
U13	integrated circuit	MM74C193N	National
U14	integrated circuit	HI-506-A	Harris (optioned w/U32)
U15	integrated circuit	OP07CZ	PMI
U16	integrated circuit	MM74C193N	National
U17	integrated circuit	MM74C193N	National
U18	integrated circuit	MM74C373N	National
U19	integrated circuit	CD4043BE	National
U20	integrated circuit	CD40106BE	National
U21	integrated circuit	MC14081BCP	Motorola
U22	integrated circuit	ICL7109IJL	Intersil (ext. temp.)
U23	integrated circuit	LM236H-2.5	National (ext. temp.)
U24	integrated circuit	MC4081BCP	Motorola
U25	integrated circuit	CD4075BCN	National
U26	integrated circuit	MC14017BCP	Motorola
U27	integrated circuit	CD4001BCN	National
U28	integrated circuit	IM6402IPL	Intersil
U29	integrated circuit	IM4712IPE or IM4702IPE	Intersil
U30	integrated circuit	MC14412FP	Motorola
U31	integrated circuit	TLO22CP	Texas Instruments
U32	integrated circuit	CD4051BF	National (optioned w/U14)
J1	I/O connector	A P 925225-26-R	
J2	44 pin edge card connector		
J3	44 pin edge card connector		Spare PCB connector
	8 pin DIP socket	Augat 508-AG37D	(9 total)
	14 pin DIP socket	Augat 514-AG37D	(7 total)
	16 pin DIP socket	Augat 516-AG37D	(18 total)
	20 pin DIP socket	Augat 520-AG37D	(1 total)
	28 pin DIP socket	Augat 528-AG37D	(1 total)
	40 pin DIP socket	Augat 540-AG37D	(2 total)

Clock

The clock (U1, CD4047) is a low-power oscillator whose output frequency (approximately 2 Hz) is divided into nine switch-selectable transmit intervals. The intervals range from nominally 36 seconds to 2.5 hours. A resistor and capacitor determine the exact output frequency of the oscillator. Using standard-grade components with accuracies of ±5% or poorer ensures that the transmission interval will be variable between transmitters. A nominal 10-minute transmit interval may vary between 8 and 12 minutes.

System Power Supply

A positive transition at the output of the clock circuit awakens the transmitter from its low-power sleep state by enabling the power supply. Low-quiescent-current linear regulators, U7 and U9 (ICL7663), and voltage inverters, U8 and U10 (ICL7660), provide ±6 and ±8 volts. A P-channel metal oxide semiconductor field effect transistor (MOSFET), VP0300L, provides a switched +12 volts for use in powering sensors. Power ground is switched to the radio through an N-channel MOSFET. However, the radio is not put into transmit mode at this time.

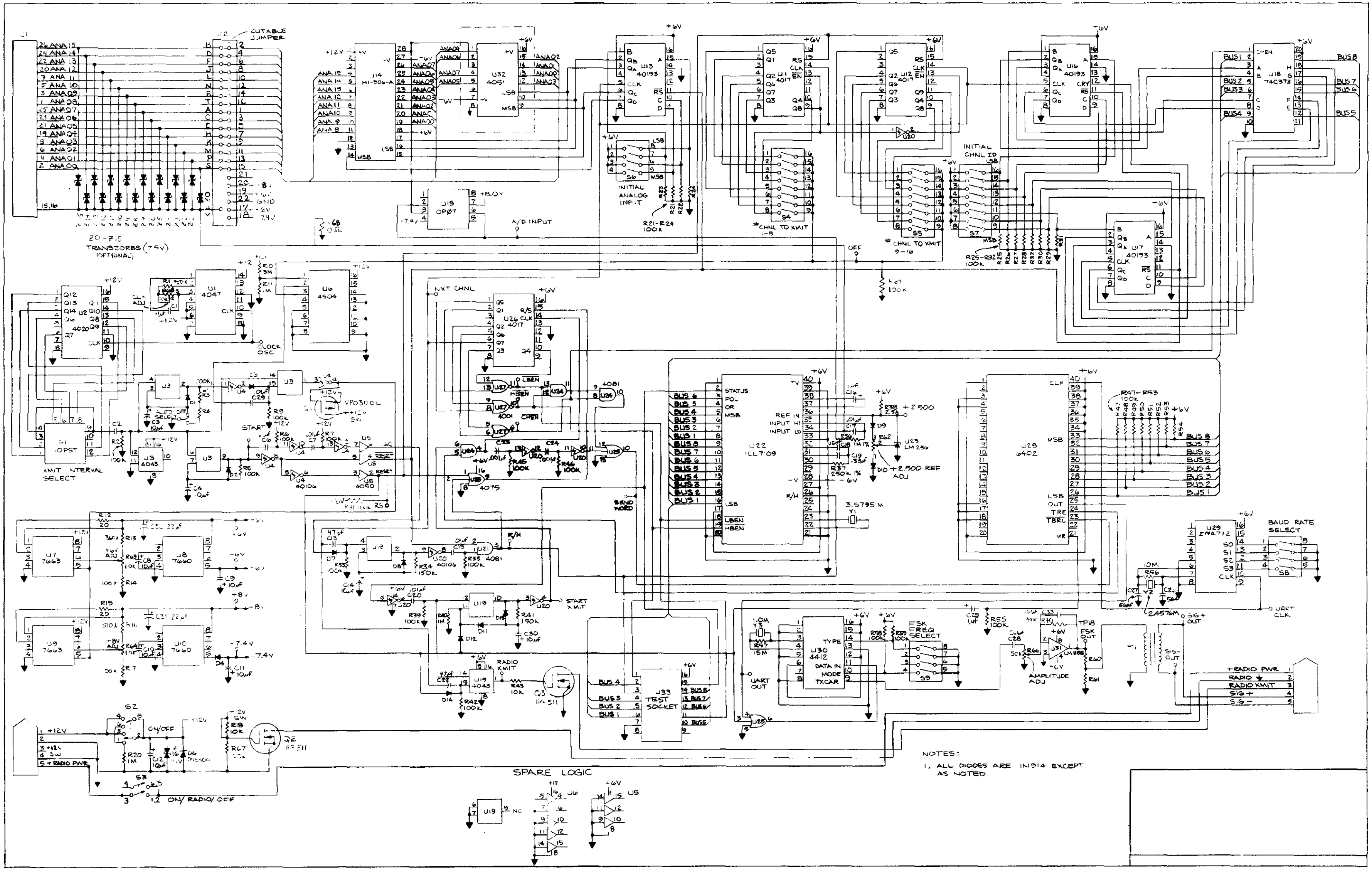


Figure 2.3. Circuit schematic for transmitter.

Transmission-control Logic

ICs U19-U20 and U24-U27 control the sequence of events after the transmitter is awakened from its sleep state (fig. 2.4). Using resistor-capacitor circuits for timing delays, the control logic increments the counters, initiates the A/D conversions, controls the radio transmitter, and sequentially gates data and the channel ID into the UART (discussed below) for the parallel-to-serial conversion.

Analog Multiplexer

Either of two multiplexers, the HI-506-A (U14) or the CD4051 (U32), is used to switch the analog input signals to the A/D converter for digitizing. The HI-506-A allows up to 16 inputs and is overvoltage-protected; it can withstand ±25 volts applied to its inputs even when it is not powered. The HI-506-A is manufactured by Harris Semiconductor and currently costs about $20. The CD4051 is an 8-channel multiplexer with no overvoltage protection. It is readily available from numerous suppliers for less than $1.

I originally thought that the HI-506-A, with its overvoltage protection, would be used in situations where analog input signals are present while the transmitter is in its sleep state. This would occur if the sensors were always on. If the sensors are active only when the transmitter is in its active state, the CD4051 could be used.

I later found that although the HI-506-A is not damaged by applying signals to it when the power supplies are off, the applied voltage leaks through the multiplexer to its power pin. Owing to the low power requirements of the

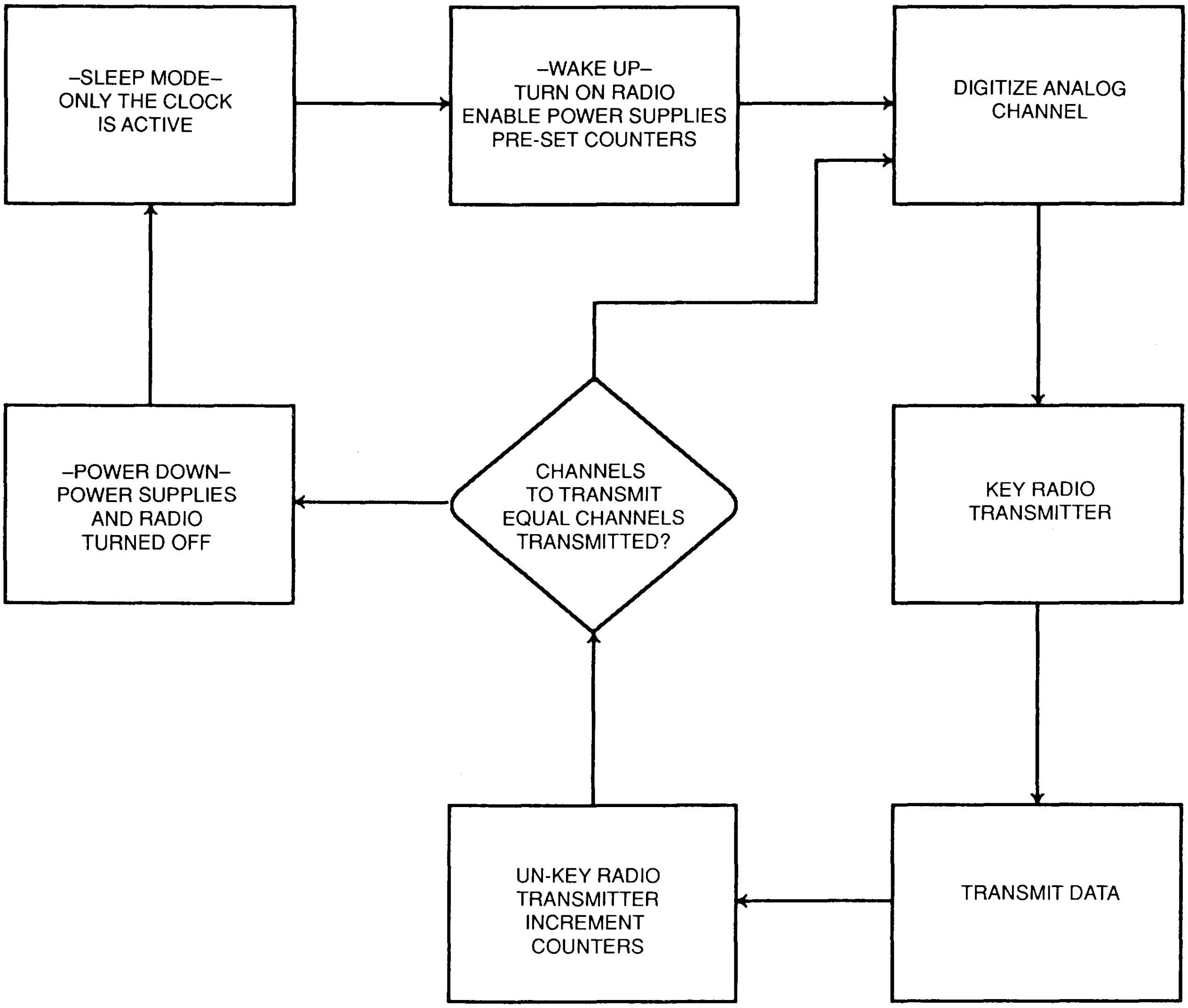


Figure 2.4. Flow chart for transmission control logic.

transmitter, this leakage can be sufficient to power the board. When this occurs, the transmitter never returns to its sleep state, but instead continues to transmit. This problem was solved by powering the HI-506-A continuously from the +12 volt supply.

Conner (1990) presented a more elegant solution to the problem. He inserted diodes between the multiplexer and its power supplies (fig. 2.5). This blocks the leakage current from powering the transmitter. He also stated that this scheme will protect "most CMOS [complementary metal oxide semiconductor] switches from damage caused by analog signals that are present when the switches' power supplies are off." This suggests that a CD4051 with series diodes on the power supply pins may be used in situations where the sensors are always operating. The HI-506-A needs to be used only if more than eight input channels are to be transmitted or if the possible output swing of the sensors' voltages is greater than the maximum voltage rating for the CD4051 (± 9 volts).

A pre-settable binary counter, U13, controls which analog input (0–15) is selected by the multiplexer. The counter is incremented after each channel is transmitted, and the multiplexer consequently switches the next input to the A/D converter. The initial analog input to be sampled is designated by switch S6. When using the 8-channel CD4051 multiplexer, the fourth bit (MSB) of the counter is ignored.

Before going to the analog-to-digital converter, the output of the multiplexer is buffered by a voltage follower, U15 (OP07).

Analog-to-digital Converter

U22 (ICL7109) is a 12-bit-plus-sign dual-slope integrating A/D converter. The output of buffer U15 is connected to the INPUT HI of the A/D converter through R36. INPUT LO is connected directly to the analog input ground.

Full-scale input is twice the reference voltage. R62 is adjusted to give the voltage reference U23

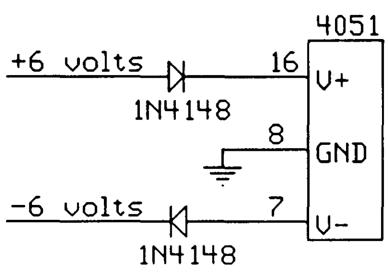


Figure 2.5. Circuit for preventing current from analog inputs leaking onto power rails. Since input range of the A/D is ± 5 volts and multiplexer is powered by ± 6 volts, voltage drop owing to diodes does not affect analog-input range of signals (after Conner, 1990).

(LM236-2.5) an output of +2.500 volts so that the transmitter has a full-scale input range of ± 5 volts. The maximum conversion time is 33.3 ms. The resolution of the converter is 1.22 mV.

For proper operation, C16, C18, and C19 must be capacitors with low self-adsorption such as polypropylene.

Channel-ID Counter

Binary counters U16 and U17 (both CD40193) determine the channel ID that is transmitted with the data for each analog input. Each analog input for each transmitter has a specific ID (0–255) assigned to it. The receiver uses the channel ID to associate the correct sensor with the data in the message. The initial channel ID for the transmitter is set by switch S7. After each input is transmitted, the channel ID is incremented. Thus the channel ID's for each individual transmitter are incremented sequentially from the initial channel ID of the transmitter set with S7. For example, if three transmitters, each transmitting four channels, were deployed, transmitter 1 should have an initial channel ID of 1 and transmit channels 1–4. Transmitter 2 should have an initial channel ID of 5 and transmit channels 5–8. If it was expected that two more channels would be added to transmitter 2 later, channels 9 and 10 should be set aside for this expansion. Thus transmitter 3 should have an initial channel ID of 11 and transmit channels 11–14.

Number-of-channel-transmitted Counter

Johnson decade counters U11 and U12 count the number of analog signals that have been transmitted and return the transmitter to its sleep state after the programmed limit has been reached. The counters are configured so that after each channel is transmitted, one of 16 outputs, in turn, goes high. Setting one of the 16 switches of S4 and S5 to "on" selects which counter output is connected to the circuit that returns the transmitter to its sleep state.

If no switch on S4 or S5 is on, the transmitter will continue to transmit until power is disconnected.

Universal Asynchronous Receiver Transmitter (UART)

The UART, U28 (IM6402), converts the 8-bit parallel data to 8-bit, even-parity, 2-stop-bit serial data. Switch S8 sets the baud rate. Either 50 or 300 baud is used at CVO; 300 baud is preferred because its quicker transmissions decrease the time the radio is transmitting, thereby reducing power consumption. The 50 baud rate is used on the telemetry link which utilizes the 455–505 Hz audio band instead of the normal Bell 103 1,070–1,270 Hz audio band. The frequency of the 455–505 Hz band is too low to allow 300-baud transmissions.

If the data are to be received by an IBM PC or compatible computer executing a GWBASIC program, the circuit board must be modified to disable parity generation (fig. 2.6). GWBASIC does not allow parity bits with 8-bit data.

Modem

A frequency-shift keying (FSK) modem, U30 (MC14412), encodes the serial output of the UART in audio tones. The transmitter is normally configured to transmit in Bell 103 Originate mode. In this mode, the modem produces a 1,270-Hz tone when it detects a logic high on the serial output of the UART. A 1,070-Hz tone is produced when it detects a logic low. The Bell 103 Answer mode can be selected using switch S8. In Answer mode, the modem produces tones of 2,225 Hz and 2,025 Hz for logic high and low.

The transmitters can share radio links with analog seismic data if the audio frequency band used by the transmitter is available. For Originate frequencies, this means that standard seismic channels with center frequencies of 1,020 and 1,360 Hz cannot be present. For Answer frequencies, the seismic channels with center frequencies of 2,040 and 2,380 Hz cannot be present.

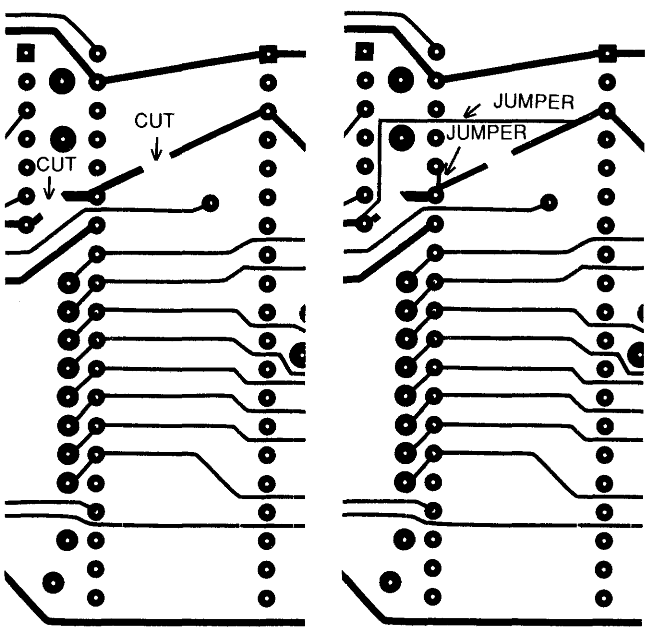


Figure 2.6. Modification to circuit board to disable parity generation.

Precautions must be taken to ensure that the low-data-rate telemetry does not interfere with the seismic telemetry. Since the low-data-rate transmitters send data in bursts, the radio receiver is likely to receive bursts of noise as the radio transmitters turn on and off. To prevent this, the low-data-rate signals need to be buffered. This is done with a single-chip modem (fig. 2.7). In this circuit, the output of the radio receiver is demodulated by the receive section of the modem. The demodulated output is sent to the transmitter section of the modem, where it is remodulated and put on the seismic line. Noise from the radio receiver will cause the output of the modem to modulate between its two output tones but will not cause the output to deviate outside that band.

Note that the output of the "modem buffer" will be the Originate tones if the input is the Answer tones, and vice versa. A second modem buffer would be needed to reverse the tones again if this were a problem.

Radio

Power and controls for the radio are available from the board via J5. Power ground is switched on and off to the radio through Q2. With the transmitter in its sleep state, Q2 is off and the radio ground is essentially disconnected from the battery ground. When the transmitter is active, Q2 is switched on, providing a low-impedence path between radio ground and battery ground. By switching the ground in this manner, the radio voltage does not necessarily have to be the same voltage as that powering the transmitter. The drawback is that the radio ground must be isolated from the power ground.

To prevent radio-frequency interference while sampling the analog signals, the radio transmitter is activated only when data are to be transmitted. Radios are normally put into transmit mode by shorting the

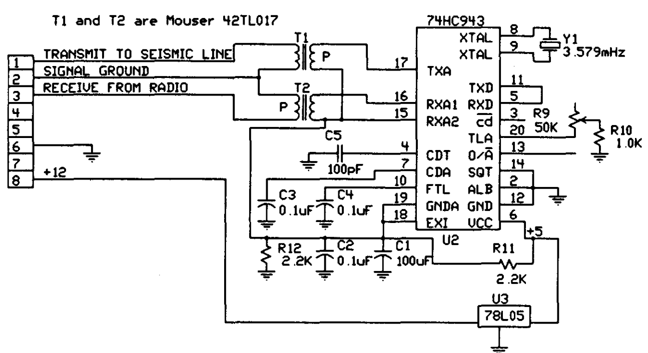


Figure 2.7. Circuit that buffers transmissions, enabling them to share a radio link with analog seismic data.

push-to-talk control line (PTT) to ground with a switch. Q3 provides this function. When on, Q3 provides a low-impedence path between PTT and power ground, activating the radio transmitter.

The output of the digital transmitter is transformer-coupled through T1 to the radio. The output level is normally 0.8 volt peak-to-peak. If the radio uses signal inputs in the millivolt range, I recommend that a resistor divider network be placed as near the radio as possible, to bring the signal down to the proper level. This configuration minimizes interference problems.

POWER CONSUMPTION

The power consumption of the digital transmitter is not a major problem. Even transmitting all 16 channels every 10 minutes at 300 baud, two 6-volt 20-amp-hour alkaline lantern batteries (Duracell ID9260) provide enough power for a year. The formula for determining average current consumption is

AVERAGE CURRENT = QUIESCENT + ((CHNLS · 2/ INTERVAL) · ACTIVE)

where

- QUIESCENT = the quiescent current consumption (0.06 mA if U32 is used, 0.4 mA if U14 is used),
- CHNLS = the number of channels to transmit,
- 2 = the number of seconds to transmit one channel at 300 baud (substitute 5 for 50 baud),
- INTERVAL = the time between transmissions (in seconds), and
- ACTIVE = the active current consumption (13 mA + current drawn by external sensors).

Powering the radio is a greater problem. A typical 4-watt radio may require 900 mA while transmitting and 20 mA while in receive mode. The formula for determining average current consumption for the radio is

RADIO CURRENT CONSUMPTION = ((RCV · 1) + (XMIT · 1)) * CHNLS / INTERVAL

where

- RCV = radio current consumption in receive mode,
- 1 = seconds/channel that the radio is in receive mode,
- XMIT = radio current consumption in transmit mode,
- 1 = seconds/channel that the radio is in transmit mode at 300 baud (substitute 2 for 50 baud),
- CHNLS = number of channels to be transmitted,

and

- INTERVAL = time between transmissions (in seconds).

Batteries such as alkalines and carbon-zinc do not have flat-discharge voltages. Instead, the voltage slowly drops as the battery is discharged. Though a 12-volt battery may be rated at 10 amp-hours, 5 of those amp-hours may be at voltages below 10 volts. Below 10 volts the power output of the radio may fall to an unacceptable level. If the radio can operate safely at 16 volts, it is preferable to power it with 7.5-volt batteries in series/parallel to provide a nominal 15-volt supply (Lockhart and others, chapter 3). However, the nominal 15-volt supply would exceed the maximum operating voltage for the digital transmitter. For this reason, the digital transmitter allows the use of a separate set of batteries to power the radio.

CONCLUSION

The system described here has been in use at CVO since 1984. The low cost, small size, and robustness of the transmitters have allowed sensors to be installed in areas at Mount St. Helens and other volcanoes that might otherwise have been considered impractical. Data transmitted using the system continue to provide essential monitoring information at Mount St. Helens and elsewhere.

The digital transmitters are not as flexible as microprocessor-based transmitters. However, more complex data processing in the field is usually not needed when telemetering such data as tilt, strain, or temperature. Until it is demonstrated that more complex processing is necessary, this system will continue to be useful.

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APPENDIX

Transmitter Specifications

Power Requirements:

Supply voltage	8.7 - 15 volts DC
Supply current	
(U32 installed)	60 µA quiescent
(U14 installed)	400 µA quiescent
(without radio)	15 mA transmitting

Average current (four channels transmitting every 10 min, 300 baud, and U32 installed):
<300 µA

Analog Inputs:

Range	± 5 volts
A/D converter	integrating 12-bit-plus-sign
A/D converter output range	0-8192
Resolution	1.22 mV
Number of inputs	16 single ended (U14) 8 single ended (U32)

Power Output:

Switched +6.0 volts	10 mA at 5.7 volts
Switched -6.0 volts	5 mA at 5.7 volts
Switched +8.0 volts	25 mA at 7.8 volts
Switched -7.4 volts	5 mA at 7.0 volts
Switched supply voltage	>100 mA

Data Out:

8 bit binary, even parity, 2 stop bits (incorrectly stated as odd parity in Murray, 1988).

Baud switch selectable 50, 75, 110, 150, 300
Bell 103 standard FSK frequencies

Originate HI	1,270 Hz
LO	1,070 Hz
Answer HI	2,225 Hz
LO	2,025 Hz

Each channel's data are transmitted in a 6-byte message. The first 2 bytes contain the data. Because the output of the A/D converter is 13 bits (12 bits plus one sign bit) and data are transmitted in 8-bit bytes, 2 bytes are necessary to transmit the channel's data. The 8 least-significant bits are transmitted in the first byte and the 5 most-significant bits are transmitted in the second byte. The channel ID is transmitted in the third byte. Then the 3 bytes are transmitted again to complete the message. The data and ID are transmitted twice to provide a means to check the validity of a message.

Packaging:

Watertight steel drum 35.1 cm diameter × 36 cm high.
Antenna sheath constructed with 10 cm diameter plastic pipe.

Receiver Requirements

Most computers with a Bell 103-compatible modem can be programmed to receive data sent by the transmitter. BASIC programs have been written for the Radio Shack Model 100/102 and an IBM compatible computer (Toshiba T1000) to receive the data.

Although one radio receiver and computer can receive data from numerous transmitters, the total number of channels should be kept to less than 30. Transmissions from separate transmitters will interfere with each other too often if more than 30 channels are used.

FIELD RECEIVER PROGRAM FOR THE RADIO SHACK MODEL 100/102

A Radio Shack Model 100/102 computer is used for the portable field receiver. The following BASIC program for the Model 100/102 monitors the modem. When a valid message is received, the channel ID and data are printed on the screen. Owing to the slow speed of the Model 100/102's BASIC, a portion of the program is written in machine language specific to the Model 100/102.

The transmitted signal is connected to the Model 100/102 through the modem port. Signal high goes to pin 4 and signal low to pin 2. The modem selecter switch should be in the ACP position and, if the transmitter is transmitting on the normal originate frequencies, the ANSwer/ORiGinate switch should be in the ANS position. If the transmitters are using the answer frequencies, the switch should be in the ORG position.

Lines 21-31 contain the machine code for the routine that receives the data from the modem. The routine first checks the data for parity and framing errors. If no errors are detected after six bytes are received, it will determine if the first three bytes of the message are the same as the last three bytes. If they match, the message is considered valid and the routine is exited with the value at location 62700 equal to 6. The routine is also exited every 10 seconds to check for keyboard input. In those cases, the value at location 62700 does not equal 6.

```
20 ' FLDRCVR
21 DATA 00,00,00,E3,D5,C5,E5,C9,00,E1,C1,D1,E3,C9,00,48,0C,62,6B
22 DATA C3,24,F5,78,91,3C,32,EC,F4,AF,32,EB,F4,C9,CD,ED,F4,EB,48
23 DATA 0C,23,0D,CA,1D,F5,7E,2B,77,23,C3,11,F5,CD,F3,F4,C9,CD,6B
24 DATA F5,CD,ED,F4,CD,87,F5,C6,00,C2,A1,F5,00,00,00,CD,6D,6D,CA
25 DATA 27,F5,CD,7E,6D,CD,F3,F4,C2,F9,F4,77,23,0D,C2,24,F5,E5,2B
26 DATA CD,AF,F5,C2,61,F5,2B,CD,AF,F5,C2,61,F5,2B,CD,AF,F5,C2,61
27 DATA F5,E1,CA,00,F5,E1,CD,0B,F5,0C,2B,C3,24,F5,C9,47,23,7E,5F
28 DATA 23,7E,57,6B,62,3A,EB,F4,4F,C5,AF,47,09,C1,78,91,3C,4F,C9
29 DATA 00,00,00,00,00,00,21,E2,F4,CD,0F,19,3A,E8,F4,21,EA,F4,BE
30 DATA 77,3E,00,CA,9D,F5,3E,01,00,00,00,C9,CD,F3,F4,78,91,3C,32
31 DATA EB,F4,AF,32,EC,F4,C9,E5,7E,2B,2B,2B,96,E1,C9
32 ' clear the area for the machine code
33 CLEAR 512,62650
34 PRINT "LOADING MACHINE CODE"
35 ' the following POKEs the above machine code into memory
36 FOR I=0 TO 204
38 READ A$
40 H%=ASC(LEFT$(A$,1))
42 L%=ASC(MID$(A$,2,1))
44 IF H%60 THEN H%=16*(H%-55):GOTO 48
46 H%=16*(H%-48)
48 IF L%60 THEN L%=L%-55 ELSE L%=L%-48
49 ' the code is inserted into memory starting
50 ' at location 62698
51 H%=H%+L%:POKE(62698+I),H%
52 NEXT I
60 '----------------------------------------------------------------
85 PRINT "PROGRAM STARTED"
135 ' DA% is used to decode the 6 byte message
140 DIM DA%(6)
600 ' line 604 opens the modem port. if the transmitters'
601 ' parity generation has been disabled, it should
602 ' read as is. Otherwise it should be opened as
603 ' "MDM:8E2D"
604 OPEN "MDM:8N2D" FOR INPUT AS 1
605 ' the default baud rate is 300. for 50 baud execute the
606 ' following
610 ' OUT 188,0 : OUT 189,76 : OUT 184,195
612 ' for 75 baud execute the following
615 ' OUT 188,0 : OUT 189,72 : OUT 184,195
616 '----------------------------------------------------------------
617 'Q$ is the buffer to receive the 6 byte message.
618 ' it must be one byte longer than the message
620 Q$="1234567"
621 ' if the following line is not executed, data received
622 ' into Q$ will appear in line 620 the next time the
623 'program is executed.
624 MID$(Q$,1,6)=MID$(Q$,1,6)
625 '----------------------------------------------------------------
626 ' go look for a valid message
630 CALL 62753,5,VARPTR(Q$)
635 ' if the peek=6 then a valid message has been received.
636 ' otherwise it was just a 10 second time-out.
640 IF PEEK(62700)=6 THEN GOSUB 900
645 ' go back for more data
650 GOTO 630
731 '----------------------------------------------------------------
900 'decode the message
902 'first load the 6 bytes into DA%
1000 FOR I%=1 TO 6
1020 DA%(I%)=ASC(MID$(Q$,I%,1))
1021 NEXT I%
1090 'convert the binary data to an integer value
1100 DA%(2)=DA%(4)+(DA%(5)AND15)*256
1120 IF DA%(5)AND32 THEN GOTO 1122
1121 DA%(2)=4096-DA%(2):GOTO 1140
1122 ' DA%(2) will hold the data, DA%(6) already
1123 ' has the channel ID
1124 DA%(2)=DA%(2)+4097
1130 ' go print the message on the screen
1140 GOSUB 1300
1162 RETURN
1300 '----------------------------------------------------------------
1301 ' print the decoded message
1500 PRINT USING "ID=### ";DA%(6);
1501 PRINT USING "DATA=#### ";DA%(2);
1502 ' calculate the voltage from the data
1502 V!=((DA%(2)-4097)*.00122)
1503 PRINT USING "+#.### VOLTS ";V!;
1504 PRINT TIME$
1540 BEEP
1541 ' go back for more
1550 RETURN
1600 ' end of program
```

3. Operating Low-Power Telemetry Networks in Severe Environments

By Andrew B. Lockhart, Thomas L. Murray, *and* Bruce T. Furukawa

ABSTRACT

The major problems affecting the low-power telemetry networks at Mount St. Helens have been weather and corrosive gases, with power supply problems secondary. Lightning and vandalism have also been concerns. We have found that these problems can be minimized with proper site preparation and instrument packaging. Airtight instrument cases protect sensitive electronic equipment from corrosive gases and moisture. Nonmetal instrument cases are used in highly corrosive environments where metal cases quickly deteriorate. Instrument cases are protected from direct exposure to the environment by enclosures ranging from metal drums to small buildings. Problems due to rime ice formation on the antennas are minimized by using antennas protected by radomes or by using log-periodic antennas. Circuit damage from lightning and from improper power connections during battery changes may be minimized by grounding and use of diodes and transient-suppressant devices. To power remote sites, we have used solar panels with rechargeable batteries, primary batteries, and propane-fueled thermoelectric generators. We find solar panels with rechargeable batteries to be the cheapest long-term power source although primary batteries are the most reliable power source. On-site repair and maintenance is made more difficult by poor conditions, requiring prior planning and realistic expectations. Attention to detail is the key to operating low-power telemetry networks.

INTRODUCTION

Telemetering data from sensors located on active volcanoes provides valuable information with which to assess the volcanic hazards in real time. The sensors and telemetry equipment in the field are subject to a number of problems, both environmental and cultural, which may damage equipment and interrupt the flow of data to the observatory. Problems unique to active volcanoes include corrosive gases and tephra.

The major problems encountered in maintaining electronic equipment on active volcanoes are

1. Weather and corrosive volcanic gases.
2. Power surges due to lightning or incorrect hookup to batteries.
3. Maintaining sufficient power for remote operation.
4. Vandalism.

Weather and corrosive gases have been the primary cause of problems in field equipment at the Cascades Volcano Observatory (CVO); power-supply concerns are secondary. Although storm-caused lightning and vandalism have not been a major problem at Mount St. Helens, they have been serious problems at other volcanoes we have visited.

Proper site preparation and instrument packaging can minimize, though not eliminate, most problems. We discuss methods for protecting and powering field instrumentation based on our experience at Mount St. Helens and other volcanoes. We also outline a troubleshooting guide and list tools we have found useful during the installation and maintenance of field instruments in severe conditions. Our report is directed toward people who must prepare and install the instruments.

INSTRUMENT PACKAGING

Improper packaging of electronic equipment used in severe environments can allow moisture or corrosive gases to damage the sensitive circuitry. Moisture is an especially insidious problem, and its presence can cause total failure of electronic circuits. Perhaps worse, it can cause incorrect or noisy data by its presence on high-input-impedance circuits. Such a problem may go undetected if the circuit is otherwise unaffected. Corrosive gases can magnify the problem. Sulfur dioxide combines with moisture to form sulfuric acid, which greatly accelerates corrosion of improperly protected circuits, wires, and metal enclosures.

The primary method to protect electronic circuitry from moisture and corrosive gases is to package the circuit to prevent the moisture and gases from contacting it. We divide packaging into three categories, (1) instrument cases that contain the electronics, (2) protective housings that surround the instrument cases, batteries, and incidental wiring, and (3) interconnection hardware and printed-circuit-board coatings.

Instrument Cases

Instrument cases are the primary barrier between the electronics and the environment. A good instrument case is airtight to allow neither moisture nor corrosive gases to contact the circuitry. The case should have a gasket or O-ring seal on the lid and around each hole that penetrates the case, such as the screws or rivets attaching a handle or hinge. If no gasket or O-ring is present, a sealant such as Scotchkote or room-temperature-vulcanizing (RTV) silicone should be liberally applied to the area in question to prevent moisture and air from entering the case.

Some RTV's contain small amounts of acetic acid. Though the acid is not sufficiently corrosive to penetrate metal cases, it can damage copper wires, resistor leads, and sockets. A nonacidic RTV such as Dow Corning 3145-RTV should be used with metal or electronic components and cabling.

Nonmetal cases, such as those manufactured by Pelican Products Inc., are preferred for use in areas where corrosive gases are concentrated enough to rapidly destroy metal cases. Most nonmetal cases use some metal parts for bolts or pins in hinges. A protective coating should be applied to these parts if they are not stainless steel.

As the nonmetal cases do not provide any shielding for the electronic circuits, the circuits should be enclosed in a grounded metal box inside the instrument case.

In less corrosive environments, metal cases such as those manufactured by Zero Corp. can be used. The metal cases, if grounded, give better electrical shielding to the circuitry than the nonmetal cases, decreasing the possibility of interference by the radio transmitter. They also provide a suitable ground plane on which a whip antenna may be mounted. An alternative to metal cases designed specifically to house electronic circuitry are "ammunition cans," commonly found in army surplus stores, or small (4 or 9 gallon, approximately 16 or 36 liter) metal drums. They provide inexpensive airtight containers when their gaskets are in good shape.

Whenever possible, connectors should be used to pass signals and power through the case. Do not just pass a wire through a hole drilled in the case, and then apply a sealant: One tug of the wire can destroy the integrity of the seal by breaking its bond to either the wire or the case. Jacketed cables that pass through the case provide a conduit for moisture and also should be avoided.

We use Amphenol MS-series environmental-resistant standard circular connectors to pass signals and power through the instrument enclosure. Moisture cannot pass through these connectors, although the mounting holes must still be sealed. Non-environmental connectors are less expensive than the environmental ones and may be substituted if they are carefully sealed on the inside of the case with Scotchkote or other sealant. One drawback to using the metal MS-series connectors is that corrosion of mating connectors causes their threaded parts to bond together, making it difficult if not impossible to separate them. A light brushing with paint or Scotchkote will usually prevent this.

We use "N" connectors, preferably with gold contacts, for radio-frequency connections external to the instrument case. Unlike BNC or PL-259/SO-239 connectors, the "N" connectors are inherently waterproof, though we still wrap them with electrical tape for added protection if they are located outside a protective housing.

Desiccant should be placed in the instrument case to remove any moisture that may leak into the case or condense after the case has been closed. The desiccant should be replaced annually or whenever the case has been opened.

Protective Housings

Protective housings prevent direct exposure of the instrument cases, miscellaneous interconnecting wires, and batteries to weather, dust and ash, and corrosive gases. They can also provide security against vandals. The housings can range from generic 55-gallon steel drums, which provide enough room to house a seismic station and batteries, to small buildings, which offer room to work on equipment out of the weather (figs. 3.1–3.3). Plastic, fiberglass, and wood survive well in corrosive conditions that would quickly destroy steel.

If the bottom of the protective housing is below ground level such as is typically the case for partially buried 55-gallon drums, large (5–10 cm diameter) holes should be cut in the bottom of the housing to allow accumulated water to drain. Unless the housing sits in soil of low permeability, such as is found in the crater of Mount St. Helens, the chance of ground water flooding the enclosure is less than that of flooding by water entering from the top.

The protective housings also serve to prevent vandals and souvenir hunters from easily tampering with the equipment. Given that a persistent vandal will eventually get into any site, the focus of site security should be to deter the merely curious or the only mildly malicious passer-by from entry. Housings constructed of concrete or steel are more difficult to vandalize than those made of plastic or sheet metal (fig. 3.4). Hardening a field site against vandals may entail as much work as installing the equipment itself.

In many cases, simply securing the equipment with a lock will prevent the curious, law-abiding passer-by from unintentionally damaging equipment. The locks at the different field sites should open with the same key. A variety of locks, each using a different key, ensures that one day the key to a site will be forgotten or lost, and the servicing technician will have to damage the housing or the lock to reach the equipment. For the same reason, if combination locks are used they should all have the same combination. A lock housing open at the bottom limits access to the lock from underneath and greatly increases the difficulty of removing a lock by sawing or cutting it in two.

Camouflaging or hiding the enclosure will limit its visibility from nearby paths. Painting the enclosure to

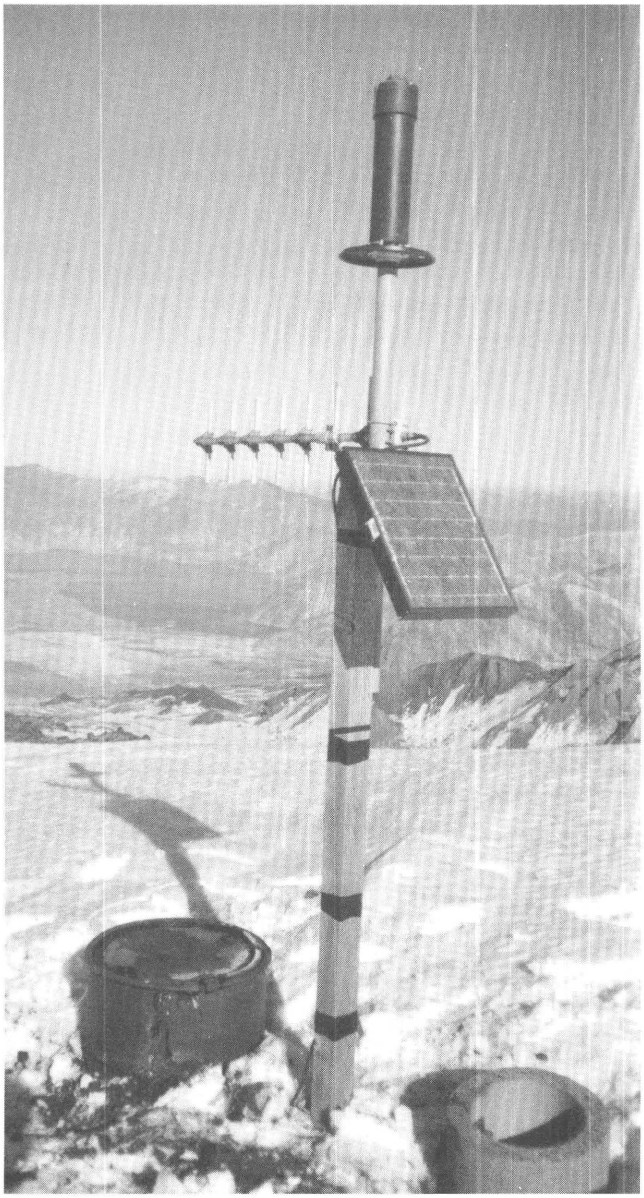

Figure 3.1. Radio repeater installation at Guacamole, north flank of Mount St. Helens. Batteries and repeater are housed in 55-gallon steel drum (left of antenna mast). Antenna mast is an unguyed wooden post cemented into ground. Cylindrical enclosure mounted at top of mast protects receiver's whip antenna inside from snow and ice. Yagi antenna is used by transmitter. Solar panel attached to mast provides power for site. Bands of tape secure antenna and solar panel cables to mast.

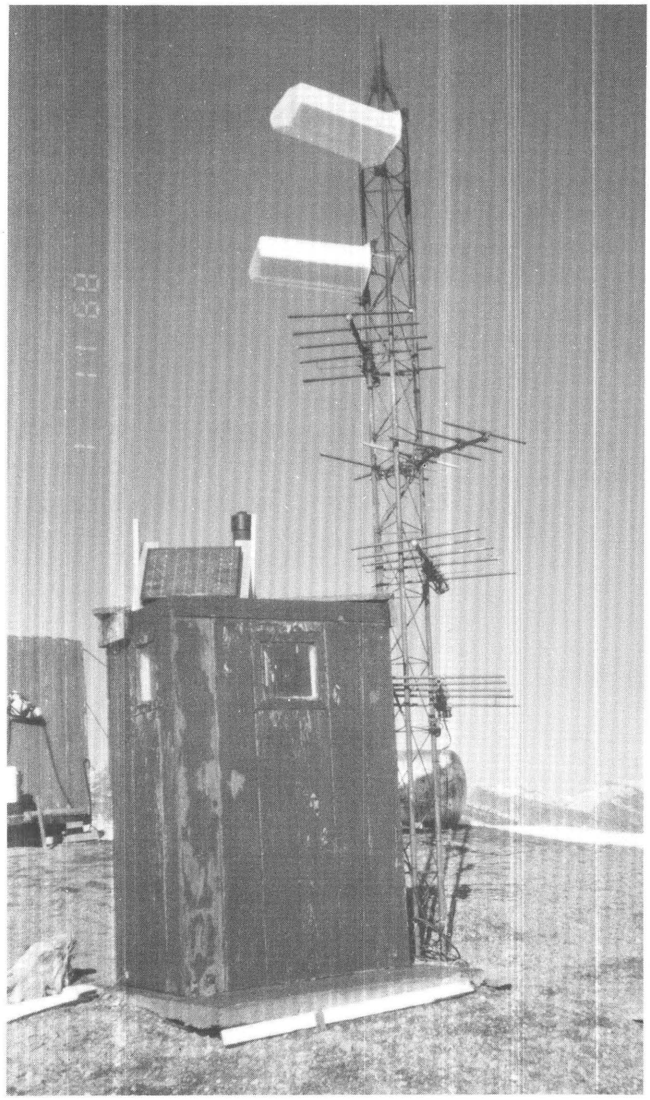

Figure 3.2. Radio repeater installation at Harrys Ridge, 8 km north of Mount St. Helens. Signals from numerous seismometers are received, summed, and retransmitted at this site. White enclosures (radomes) protect UHF antennas inside from snow and ice. Building provides protective housing for batteries and radios. At sites such as this that require numerous antennas, a tri-legged tower cemented into ground is used as a mast.

blend in with the background, burying it, or hiding it among shrubs or behind rocks will limit the number of people who notice the site and hence the chances of someone tampering with it (fig. 3.5).

Interconnection Hardware and Printed-Circuit-Board Coatings

Spraying printed-circuit boards with a urethane or acrylic coating can prevent accumulated moisture in the instrument case from affecting the circuit. Though not effective if the board is submerged in water, the spray can protect the circuit from high humidity or condensation.

All connections should be soldered. Even crimp connections should be soldered after crimping for added protection against corrosion. Soldering, in effect, transforms a stranded conductor to a solid conductor, and we have found that a solid conductor is less susceptible to corrosion than its equivalent gauge of stranded wire. The connections should be insulated with either electrical tape or heat-shrinkable tubing and, whenever possible, sealed with ScotchKote. Use of wires insulated with Teflon instead of polyvinyl chloride (PVC) will reduce the effect of corrosive gases permeating the insulation and damaging the conductor.

ANTENNAS AND ANTENNA MASTS

Snow and ice pose the major problems for antennas. Rime on the elements of a yagi antenna will detune it and may bend the elements under the extra weight. Yagis buried in snow may suffer bent or broken elements from the weight of the snow. An antenna with a build-up of rime presents more surface area to the wind and is thus more liable to rotate on its mast from its correct orientation.

All of these problems are compounded with increasing size of the antenna. Larger antennas present more surface area to the wind and collect greater weights

Figure 3.3. Yellow Rock vault tiltmeter installation, on crater floor 1 km north of dome at Mount St. Helens. Custom-built fiberglass housing placed over a cement pad was buried to form a vault to house a tiltmeter, batteries, and telemetry equipment. Data are transmitted through whip antenna enclosed in cylinder at top of wooden post. This site is buried under 3–5 m of snow in winter. Pipe located to left of vault is used to locate vault when snowpack buries antenna.

of rime than do smaller ones. Larger antennas are more difficult to protect from the weather by enclosures or sheaths and are more easily seen by souvenir hunters. In extreme conditions, the best antenna is the smallest one that will suffice. Whenever possible, we use a whip antenna instead of a yagi.

One method of preventing rime from detuning an antenna is to enclose the antenna in a plastic housing, commonly referred to as a radome. UHF yagis protected by a fiberglass radome are commercially available (fig. 3.2). VHF yagis are too large to conveniently enclose in a radome; we have either used a broad-band, log-periodic yagi or mounted the antenna inside a small wooden building. The log periodics are heavier, bulkier, and more expensive than the standard yagis and are used only when necessary. For short radio paths (30 km) we use standard yagis, because the signals are strong enough to be received even while the antenna is iced. Most of our yagis and log-periodic antennas are painted black to improve solar warming and hasten deicing.

Whip antennas are also susceptible to icing. The wind can cause the ice-covered antenna to oscillate like an inverted pendulum, eventually snapping it off near its base. To avoid this, we construct a sheath from 4-inch (10 cm) plastic sewer pipe to act as a radome for the antenna. The pipe is attached to the top of the instrument case or ground plane with a plastic-pipe floor flange. A pipe cap on the top completes the sheath. With the sheath protecting the antenna, the radio can transmit through deep snow (fig. 3.3).

Solidly tightening the antenna-mounting bracket to the mast is normally sufficient to prevent the antenna from rotating on its mast. At particularly windy sites we drill a 3-mm-diameter hole through the mounting bracket into the mast and insert a steel pin or bolt to ensure that the antenna will not rotate on its mast.

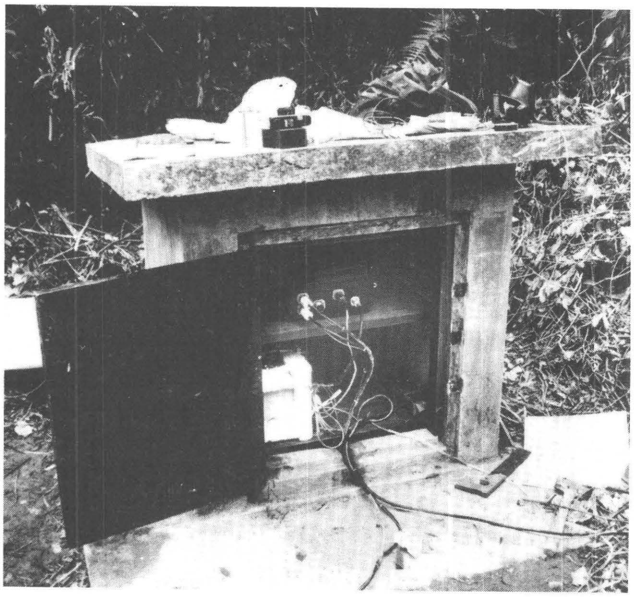

Figure 3.4. Concrete vault with steel door prevents vandals from easily gaining access to telemetry instrumentation.

Ice and snow also present problems for the antenna cable. If the cable is not securely attached to the antenna mast, wind, snow, or ice can literally pull the cable out of its connector. The cable should be taped, stapled, or secured in some manner to the mast to prevent strain at the connector-cable junction. Enough slack should be left near the antenna to prevent any rotation of the antenna from straining the cable-connector junction.

We have found that a length of 1 1/2-inch to 2-inch (3.75 cm to 5 cm) steel pipe rigidly attached to an unguyed 4 by 4 (8 cm by 8 cm) wood post cemented into the ground makes an excellent antenna mast. The pipe mount permits a more careful orientation of the antenna or solar panel than a square post. We have had no problems with this setup, even where the mast has been buried by more than 3 m of snow. We avoid guyed masts because of the possibility of problems with snow-loading on the guys. A further problem with guy wires is that wind-induced vibration can increase high-frequency noise at seismic stations.

LIGHTNING AND POWER-SUPPLY PROTECTION

Field equipment is liable to damage from lightning and from improper power connections during battery changes. Protection diodes, transient-suppressor diodes, and plasma-discharge tubes can be easily installed in equipment to counter these effects.

Protecting From Improper Power Connection

Batteries usually are the power source at the field sites. The biggest danger in using batteries is reversing the polarity of the power leads after changing batteries. The instruments can be protected from reversing the battery leads by using either a blocking diode placed in-line with one of the power leads or a shorting diode placed across the leads.

The blocking diode prevents any current from flowing through the circuit if the battery leads are reversed, but at a cost of reducing the voltage applied to the equipment by an amount equal to the voltage drop across the diode (fig. 3.6*A*). A standard silicon-junction diode has a diode drop of about 0.6 volt. A Schottky-barrier diode with a drop of 0.3 volt is preferred. The diode's current-carrying capacity must be greater than the peak current needed by the equipment it is protecting, or the diode will be damaged.

Placed across the voltage input, a shorting diode provides a short to ground for the reversed voltage (fig. 3.6*B*). The shorting diode should be used in situations where the voltage drop of the blocking diode is unacceptable. However, if the current-carrying capacity of the shorting diode is exceeded, damaging the diode and removing the short, the instrument circuitry may in turn be damaged. To prevent this, either the diode must be able to conduct the maximum output current of the battery or a fuse must be placed in the circuit between the battery and the diode. The current rating of the fuse must be less than that of the diode to ensure that the fuse will open before the diode fails. For instance, a diode rated at 3 amperes should be protected with a fuse rated at 1 ampere.

Establishing conventions for the pin connections for all in-house connectors also helps maintain proper battery polarity. At CVO, we have agreed that for all in-house connectors, whether they have 2 pins, 5 pins or 10 pins, pin A will be +12 volts and pin B will be ground. If a connector is not supplying +12 volts, its pin A is either unconnected or capable of withstanding +12 volts applied to the pin. This prevents damage to equipment if connectors are inserted in the wrong place. We always assign +12 volts to the red wire and the ground to the black.

Lightning Protection

Nothing can completely protect low-power electronic equipment from damage by a direct lightning strike. However, damage from voltage transients induced by nearby lightning strikes can be minimized through the use of transient-suppressor diodes, plasma-discharge tubes (gas pots), and proper grounding techniques.

We have found proper grounding to be the primary defense against lightning damage. Even without

A *B*

Figure 3.5. Telemetered tiltmeter installation on Galeras Volcano, Colombia. *A*, Partially buried plastic garbage container houses batteries, electronics, radio and antenna. *B*, Installation as seen from road (arrow). Vegetation later placed around container made site virtually invisible from road.

protection devices such as transient-suppressor diodes or gas pots, good grounding will minimize lightning damage to a system. The CVO radio repeater located on Coldwater Peak shares a building with repeaters installed and operated by other agencies. The other agencies' repeaters have twice been damaged by lightning, whereas the CVO repeater has suffered no damage. The only difference in the installations is that the CVO repeater is well grounded and the others are not.

In lightning-prone areas we recommend that the negative terminal of the power source (typically the battery) be connected to the ground rod with heavy-duty cable (12 gauge or greater). The antenna and instrument case, if metal, should also be shorted to the ground rod with a heavy-duty cable. Exposed connections to the ground rod should be coated with a heavy, conductive grease to retard corrosion.

One exception to this grounding configuration is the digital telemetry transmitters used by CVO (Murray, Chap. 2). The circuitry switches power to the radio by connecting and disconnecting the radio ground to power ground. If a radio with a switched ground is used, the switched ground must be insulated from the power ground. Otherwise, the switched ground and power ground will be shorted together at the ground rod, negating the switch. In such instances, only the power source ground should be connected to the ground rod.

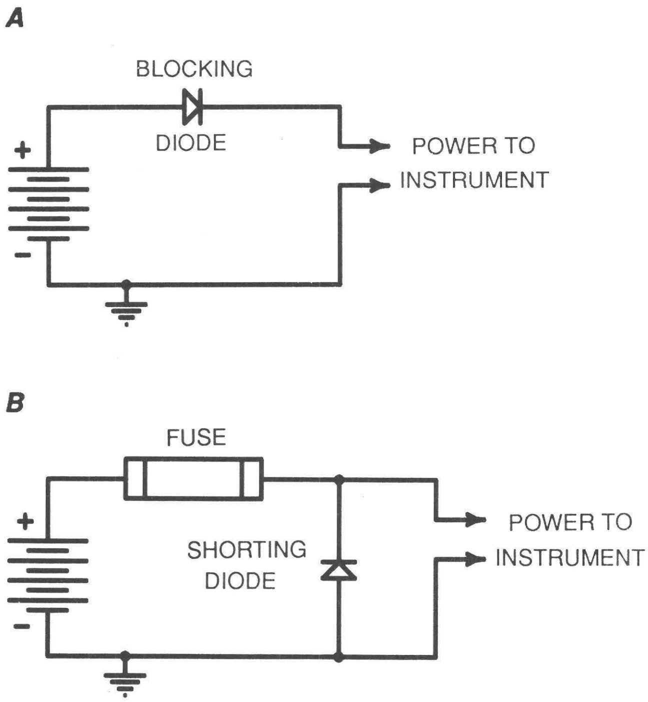

Figure 3.6. Protection of circuits from damage due to reversed battery leads. *A*, Blocking diode. Using a p-n silicon junction diode drops input voltage by 0.6 volt; a Schottky diode drops voltage only 0.3 volt. *B*, Shorting diode. Fuse must be included to prevent diode from exceeding its current-carrying capacity.

Transient-suppressor diodes such as Tranzorbs act similarly to zener diodes but clamp the voltage much more quickly (1 picosecond). Placed across the input power and signal lines, the Tranzorb will prevent lightning-induced voltage spikes from rising above acceptable levels. We use the 1.5KE series of transient suppressors. They have a peak pulse-power-dissipation rating of 1,500 watts and are available in a range of voltages from 6.8 volts to 400 volts. Bipolar types are available for use with audio signals or with sensors such as tiltmeters that may have a ±5 volt output range.

Plasma-discharge tubes installed between the antenna cable and the antenna protect the radio from voltage transients induced in the antenna. Although we have no direct evidence of the gas pot's effectiveness, we have been strongly advised to use them in areas of frequent lightning activity (H.P. Boller, oral commun., 1987).

POWERING REMOTE INSTRUMENT SITES

We have used three methods to supply power at our remote instrument sites: (1) solar panels with rechargeable batteries, (2) primary batteries, and (3) propane-fueled thermoelectric generators.

Solar Panels and Rechargeable Batteries

Of the three methods, solar panels and rechargeable batteries are the cheapest long-term solution. In this method, a solar panel charges one or more 12-volt batteries, which in turn power the instruments. The batteries act as an energy reservoir, storing the excess energy produced by the solar panel during the day to provide power during the night and periods of little sunlight.

A blocking diode and voltage regulator connect the panel and the batteries. A blocking diode allows charging current to flow into the batteries but prevents current from leaking back through the solar panel, thus discharging the batteries and possibly damaging the panel. If possible, a Schottky barrier diode should be used instead of a standard p-n junction silicon diode, because the lower voltage drop of the Schottky barrier diode decreases the power dissipated by the diode. The voltage regulator prevents overcharging of the batteries. For panels of 40 watts or smaller, a 50-watt, 14-volt zener diode (for example, Motorola #1N3313B) connected across the solar-panel output prevents overcharging. Zeners of lower wattage can be used with smaller panels. The zener should be placed as close as possible to the battery to minimize any voltage drop due to line loss between the zener and the battery.

In areas such as the Cascades, where a typical installation has a large battery capacity compared to the size of the panel, the regulator may not be necessary. In these cases, the panel is incapable of overcharging the batteries. We have developed a formula at CVO to determine the need for a regulator. If 15 times the maximum output of the solar panel (in watts) is less than the total reserve battery capacity (in amp-hours), no regulator is needed. For example, a system using a 15-watt panel and 300 amp-hours of reserve capacity would not need a regulator, as multiplying the panel wattage (15) by 15 gives a result of 225, well below the 300 amp-hours of capacity. When operating without a regulator, the electrolyte level must be checked periodically, preferably in late summer (Solar Power Corp.).

Nonregulated systems require caution. The open circuit voltage of a solar panel can be as much as 23 volts. When connected to the battery, this will drop down to the normal 11-14 volts and not be a problem. If the battery is taken out of the circuit (to be changed, for instance), leaving the panel powering the instrument directly, the instrument may not present enough load to drop the voltage more than 1-2 volts. If this happens, the maximum voltage rating for the instrument may be exceeded and its circuitry damaged. To minimize this possibility, at least two batteries wired in parallel should be used to power the station. The solar panel should be attached to one battery and the instrument to another. As long as batteries are changed or added one at a time, this configuration will prevent the solar panel from powering the instrument directly without at least one battery to buffer the voltage.

A balance must be reached in determining the necessary output of the solar panel and the necessary reserve capacity of the storage batteries. A very large panel may generate enough charging current on even the cloudiest day to allow the use of a small storage battery, one with just enough capacity to provide power through the night. At the other extreme, a panel just large enough to supply the energy needs on a yearly basis may operate well with a nominal battery reserve capacity in the summer but require a huge battery reserve to keep the instrument powered through the winter months when sunshine is scarce.

Finding the optimum combination of battery capacity and panel size is largely a matter of experience. In many areas, mountaintops are typically in the clouds while valley floors are sunny. In such areas, sites placed high on the mountain will need larger panels and (or) more batteries than those in the valley. Local topography or vegetation may also limit the amount of sunshine striking the panel. Our experience in the Cascades has been that for every 130 milliamperes (mA) of average current draw, a minimum battery capacity of 300 amp-hours coupled with a minimum 15-watt solar panel should be used. Even in the sunniest climates, we feel that the minimum setup to be used for an average current draw of 125 mA is a 10-watt solar panel and 125 amp-hours of reserve battery capacity.

Another easily overlooked factor in deciding the necessary amount of reserve battery capacity is the effect of volcanic ash on the panel. Ash is especially a problem in the tropics, where the panels are mounted almost horizontally for maximum solar input. Deposits of ash on the panel can completely block the sun and render the panel useless until it is cleaned by hand or rain. Extra reserve battery capacity should be included to carry the site through periods of ash fall.

Problems with ash fallout are compounded if a solar panel has a silicone protective surface instead of glass. Ash will become embedded in the soft surface, permanently blocking sunlight from the solar cells. For this reason, solar panels with soft surfaces should be avoided.

We have had good luck with 100-amp-hour batteries designed specifically for use with solar panels ("photovoltaic" batteries) or deep-discharge marine/RV batteries. They are a good compromise between cost, rate of self-discharge, volume, and weight. Batteries advertised to last 10–20 years in stationary operation are available but due to their higher cost (two to three times that of a marine/RV battery) and the uncertain longevity of the field sites, we have only used them at our voice repeater sites. We have not had good luck with gelled electrolyte batteries. Apparently they are not as tolerant of under- or over-charging as the liquid-cell batteries.

The batteries must be placed in a ventilated enclosure, otherwise hydrogen gas produced while charging the batteries can collect and explode. Such an explosion destroyed a concrete vault in California containing seismic equipment (F. Fischer, oral commun., 1990). Other explosions have occurred where the batteries were vented via tubing running from the battery vents to the outside. The hydrogen concentration in the tubing was sufficient to ignite and destroy the batteries when lightning struck near the outlet of the tube (L. Craven, oral commun., 1980).

Primary Batteries

Primary batteries are the most reliable method for providing power. Their only drawback is long-term cost. The cost of the primary cells required to power a typical seismometer station for one year is \$250-\$300. In contrast, a solar-powered site requires a \$500 initial investment but should run for at least 5 years with no additional investment. The savings over 5 years is at least $750, not counting procurement and battery-disposal (hazardous waste) costs.

We use primary batteries at sites that get little sunlight, at sites prone to vandalism, or at sites that are likely to be subject to ballistics from the volcano that could damage the panel. Whenever possible, we place enough batteries at a site to last at least 13 months. Then battery changes need to be made only once per year, with an extra month for leeway. All batteries at a site should be changed at the same time. Fresh batteries will be drawn down by any partially discharged batteries that are left in the circuit.

For sites whose average current draw is greater than 20 mA, we use 2.5-volt, 1,000-amp-hour primary batteries such as those manufactured by SAB/Nife Inc. Five such batteries connected in series provide the necessary 12.5 volts to power the field sites. Though the 1,000 amp-hours will supply a site drawing 105 mA for 13 months (396 days), we conservatively round off this number to 100 mA, which is sufficient for a typical seismic site. For sites drawing more than 100 mA, we connect additional sets of five batteries in parallel to provide the necessary capacity to last a year.

A limitation to these primary cells is that they cannot provide a current exceeding 1 ampere. At sites requiring periodic high current output (1 ampere), but low average current draw, we add one more cell in series for 15 volts total. The primary cells charge a secondary battery wired in parallel through a blocking diode. Unlike solar panels, which use Schottky-barrier blocking diodes to minimize the voltage drop, here a p-n junction silicon diode is desired in order to drop the voltage to an acceptable 14.4 volts, eliminating the need for a voltage regulator. With this configuration, the primary batteries provide the current to keep the secondary battery charged and to satisfy the long-term energy needs. The secondary battery provides the short-term high-current needs.

For sites whose average current draw is less than 10 mA, alkaline primary cells are used. They are available with smaller amp-hour ratings than the SAB/Nife batteries mentioned above, with corresponding reductions in size and weight. They also do not need to be vented and can be enclosed in an airtight instrument case. This allows the batteries and instruments to be packaged in a single airtight case, with no need for a protective housing (fig. 3.7).

The main drawback of alkaline batteries is that their output voltage declines gradually throughout the life of the cell (Union Carbide Corp., 1976, p. 288). A standard 6-volt 40-amp-hour alkaline is rated using a cutoff voltage of 3.2 volts (Duracell Inc., 1986). To take full advantage of the energy stored in the battery, the equipment it is powering must be able to work when the supply voltage drops to 3.2 volts. By contrast, the output voltage of the SAB/Nife batteries remains virtually at the same level until the battery is almost completely discharged. When using alkaline batteries, always choose the battery which has the highest voltage the equipment can safely accept so that as much of the

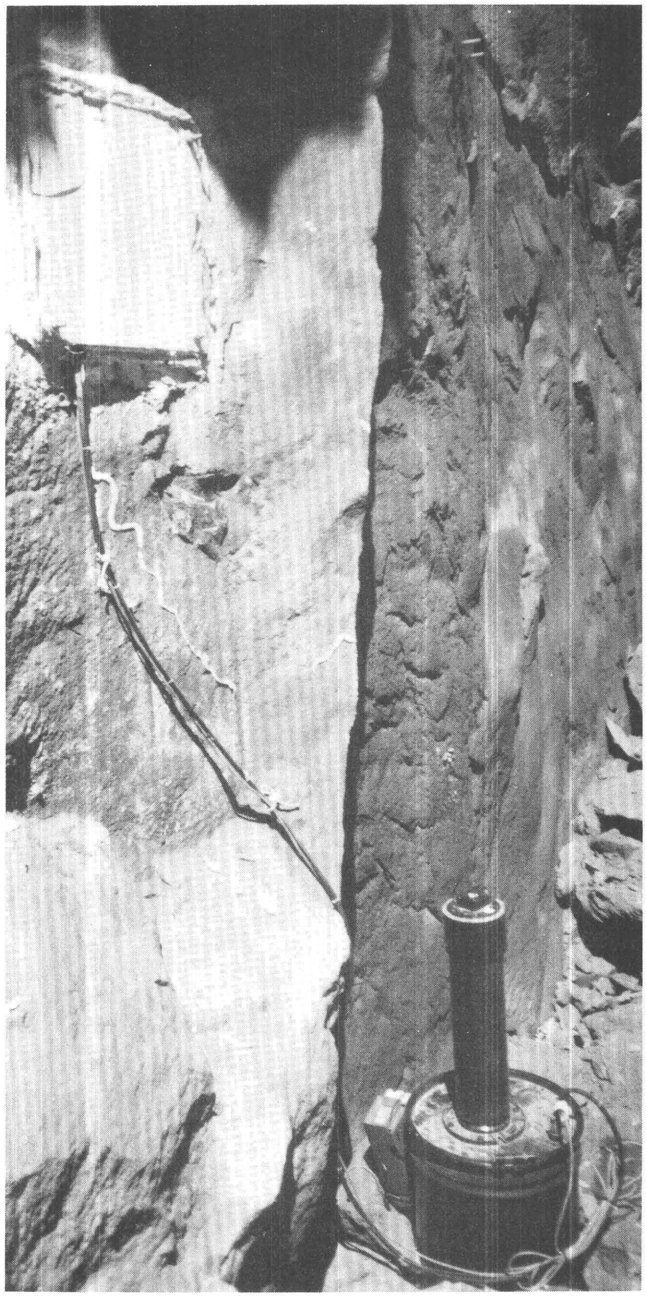

Figure 3.7. Oops telemetered-tiltmeter site, east flank of lava dome at Mount St. Helens. Tiltmeter is located on a shelf in rock wall behind steel plate at top of photograph. Telemetry equipment and batteries are housed in 9-gallon drum at lower right. Whip antenna is inside plastic pipe attached to lid of drum. Strain relief for cable connecting tiltmeter to telemetry is provided by attaching cable to P-K nails hammered into rock.

total energy of the cell as possible can be utilized (Union Carbide Corp., 1976, p. 288). The radios in our low-data-rate telemetry transmitters (Murray, Chap. 2) operate at a nominal 12 volts, but we have found that they can operate safely from supplies of up to 17 volts (if for no other reason than that they are in transmit mode for only a few seconds every 10 minutes; this is not recommended for radios in continuous operation). To power these radios, sets of two 7.5-volt 40-amp-hour batteries are connected in series to give a nominal 15-volt supply. This configuration provides 28 useful amp-hours to a cutoff of 10.0 volts. A comparable setup using 12-volt 40-amp-hour batteries would yield only 15 amp-hours until the 10.0-volt cutoff is reached.

Carbon-zinc primary cells should be avoided. They have a steeper voltage dropoff rate than do alkaline batteries (Duracell Inc., 1986), lower energy density, shorter shelf life, and poor cold-temperature performance (Union Carbide Corp., 1976, p. 20).

Thermoelectric Generators

We no longer use propane-fueled thermoelectric generators. Their advantage was the ability to provide relatively high continuous-output currents (3 amperes). Although the amount of propane required was not large (380 liters per month), the high cost of transporting the propane to the remote field sites by helicopter forced us to find alternative solutions. In place of the thermoelectric generators, we now combine large banks of solar panels with reserve battery capacity. Also, we cycle the equipment on and off to lower the average current consumption. Still, at sites where propane can be delivered by truck, thermoelectric generators should be considered.

FIELD REPAIR IN POOR CONDITIONS

Even in good weather, instrument repair is never as easy in the field as in the laboratory. In conditions of wind, rain, and noxious gases, only the most rudimentary repairs are likely to succeed. To aid in making field repairs, we carry a few items not necessary in the lab:

1. A 12-volt soldering iron and battery. The soldering iron may also be powered by the 12-volt batteries at solar-powered sites. We have found butane-powered irons to be unreliable in cold weather or at high altitudes.

2. A light tarp. This can keep us and the instruments dry in driving rain or sleet.

3. Extra desiccant. This should be carried in an airtight container, such as a sealable plastic freezer bag, so that the desiccant remains dry until needed. Desiccant should be replaced annually or after an instrument case has been opened and exposed to high humidity.

4. "WD-40" penetrating lubricant in an aerosol can. Use this in wet conditions to displace water from connectors before reconnecting them. Also, it may ease threaded connections that have corroded together. Do not use WD-40 in dry, dusty conditions; dust will collect on oiled connectors and O-rings, preventing a good seal.

5. A sealant such as RTV silicone sealant or Scotchkote to protect exposed connections from corrosion and to seal gaps. With enough sealant and electrical tape, virtually anything can be made moistureproof. The Scotchkote may be used on wet surfaces, as it displaces water.

6. Low expectations. If possible, avoid working on equipment in inclement weather. Because of impatience and added moisture, the site may be left in worse condition than before the visit.

TIPS FOR TROUBLESHOOTING IN THE FIELD

Volcano-monitoring equipment is of such diversity, with many one-of-a-kind sensors, that the need to troubleshoot unfamiliar, poorly documented equipment is not uncommon. The following basic steps can aid in troubleshooting both familiar and unfamiliar equipment.

Before departing for the field:

1. Try to hypothesize the cause of the problem by studying the symptoms. Did the station stop transmitting completely or is it only transmitting intermittently? Is it transmitting correctly, but the data are apparently incorrect? Did the problem start during a rain or lightning storm or after a site visit? Did hunting season just begin? Can it be connected with a problem at another site? A station that quit suddenly during a lightning storm most likely suffered lightning damage and, at the least, will need its radio replaced. A site that appears to be operating but whose data are getting progressively less plausible most likely has a moisture problem. A solar-powered site that operates only during the day most likely needs a new battery.

2. Check the receiver to ensure that the problem is in the field and not at the observatory.

3. Check to ensure that the equipment taken in the field to replace damaged equipment is in proper operating condition.

At the field site:

1. First, make a visual inspection. Look for corroded or broken connections, signs of damage, and so forth.

2. Second, confirm that proper power is going to the equipment. This includes checking that power is reaching the equipment and that any voltage regulators or DC/DC converters are operating correctly.

3. Attempt to isolate the problem by following signals through the circuit to see where they deviate from what is proper. Always be particularly suspicious of connectors.

4. Make sure that all integrated circuits are pressed snugly into their sockets. Chips sometimes work their way out of the sockets. Look for chips that have one side a little higher than the other.

5. A wet circuit board should be replaced. Though it is possible that a board only needs to be dried in the sun to return to a functioning condition, this should be attempted only in an emergency. The circuit may appear to be operating properly after drying, but intermittent problems or noisy data may appear later. Trimmer potentiometers and electrolytic capacitors are components that may have to be replaced after being exposed to water. Remember to find the source of the leak and seal the hole.

6. If there is sufficent time, try to determine precisely the cause of the problem before replacing a board or instrument. The problem may not be reproducible in the electronics laboratory.

7. Simply because equipment starts operating properly, do not assume that it has been repaired. A marginal contact or component may have been temporarily prodded into a functional state. Try to isolate the problem in order to ensure that the equipment will continue to operate.

CONCLUDING REMARKS

The procedures and techniques outlined here may not always be applicable. In some situations, we deviate from them. But they do provide guidelines to follow in site preparation and maintenance, especially in snow and ice environments such as those at Mount St. Helens.

One point has not been stated explicitly but is the key to operating low-power telemetry networks: attention to detail. No matter how much effort has been expended in installing equipment, one unsealed hole in an instrument case may cause the equipment to fail. At sites accessible only by helicopter, one cold-solder joint can cost hundreds if not thousands of dollars to repair. Paying attention to the details of site preparation and instrument packaging is the most important factor in achieving long-term reliability.

PRODUCTS/MANUFACTURERS MENTIONED IN THIS TEXT

RTV sealant/adhesive

Dow Corning
Box 0994
Midland, Michigan 48686-0994

Scotchkote

3M/Electronic-Products Division
P.O. Box 2963
Austin, Texas 78769-2963

Instrument cases

Pelican Products Inc.
2255 Jefferson Street
Torrance, California 90501

Zero Corp.
777 Front St.
Burbank, California 90503

Connectors

Amphenol Corp.
358 Hall Ave.
Wallingford, Connecticut 06492

Antennas

Scala Electronic Corp.
P.O. Box 4580
Medford, Oregon 97501

Larsen Electronics, Inc.
P.O. Box 1799
Vancouver, Washington 98668

Transient suppressor diodes

General Semiconductor Industries Inc.
2001 W. 10 Place
Tempe, Arizona 85281

Plasma-discharge tubes

Polyphaser Corp.
P.O. Box 1237
Gardnerville, Nevada 89410-1237

Zener diodes

Motorola Semiconductor Products, Inc.
P.O. Box 20912
Phoenix, Arizona 85036

Batteries

SAB/Nife
P.O. Box 7366
Greenville, North Carolina 27834

Duracell Inc.
Berkshire Industrial Park
Bethel, Connecticut 06801

WD-40

WD-40 Co.
San Diego, California 92110

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4. A System for Acquiring, Storing, and Analyzing Low-Frequency Time-Series Data in Near-Real Time

By Thomas L. Murray

ABSTRACT

Timely interpretation of data is essential in volcano monitoring. I developed a system at the Cascades Volcano Observatory (CVO) to provide near-real time acquisition and display in graphic form of low-frequency data (sample rates less than or equal to 1 minute). Data from the low-data-rate telemetry network and real-time seismic-amplitude system are transferred to a central computer at 10-minute and 1-minute intervals, respectively. Data collected manually are entered into the central computer by hand, while data from remote telemetry networks are collected weekly through a dial-up procedure. In the central computer, the program BOB, which I developed at CVO, provides for rapid interpretation of data by displaying them in graphic form. Although at CVO a VAX 11/750 is used as the central computer, the system can also use an IBM PC XT/AT or compatible for the central computer, increasing the system's portability.

INTRODUCTION

To provide timely warnings of impending volcanic eruptions, the scientific staff of the Cascades Volcano Observatory (CVO) must collect large amounts of data and analyze new data within minutes of collection. Comprehensive analysis of data is not required in real time, but precursors to eruptive activity may be missed if the data are collected and stored without being inspected. At CVO, I developed a system (fig. 4.1) to acquire and process low-frequency data (data sampled at intervals greater than or equal to 1 minute) for detecting anomalous activity and to archive data for further analysis.

Ground tilt, fumarole temperature, gas concentration, and earthquakes per hour are typical low-frequency measurements. A single telemetered tiltmeter transmitting three measurements every 10 minutes (radial and tangential tilt components plus temperature), produces 432 measurements per day, or over 150,000 measurements per year. Seismic-amplitude measurements from eight stations sampled at 1-minute intervals produce more than 10,000 measurements per day. Acquisition of these real-time data from the low-data-rate telemetry networks (Murray, 1988) and the real-time seismic-amplitude measurement system (RSAM) (Murray and Endo, chapter 1) is done by inexpensive laptop computers. Each laptop stores data in its internal memory and, at either 1- or 10-minute intervals, transfers the most recent data to a central analysis computer. Data collected manually, such as single-setup tilt measurements, sulfur dioxide flux measured with a Correlation Spectrometer (COSPEC), electronic distance meter (EDM) measurements, and the number of earthquakes per hour are entered into the central computer manually. Once in the central computer, data are immediately available for viewing and correlation with other measurements through the program BOB (Murray and Endo, 1986).

CENTRAL COMPUTER

At CVO, the central analysis computer is a VAX 11/750 minicomputer. Full multitasking, multiuser capability allows numerous users to access data simultaneously. Several dial-in ports allow scientists to keep abreast of the latest data while absent from the observatory. The resources of the VAX (such as dial-in ports and hundreds of megabytes of disk space) enable data collection not only from Mount St. Helens but also from local telemetry networks in Yellowstone National Park, Wyoming, and Kileaua Volcano, Hawaii, and from various other sites via the GOES satellite network. All the data go into a data base, accessible by a single program, BOB.

The VAX functions superbly in an established observatory, but is not easily transported. To monitor a volcano far from the observatory, data could be transmitted to the CVO VAX from the volcano (as is done with the Yellowstone telemetry network), and scientists at the volcano could use the VAX's dial-in ports to view the data. However, dedicated phone lines are expensive, and an eruption could disrupt the phone system. It is preferable to have the computer on site for the most efficient flow of information to the scientists monitoring a volcano. To this end, I modified the CVO system's programs to run on an IBM PC XT/AT or compatible computer. Installation and users' guides for the PC version are available (Murray 1990a, 1990b). Differences between using a VAX and an IBM PC as the central analysis computer are minor and usually transparent to the user. The major drawback to the PC is that it is not inherently a multitasking, multiuser computer. Commercially available software (Desqview), however, provides the computer with multitasking capability to enable automatic data acquisition in "background" mode while the computer is performing other tasks, such as plotting data, in the foreground. Furthermore, the computer need not be dedicated only to collecting and displaying low-frequency data; it can also be used as a standard PC. But the computer is still limited to one keyboard and monitor, and only one person can use it at a time. Experience has shown this

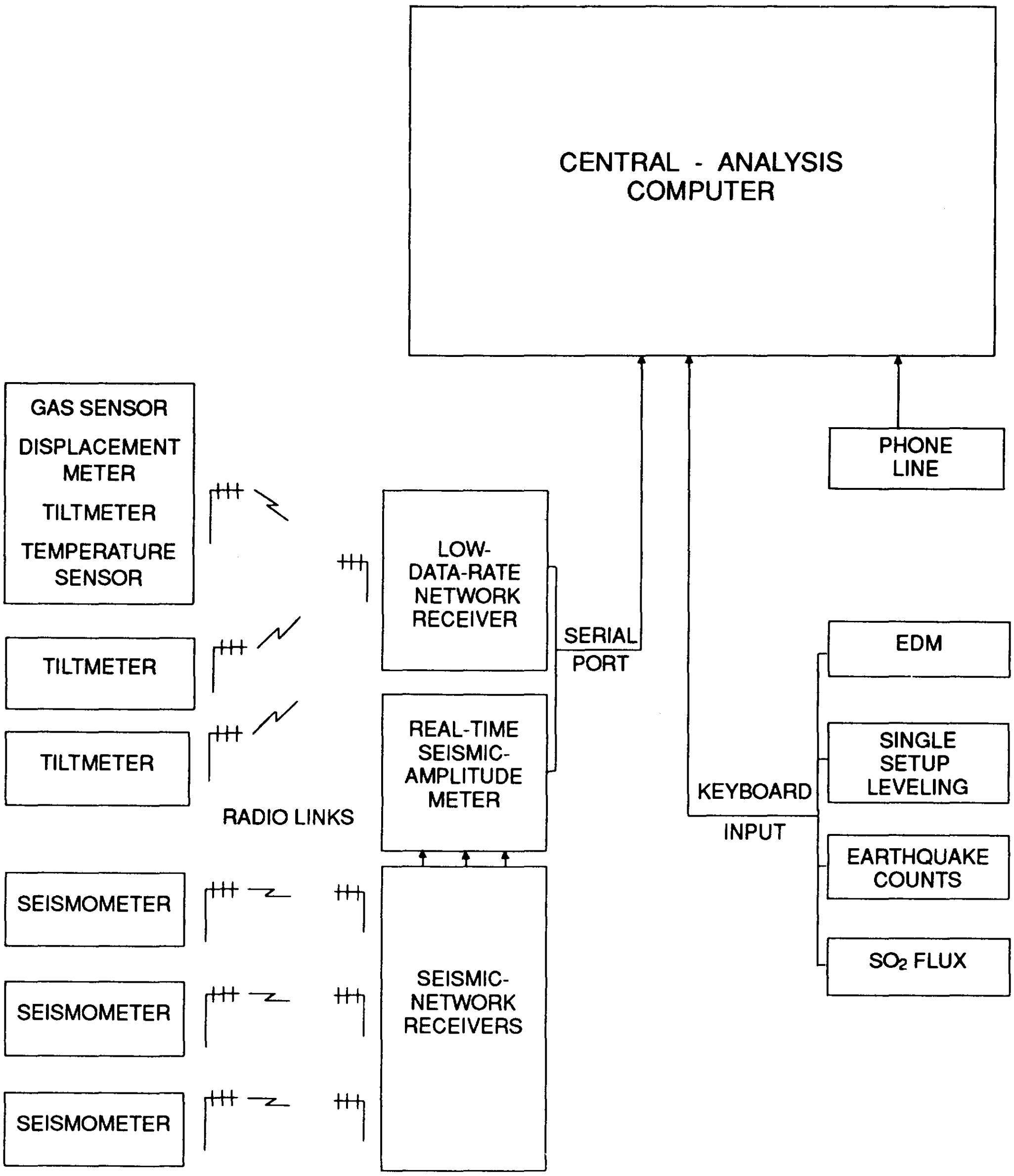

Figure 4.1. CVO low-frequency data-acquisition system.

not to be a problem during crisis situations, because at such times most of the analysis is performed by looking at trends and correlating data from different precursors. The 10 minutes typically available between telemetered updates is usually sufficient time to plot and inspect the data.

The lack of a dial-in port is no longer a major problem for the PC, since the proliferation of facsimile (fax) machines has provided a means for quick distribution of plots to scientists outside the observatory. Current developments in networking PCs should provide the means in the future for multiuser sharing of the data and dial-in ports to the system.

With their decreasing cost, IBM PCs and compatibles are the current central-analysis computer of choice. The minimum recommended system for a PC to serve as a central-analysis computer is the following:

Hardware:

IBM AT or compatible
EGA, VGA, or Hercules monitor
Math coprocessor
2 megabyte EMS 4.0 memory with memory manager
30 megabyte hard disk
5 1/4 inch floppy drive, 360 kilobyte minimum
3 1/2 inch floppy drive, 720 kilobyte minimum

Required software:

DOS 3.2 or 3.3 by Microsoft, Redmond, Washington

Interpretive BASIC (GWBASIC) by Microsoft, Redmond, Washington

Geograf Graphics Utilities by Geocomp, Concord, Massachusetts

Desqview by Quarterdeck Office Systems, Santa Monica, California

QDOS II by Gazelle Systems, Provo, Utah, or similar utilityprogram with an ASCII word processor

Substituting more powerful hardware for the equipment listed above, such as an 80386-based machine or a larger hard disk, is encouraged. Though an IBM XT or compatible may be used in place of the AT, the XT's slow clock speed and 8086 processor may slow the computer's response time to unacceptable levels while running Desqview.

DATA ACQUISITION

The central computer acquires data by one of three methods: (1) automatically by direct connection of data-acquisition computers to the central computer, as with the Mount St. Helens low-data-rate telemetry networks, (2) manually by keyboard entry, as with data not recorded electronically such as EDM or magnetometer-survey measurements, and (3) semiautomatically by periodic transfer of data over phone lines, as with remote low-data-rate telemetry networks at Yellowstone and Hawaii.

Data collected automatically can be viewed in near-real time as the data files on the central computer are automatically updated within 10 minutes of the time of measurement. Phone-line and labor costs limit how close to real-time data collected semiautomatically or manually can be viewed. For example, a dedicated phone line could be established between the telemetry network at Yellowstone and the CVO VAX. Data could be transferred automatically at 10-minute intervals, as is now done with the Mount St. Helens networks. The phone line and modem would be transparent to the VAX, which would see no difference between the Yellowstone network and the Mount St. Helens networks.

Automatic Data Acquisition

Data from the low-data-rate telemetry network and the real-time seismic-amplitude meter are automatically acquired by several Radio Shack Model 100 or Toshiba 1000 laptop computers connected to a serial port of the central computer. The laptops collect and periodically transfer the data over a serial line to the central computer. There are several advantages to using laptops for data collection:

1. They relieve the central computer from data-acquisition tasks so that its greater processing power can be put to better use in analysis and other tasks.
2. They provide redundancy, as the laptops can store a few days of data in the event the central computer is inoperative.
3. They increase immunity to power failures and brownouts because the laptops are battery powered. Battery-powered computers consume less power than normal desktop computers and can operate longer during power failures when powered by an uninterruptible power supply.
4. They increase the robustness of the system as it is not dependent on a single machine.

The low-data-rate receiver's operation will not be affected by a malfunction of the RSAM, and vice versa. If the central computer fails, the ability to quickly plot and correlate data is lost, but the laptops would still acquire and display data that could be monitored and plotted manually, if necessary.

The laptops share a single serial port of the central computer. This sharing, done by a circuit I developed at

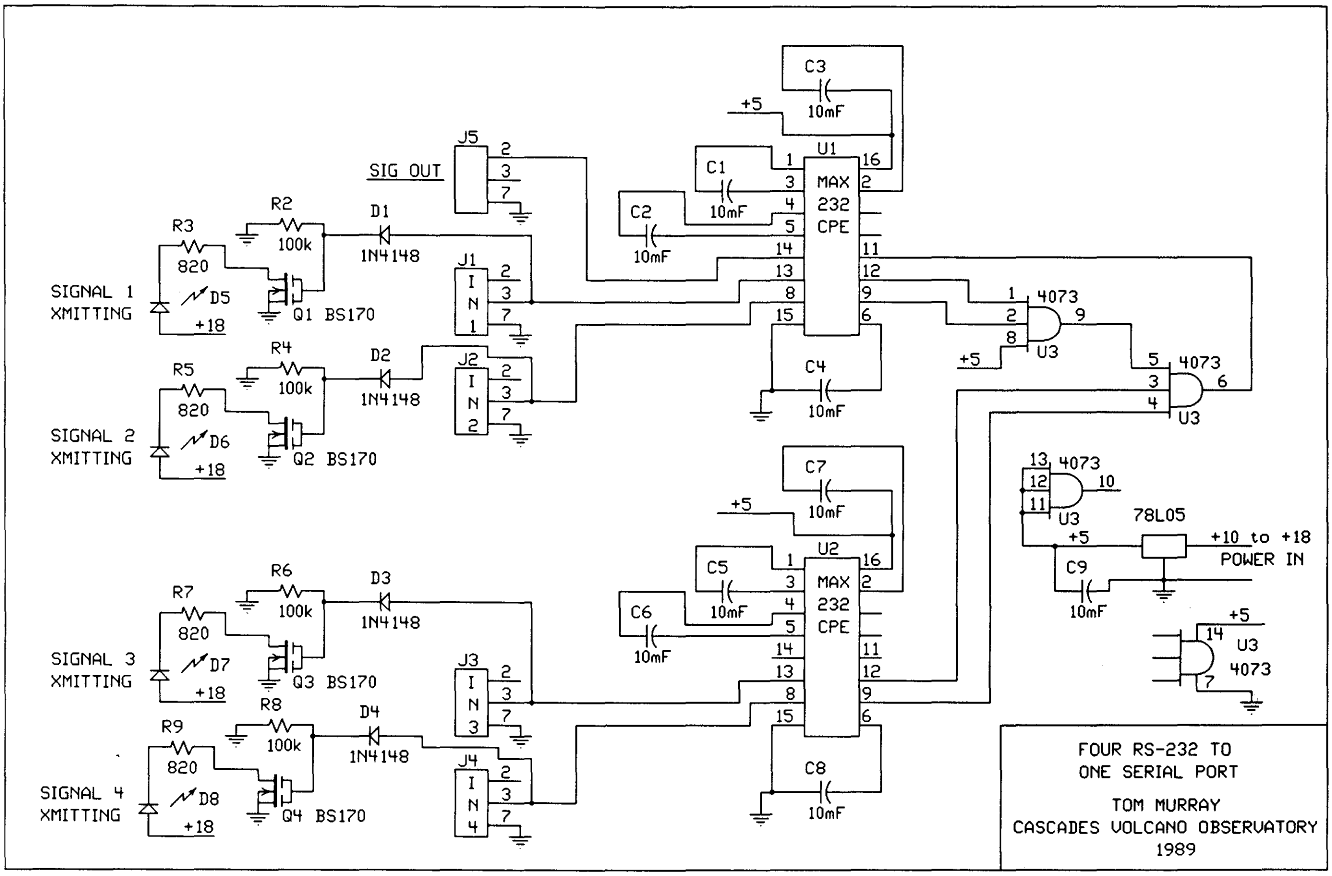

Figure 4.2. Circuit to allow up to four devices to transfer data through a single serial port.

CVO (fig. 4.2), has enabled as many as four laptops (three low-data-rate telemetry receivers and one RSAM) to use a single serial port.

As currently configured, data are transferred only from the laptops to the central computer. No data or commands are sent from the central computer back to the laptops. This eliminates the need to establish any protocol for communication between the computers, other than that the data must be sent to the central computer in a specified format. Thus, no possibilty exists for the central computer to cause a malfunction in the laptops by sending them a strange control character, such as might occur if the central computer were to be accidentally reset. The laptops will continue to transmit data to the central computer whether or not it is operational.

A major problem with this system is the possibility of two of the laptops attempting to transfer data to the central computer at the same time. Simultaneous messages will interfere with each other, the result being that no data will be correctly received. To prevent this, each laptop has an assigned time window (minimum of 10 seconds) in which to transmit data. Weekly synchronization of the laptop's clocks keeps them in their respective windows.

Manual Entry of Data

Another method for the central computer to acquire data is by direct keyboard entry. Data collected infrequently are best entered in this manner. For example, EDM or single-setup leveling data collected in the field are entered manually into the computer and a program is run to update the data files. Other data files are updated simply by editing the files using a word processor.

Semiautomatic Data Acquisition

The third method for data acquisition is a combination of the previous two. Laptop computers operating in Yellowstone National Park and in Hawaii receive data from local low-data-rate telemetry networks. These laptops, with 256-kilobyte memory modules for greater data-storage capability and 1200-baud modems for phone-line communications, run a modified version of the programs run by the laptops at CVO. Once a week, these "dial-up" networks are called and their data transferred to the CVO VAX. A program is then run to update the data files. A similar procedure is used to retrieve data transmitted via the GOES satellite to a ground station at Wallops Island, Virginia.

DATA STORAGE

The system divides the data into two groups. One group consists of data collected at irregular intervals, such as EDM measurements. These data may consist of as few as 30 readings per year. In contrast, readings from a single axis of a telemetered electronic tiltmeter taken every 10 minutes throughout the year result in more than 52,000 data points per year. I decided not to attempt to use a single file format for both types of data sets but instead to provide two file formats, one for large amounts of data collected at regular intervals and one for small data sets collected at irregular intervals.

Data collected at frequent, regular intervals are stored in binary format in direct-access files (fig. 4.3). Each file is allocated memory sufficient for one year's worth of data for the specific measurement. For data collected at 10-minute intervals, this amounts to just under 215 kilobytes. These files are subdivided into 366 records (367 records for a leap year), one record for each day of the year and an initial record indicating the number of data points per day (which is equivalent to the data points per record). Each record contains the data for its day of the year. The time interval between data points is calculated by dividing 1,440 (number of minutes in a day) by the number of data points per day. Intervals that are not integral divisors of 1,440, such as 17 minutes, are not allowed.

Serial access, ASCII-format files are used for the data sampled at irregular intervals (fig. 4.4). Data in these files are in columns, with the date and time of the measurements in a standard format at the beginning of each line. New data are appended to these files through programs or with a word processor. The entire file must be read to access the latest data. For long files, this may require an unacceptably long time. If necessary, large files can be subdivided into smaller, separate files for each day, month, or year to speed access.

The data-plotting and analysis program BOB, which I developed at CVO, provides easy access to data from both types of files. BOB also has the ability to access data from an archive device as well as the current on-line drive. If data are not found on the on-line drive, BOB searches for data on an archive device such as an optical disk. BOB treats data retrieved from separate devices as one continuous data set. Programs also exist that convert files from one type to the other.

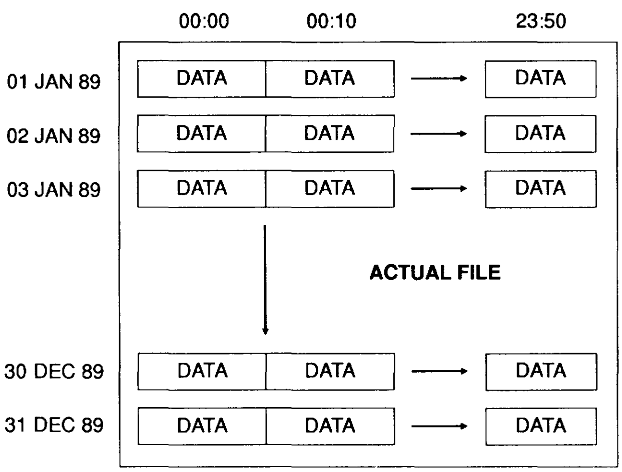

Figure 4.3. Direct-access binary data file format. Example uses 10-minute sample rate.

DATA ANALYSIS

The interactive, command-driven program BOB is the core of the data analysis. It provides quick retrieval of data from either file format and easy correlation between the data sets. BOB was developed especially for quick analysis of time-series data in crisis situations. The time axes in BOB plots are in day-month-year format instead of julian days for quick determinations of when things happened, especially for nonscientists. Time periods as short as one day or as long as 50 years can be plotted to see the relation between recent trends and long-term records. Missing data points are handled easily. Making multiple plots in which each data set has a different number of data points per day requires no special commands. The maximum number of data points allowed by BOB is just over 400,000 data points on the VAX, while on the PC it is limited only by the available disk space. BOB also converts between GMT and local time if necessary. The following lists the BOB commands that produced the plot of earth tides and

DATE	TIME	DATA 1	DATA 2
01 JAN 89	08:10	+ 1.233	- 456.7
07 JAN 89	13:30	+ 1.238	- 998.0
12 FEB 89	10:42	+ 1.238	- 998.0
12 FEB 89	14:13	+ 1.235	- 455.9
21 FEB 89	12:05	+ 1.235	- 460.0

Figure 4.4. Sample ASCII data file. Note that -998.0 is used to indicate no measurement made.

RSAM for the first two weeks of the 1989 eruption of Redoubt volcano, Alaska, shown in figure 4.5.

EXE REDOUBT	Select Redoubt volcano
B_DATE 12 DEC 89	Select beginning date
E_DATE 25 DEC 89	Select ending date
STID RSAM	Choose the station to be RSAM
MEAS RDNZ	Choose the measurement to be for seismometer RDNZ
FILL A	Put the data for the time period and measurement indicated into column A
AVG 6 A	Average every six measurements to produce an hourly average
TITLE A RDN SEISMIC AMPLITUDE	Assign a title to column A
LABEL A HOURLY AVERAGE	Assign a label for the units of A
STID TIDE	Choose station for tides
MEAS TIDE	Choose earth tide measurements
FILL B	Put the data in column B
TITLE B EARTH TIDES	Assign a title to column B
TZONE AST	Set time zone for Alaska Standard Time
TOPTITLE REDOUBT VOLCANO	Assign the overall title for the plot
PLOT 2 A B	Plot the data in columns A and B

A sample plot produced by BOB for the October 1986 Mount St. Helens dome-building episode at Mount St. Helens is shown in figure 4.6.

Simple macros, batch files, and menu-driven programs provide easy access to the data for people with little or no knowledge of the system. For the PC as the central computer, these programs are written in BASIC so that modifications and enhancements can be made easily by staff members with programming experience in almost any language. For the VAX, these programs are written in FORTRAN. With these programs, observatory staff can print plots for all the data for the last few days or months with a single command. In interactive mode, BOB provides the means to look closely at short-term trends and then see how they relate to long-term trends.

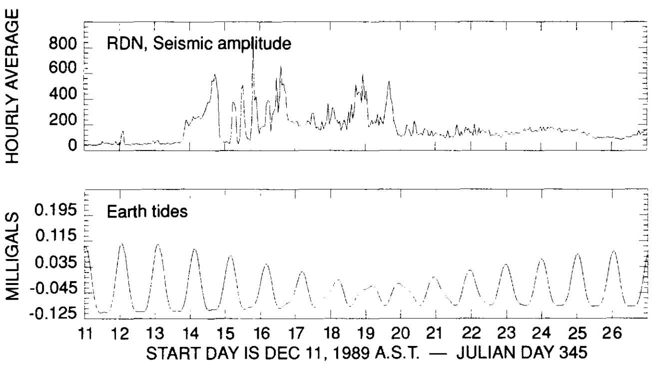

Figure 4.5. Example plot produced by the program BOB for Redoubt volcano. See text for explanation.

Various types of data can be plotted on a common time scale to search for crosscorrelations.

BOB also provides the user with convenient locations for files containing pertinent information about the field sites and instruments. These files can contain such information as instrument serial numbers, calibration factors, and site locations. Such information can be critical during a crisis.

If the user requires more statistical analysis or greater graphics capability, BOB can write the data in ASCII formats usable by commercial data-analysis programs. The greater statistical or graphics capabilities of these programs can then be utilized.

CONCLUSION

The system in use at CVO can provide the core for volcano monitoring systems for the future. The VAX version, in operation since 1985, has evolved from a method to merely plot tiltmeter data to its present state. The PC version performed well in crises at Galeras Volcano, Colombia, in 1989, and Redoubt volcano, Alaska, in 1989-90.

As currently configured, the system provides a flexible means for gathering, analyzing, and archiving low-frequency measurements, whether telemetered directly to the system, stored in computers at remote locations, or collected manually. As more powerful and less expensive hardware and software become available, improvements will be made.

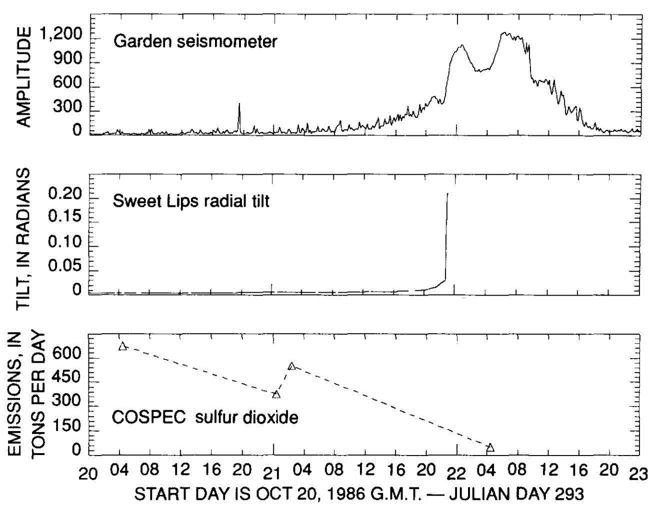

Figure 4.6. Example plot produced by the program BOB for the October 1986 dome-building eruption of Mount St. Helens.

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5. Seismic Data-Acquisition Systems at the Cascades Volcano Observatory

By Elliot T. Endo *and* Gloria Smith

Abstract

From late 1987 to early 1990 the Cascades Volcano Observatory (CVO) installed and operated two different seismic-data-acquisition systems for a small seismic network. The systems were set up to detect and record small earthquakes beneath Mount St. Helens from a 14- to 16-station seismic network. The first data-acquisition system is a PC/AT system, which utilizes software distributed by the International Association of Seismology and Physics of the Earth's Interior (IASPEI). The second system uses a Sun workstation, an analog-to-digital subsystem with an SCSI interface, and data-acquisition software written for computers that use the UNIX operating system. Recording with both systems in 1989 gave CVO the opportunity to evaluate two relatively inexpensive digital seismic data acquisition systems. Both systems were easy to install and performed as expected.

INTRODUCTION

Since December 1987 the Cascades Volcano Observatory has been a Beta test site for testing and evaluating seismic-data-acquisition and analysis software written by Tottingham and others (1989), Lee and Valdes (1989), and Valdes (1989) for IBM PC/AT and compatible computers. We began testing early versions of the current release of the IASPEI software in November 1988 (Toolbox for seismic data acquisition, processing, and analysis). An AST Premium 286 computer (an 80286-based PC/AT clone) used for seismic-data acquisition has been in continuous operation for over 2 years. The system currently records 15 channels of seismic data, 8 for seismic stations maintained by CVO and 7 for seismic stations maintained by the University of Washington's Geophysics Program (UWGP) in the Mount St. Helens area (fig. 5.1). During normal activity, seismic data recorded by the PC/AT system are routinely processed on a daily basis. In 1989 more than 600 earthquakes were picked for routine locations, about 400 of which qualified as "A" or "B" quality (Lee and Valdes, 1985) earthquakes (figs. 5.2–5.4).

In late January 1989 we began operation of a Sun workstation (WS) seismic-data-acquisition system using one of the first production Data Samplers (analog-to-digital subsystem) built by Cutler Digital Design (Ward and Cutler, 1987). The seismic-data-acquisition system utilizes the same software that Peter Ward of the U.S. Geological Survey modified for a similar workstation that records data from the Katmai seismic network. The CVO system currently records Mount St. Helens seismic signals from 13 single-component seismic stations and 1 three-component site. For a number of reasons, routine processing of earthquakes recorded by the Sun workstation system has not been implemented, thus a rigorous comparison of the two systems was not possible.

Implementation History

After the two dome-building events in 1986, it was clear that CVO required more than portable digital seismic-event recorders for analyzing Mount St. Helens earthquakes. Our preliminary research results pointed out the need for relatively complete digital recording of precursory eruption seismicity at a higher sampling rate than previously to detect evidence for hypocenter migration. We also required data from additional stations within the crater to improve locations of shallow earthquakes associated with magma migration. In fall 1986, when a decision was made to install a real-time seismic-data-acquisition system, the only appropriate software available was Caltech-USGS Seismic Processing system (CUSP, Tanigawa and others, 1987) written by Carl Johnson. CUSP required a VAX processor with the Digital Equipment VAX VMS operating system. We could have installed CUSP on the existing VAX 11/750 at CVO, but the cost for the required analog-to-digital converter (A/D), graphics terminal, and high-speed interface board was estimated to be about $30,000 in 1987. One potential problem with such an installation was the impact it would have on existing VAX users and on high-priority processes. A reasonable solution was to procure a MicroVAX WS, which we assumed would complement the existing VAX 11/750 and provide us with the required high-speed graphics capability. CVO was also faced with the problem of implementing CUSP, for which no documentation existed. In spring 1987 a MicroVAX RC graphics WS was ordered through a national MicroVAX procurement effort. The GSA schedule price for a fully configured MicroVAX RC was $17,600. That price did not include the roughly $12,000 cost of the A/D subsystem.

While we were waiting news of the national procurement effort, P.L. Ward was involved in identifying a low-cost recording system that could be used for a project at Katmai National Monument, Alaska. Analog recording was out of the question owing to the labor-intensive process of converting the data to a digital format. Real-time digital data acquisition was the only reasonable solution. Portable recorders were considered and rejected because of the time-consuming process of playback into a computer system for analysis and severe limitations in network expansion. Commercially available seismic-data-acquisition systems as well as CUSP were rejected owing to their high hardware and software costs as well as the high cost of site requirements. CUSP would also have been unnecessarily large and complex for such a small network as Katmai. A PC-based system was rejected because of the limitations of the DOS operating system. Ward also wanted to use his expertise with UNIX and the UNIX seismic-data-analysis software that was available from Lamont Doherty Geological Observatory (LDGO) and Lawrence Livermore National Laboratories. Because no

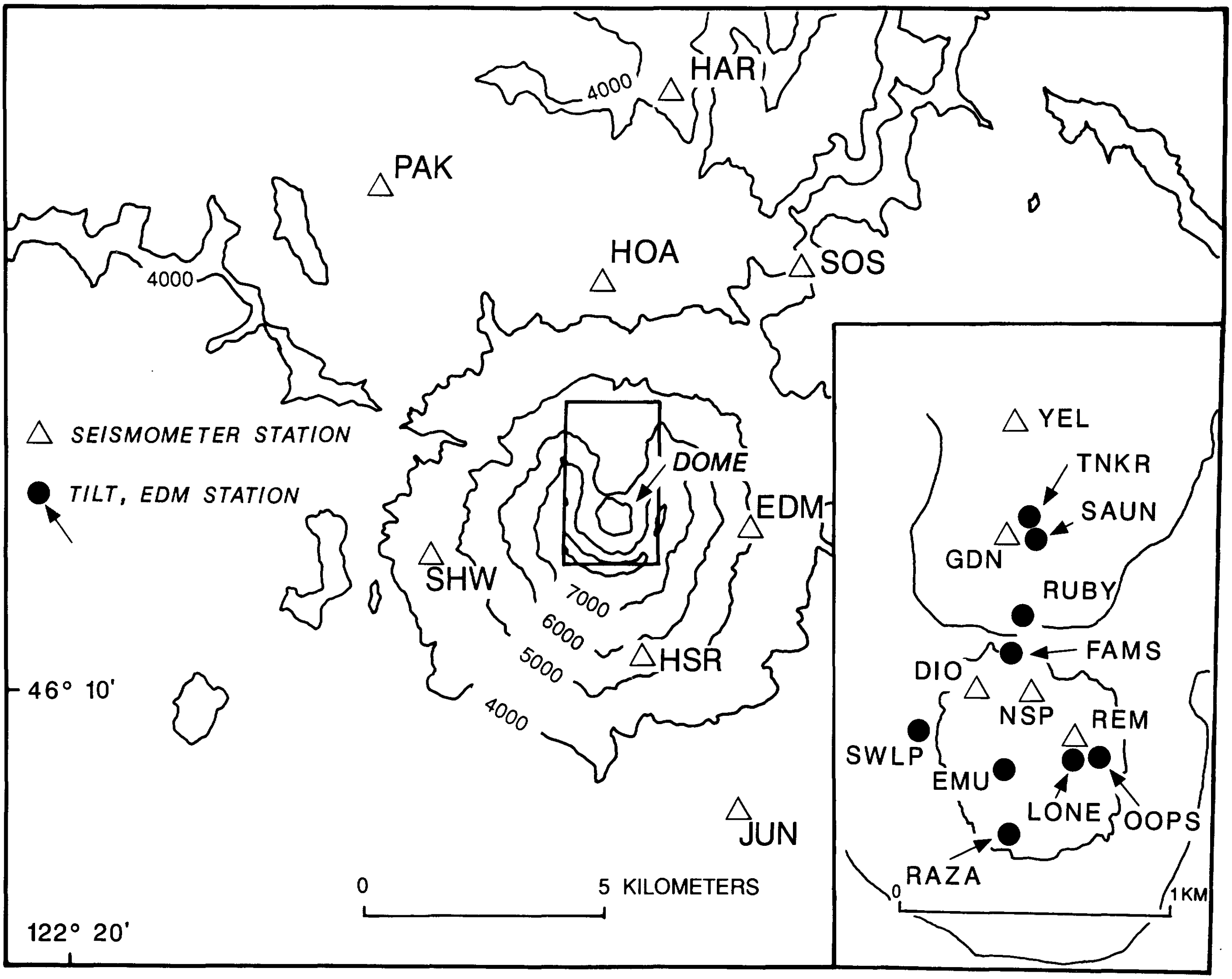

Figure 5.1. Distribution in 1989 of seismic stations at Mount St. Helens. Seismic stations ERT (15 km west), CDF (14.5 km southeast), and MTM (20 km south) are not plotted. Locations of a subset of telemetering tiltmeter sites are plotted in insert. Contours are in feet.

A/D subsystem was available to operate under generally available UNIX operating systems, Ward together with Reese Cutler (Cutler Digital Design) designed and built the Data Sampler (Ward and Cutler, 1987), which could interface with a UNIX type of computer system via a standard small computer standard (SCSI) interface. Although any computer using the UNIX operating system could have been used, the choice of the Sun WS was probably due to the fact that LDGO was well along in its software development under the Sun window environment. The Sun WS was not designed for expansion via a computer bus as were VAX computers.

In September 1987, while working with Ward at King Salmon, Alaska, Endo had the first opportunity to observe the Sun WS and prototype Data Sampler in operation. He was impressed by the fact that the Data Sampler was designed, built, and tested with the Sun WS and operational in a period of about 3 months. The Sun WS system could be monitored from Menlo Park, California, via a modem port. With help from the National Park Service, data were written to a magnetic tape, which was then mailed to P.L. Ward in Menlo Park. Attractive features of the data sampler were its estimated $5,000 price for a 16-channel version and the low cost for expansion.

Shortly after returning to CVO near the end of September, we were informed that the MicroVAX RC was no longer available on GSA schedule and that an equivalent replacement system would require another $12,000 or so from the project. The additional funding required at such a late date in the fiscal year was out of the question. Even if the funding were available, the cost of the MicroVAX system was approaching an unreasonable level. We were given less than a day to make a decision regarding the disposition of the previously committed funding. After having observed the Sun WS in action, there was no hesitation to select the Sun WS as replacement for the MicroVAX RC WS. For the $17,600 originally committed to the MicroVAX RC, we were able to order a 141-megabyte Sun WS with 1/4-inch tape drive and a Sun WS with a 71-megabyte disk drive. The Sun WS arrived at CVO in early December 1987. An unknown at that time was when would a production-model Data Sampler be available for the Sun WS. We still had an immediate need for a real-time system capable of recording up to 16 channels.

In late December 1987 a copy of the earliest version of the IASPEI data-acquisition software for the PC/AT system was obtained. Due to its relatively low cost and commitment to PC-type hardware, which could be used for other purposes if we decided to abandon the PC/AT, a decision was made to use the PC/AT system until we could fully implement the Sun WS system. The PC/AT system was a low-risk system, because of the relatively inexpensive A/D board. Owing to the simplicity of DOS, the PC/AT system was installed in a few hours. Much of that time was used for wiring discriminator outputs to the A/D and verifying inputs.

The original version of the program was a disappointment. While the program did pick and locate earthquakes in real time, a programming error resulted in numerous files being generated for one earthquake. It was in essence a one-earthquake system. In spring and summer 1988 no analysis software was available for the PC/AT to confirm computer picks. In October 1988 we received an improved version of the seismic-data-acquisition software and, a few weeks later, data-analysis software written by Carlos Valdes. The

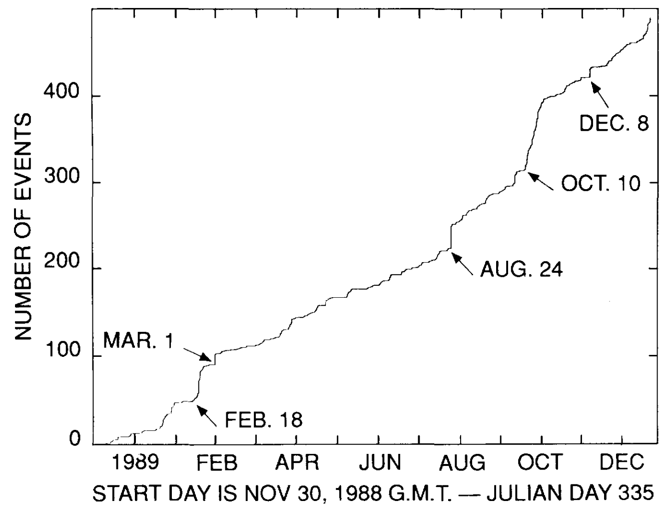

Figure 5.2. Cumulative number of "A" and "B" quality Mount St. Helens earthquakes recorded by CVO PC/AT seismic-data-acquisition system from November 1988 to January 1990.

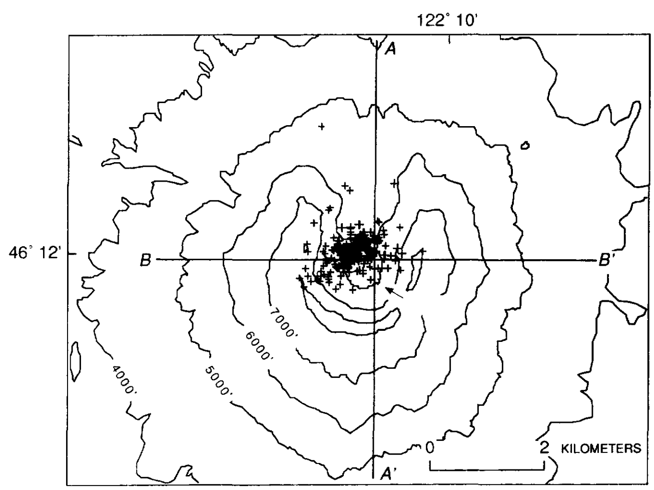

Figure 5.3. Epicenters of "A" and "B" quality earthquakes located during the period from November 1988 to January 1990. Lines *A–A'* and *B–B'* are locations of profiles in figure 5.4. Contours are in feet.

latest version has been operating and detecting earthquakes since October 15, 1988. To this date we have detected no problems with the software. The analysis software is currently being used for manual picks to routinely locate Mount St. Helens earthquakes.

The Sun WS Data Sampler, which was ordered at the end of June 1988, arrived on September 27, 1988. By late October, wiring to the Sun WS room was completed, the GOES clock installed, and a discriminator rack rewired for a ribbon-cable connector. After about 2 weeks of studying UNIX manuals and P.L. Ward's help, Endo upgraded the UNIX operating system to version 3.5, a requirement for operation of the data sampler. On November 9 the Data Sampler was successfully operated in develocorder mode. On December 5, we received additional software from Ward to put the Sun WS in detection mode. Further installation was temporarily delayed until we received additional discriminators for the rack located in the Sun WS room. On January 26, 1989, the Sun WS seismic-data-acquisition system was put into full-time operation.

PC/AT Seismic-Data-Acquisition System and Analysis

The PC/AT (AST Premium 286) system utilizes the seismic-data-acquisition software published by IASPEI (Lee, 1989). The current version is capable of monitoring 16 channels (single ended) and detecting and recording earthquakes, optionally locating earthquakes in real time. The CVO system currently monitors 15 seismic stations. The sixteenth channel is used for recording IRIG-B (Inter Range Instrumentation Group) time code from a satellite clock. Although not essential for locating earthquakes with the AT clone, the time code (preferably IRIG-E) is required to tie the computer-system time to that of other seismic networks and to determine the correct origin time.

With help from Lee the input-parameter file was modified to trigger and record successfully most of the small Mount St. Helens earthquakes observed on analog seismic records. Any event recorded at 20 to 25 mm peak-to-peak amplitude and with coda lengths greater than 5 seconds appears to be recorded by the system. As

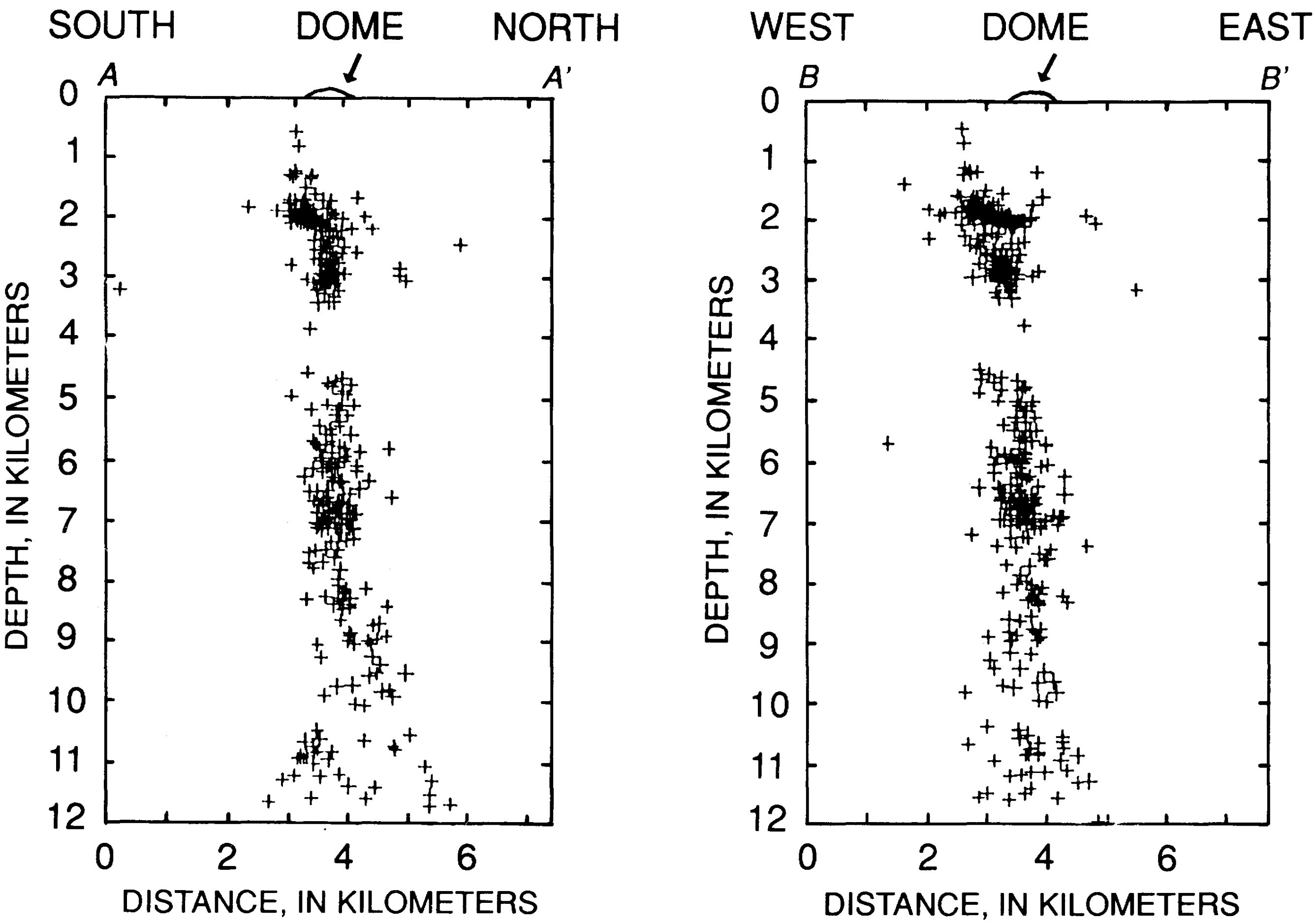

Figure 5.4. South-north and west-east cross-section plots of "A" and "B" quality hypocenters. Locations on figure 5.3.

with any online system, telemetry noise occasionally produced numerous false triggers that filled the hard disk system. About 27 megabytes (approximately 100-150 events) of disk storage is available for recording earthquake data and false triggers. A typical file with 16 traces digitized at 200 samples per second for 35 seconds, requires 230,400 bytes of storage. A sampling rate of 100 samples per second would be more than adequate for most small networks and would double the number of events that could be recorded. Our practice has been to check the file system daily. Analog records are checked and earthquake files identified. Files for false earthquake triggers (telemetry noise, avalanches, or rock-fall signals) were deleted and earthquake files written to an optical disk (200 megabytes capacity) or floppy disk (1.2 megabytes capacity). Because we do not have a PC Local Area Network (LAN) system for file inspection and transfer, the data-acquisition system is offline for the 15 to 60 minutes required for the file transfer. We are currently using IASPEI software written by Carlos Valdes (Valdes, 1989). With EGA graphics and a mouse, it is easy to pick earthquake phases and locate earthquakes using HYPO71PC (Lee and Valdes, 1985). A version of the picking program allows the user to select a time window for spectral analysis. If the system's absolute response is known, seismic moment for individual earthquakes can also be computed.

Following is our current hardware configuration for the AST 286 system:

40 megabyte hard disk, 28 ms access time
1.2 megabyte 5 1/4-inch floppy drive
2 megabyte RAM, 100 ns chips
80287 math coprocessor
One serial, one parallel port
EGA video card
NEC multisync color monitor
Keyboard
MS-DOS
IBM 3363 200 megabyte WORM drive
Data translation DT2821 A/D + license to use ATLIB software
Hercules compatible monochrome graphics card
Monochrome monitor

Cost for above system:

AST 286 Premium system	$3,595
IBM 3363 WORM drive	$1,858
DT2821 A/D and license	$1,524
Total	$6,977

For display of seismic traces a monochrome monitor and card added about $200 to the AST system. For data analysis an Everex 1700 12-MHz AT clone is used. It has the following configuration:

40 megabyte hard disk
1.2 megabyte 5 1/4" floppy
720 kilobyte 3 1/2" floppy
1 megabyte RAM
80287 8 MHz math coprocessor
EGA graphics card and NEC monitor
Microsoft mouse
IBM 3363 WORM drive

The approximate cost for the Everex system, without WORM drive, was about $3,000. The actual Everex system procured was a $2,100, 1-megabyte, monochrome system without EGA graphics, mouse, math coprocessor, or WORM drive. Components (EGA video card, mouse, EGA monitor) from an existing XT system normally used for word processing, graphics, and other tasks were put into or used with the Everex system. An A/D board was not installed on the Everex, which was not configured to be identical to the AST system. Total cost for the two AT clone systems was about $12,000. Continuous data acquisition and routine analysis cannot be accomplished with one AT clone; two identical systems are required to ensure continuous recording. While analysis takes place on one system, the user can be recording on the other system. The second system also serves as a backup in case of failure of the first system. Should we have a major earthquake swarm, our current plan is to transfer all data to the optical disk to minimize recording down time. If the data-acquisition and analysis systems are in close proximity, the use of a LAN system would eliminate the need for a second A/D board and the need for a similarly configured system. Furthermore, trigger files could be transferred to the analysis system without interrupting data acquisition. Only one WORM drive would be required for the archiving of data. Systems procured for use elsewhere should consider the problem of continuous recording (backup system) and routine data analysis. Analysis software written by Carlos Valdes could operate (somewhat slower) on a PC/XT with EGA graphics, math coprocessor, hard disk, and mouse.

The implementation process for the PC/AT software was a relatively simple task. The user needs only to set up appropriate directories, copy files from floppy to hard disk, change config.sys and autoexec.bat files, and edit input files for station names, channel numbers, triggering parameters, and so forth. A monochrome graphics board and the A/D board had to be installed with jumpers appropriately set. The monochrome monitor was used for continuous display of seismic traces.

Like all other PC equipment at CVO, none of the above equipment is on a maintenance contract, since

CVO has in-house capability to handle much of the maintenance. The relatively low cost of PC hardware also discouraged a maintenance contract.

Sun Workstation System

The Sun WS system implemented at CVO consists of two Sun 3/50 workstations. One WS is configured to handle data acquisition via a Data Sampler (A/D subsystem, Ward and Cutler, 1987) built by Cutler Digital Design. The Data Sampler used has one input module for 16 channels. Additional modules can be installed in the data sampler to provide inputs for up to 256 channels. The primary functions of the Data Sampler are to accept analog seismic inputs from a number of channels, digitize signals at a specified rate, and provide temporary storage until transfer to a host computer. The use of parallel binary coded decimal (BCD) time from a GOES satellite clock for the four least significant data bits is unique to the Data Sampler. If parallel BCD time is not available, the user is provided the option of using a less accurate internal clock. The Data Sampler appears to the UNIX operating system as a SCSI nine-track tape drive. Software to test the Data Sampler and to detect and record earthquakes was written or modified by P.L. Ward.

The CVO system is fully operational, with the sampling rate set at 100 per second. During the latter part of 1989 we started to process earthquake data recorded by the Sun WS system to evaluate its performance along with that of the PC/AT system. The second WS was set up primarily for data analysis, but a directory structure similar to that of the data-acquisition system has been installed to facilitate the use of the system as backup hardware for data acquisition. SUNPICK from LDGO is the primary software used for routine analysis. At CVO, the Sun WS's are connected by ethernet. The ethernet system provides a convenient way to share files and resources.

The current configuration for the Sun WS system is:

One Sun 3/50 WS with:
- 320 megabyte hard disk
- 60 megabyte 1/4-inch tape drive
- 4 megabyte RAM, floating point accelerator
- 19-inch monochrome monitor

One Sun 3/50 WS with:
- 141 megabyte hard disk
- 60 megabyte 1/4-inch tape drive
- 4 megabyte RAM
- floating point accelerator
- 19-inch monochrome monitor
- 16 channel Data Sampler
- GOES satellite clock
- 292 megabyte Delta Microsystems SCSI disk drive

Cost for above system:

Two Sun 3/50 systems	$17,421
One Delta Microsystems drive	4,702
One Data Sampler	4,975
One GOES satellite clock	4,275
One 320 megabyte disk upgrade	6,500
Total	$37,873

The 292-megabyte Delta Microsystems disk provides space for seismic-data-acquisition software and 224 megabytes of data. Approximately 500 to 700 earthquakes 75-100 seconds long can be recorded on the available data space. This configuration provides backup hardware for the seismic-data-acquisition system. Hardware maintenance for the above workstations will be $800 for this fiscal year, and we expect software maintenance to be about $1,600 for both workstations. In this final hardware configuration, the Sun workstations cost $37,873. The data sampler can be expanded to a 256-channel input device for $3,500.

Preliminary Evaluation of the PC/AT and Sun WS Systems

In 2 years (December 1987 to December 1989) of continuous operation, the AST Premium 286 PC/AT experienced no hardware failures. Approximately 75 to 85 percent of the earthquakes detected at three or more seismic stations in the crater of Mount St. Helens were successfully recorded by the PC/AT system. Recording failures were largely due to late triggers that resulted in missed *P*-wave arrivals at the seismic stations. Selection of a lower sampling rate and a longer pre-event time partially solved that problem. Some events were missed during a sequence of closely spaced earthquakes; perhaps a longer post-event time could solve this problem. A problem in proper triggering in late 1989 was related to CVO network configuration, the trigger net which utilizes mostly CVO seismic stations, and the relatively lower gains of crater seismic stations. A significant number of small earthquakes at depths greater than 5 km were not recorded by the PC/AT system. We are experimenting with different trigger parameters to correct the problem.

Telemetry failure creates the most serious problem with the PC/AT system. Numerous event files have been generated by the detection program whenever there was a telemetry disturbance on either one of two main telemetry links from Mount St. Helens. Discriminators such as the USGS J120, which clamp on the loss of carrier signals, would eliminate the problem of numerous false triggers. Without a LAN, routine data analysis is awkward compared to that of the Sun WS, because data cannot be acquired during the time needed to determine which files were appropriate for routine analysis. If a swarm had occurred, all files would have been copied to an optical disk, the only mass-storage device installed on the CVO PC/AT computers.

During the 10 months of operation, the Sun WS system has gone through one monitor failure and one hard-disk failure. The Sun WS systems appear to have triggered on almost all Mount St. Helens earthquakes detected at three or more seismic stations. There have been no failures to completely record all P-wave arrivals of earthquakes. The Sun WS system has the advantage of using time bits from the parallel BCD output of a satellite clock for an absolute time stamp on the digital trace data. The Sun WS system also has the advantages of a larger disk system and the use of the UNIX operating system, which enables flexibility in directory and file names, use of script files, use of aliases, use of the window environment, and higher-resolution graphics.

Both of the systems detect and record local earthquakes well, and each has its advantages and disadvantages. The PC/AT system implemented at CVO was one-third the cost of the Sun WS system and was simple to install, but it suffers from the limitations of the PC/AT and DOS. A brief earthquake swarm in August 1989 quickly filled the available disk space on a standard 32-megabyte partition of the DOS 3.3 operating system. During a lull in activity, event files had to be moved to an optical disk to make room for additional events. By comparison, the Sun WS was more difficult to install, because of the need to understand UNIX and the details required for its configuration. The Sun WS recorded more earthquakes during the same period and required little attention owing to the substantially greater disk space available. Files could also be checked without interrupting the data acquisition process. In addition, the accurate timing of Sun WS files required no time correction of picked phases.

Operational Philosophy

The implementation of a seismic-data-acquisition system at CVO was motivated by the need to better locate shallow earthquakes at Mount St. Helens. Part of the problem in locating small shallow earthquakes is the limited flexibility in reconfiguring telemetry in the regional seismic network (about 128 seismic stations) operated by the University of Washington. Another problem associated with recording small earthquakes by a regional seismic network is that of inefficient use of data storage. A small earthquake that might be detected by only 15 seismic stations less than 20 km from Mount St. Helens would require recording digital data for 112 more distant seismic stations in the network. Recording a subset of the regional network and a few additional stations was more efficient and less costly on smaller-capacity seismic-data-acquisition systems such as the PC/AT or Sun WS.

The installation of two different seismic-data-acquisition systems at CVO arose from the need for a real-time system that could routinely provide CVO with quick earthquake locations and a means of doing the best possible job of recording precursory seismicity associated with future dome-building activity of Mount St. Helens. We were caught in the evolution of two systems. The PC/AT system was very easy to install, but its limitations for our requirements were recognized and hence the Sun WS system was tested. Some additional work on the Sun WS is required for real-time locations, plots, and a complete data-analysis system using P.L. Ward's proposed data format. After complete installation of the Sun WS system, our plan is to keep a PC/AT system available as a backup. These systems allowed CVO staff involved in seismic studies to improve their skills in seismic-data acquisition and analysis. During the past year we have been able to participate in the routine analysis of Katmai seismic data, thanks to the systems. A half-time seismic analyst assists with the routine evaluation of Mount St. Helens and Katmai digital seismic data. We have processed 37 DC600 (60 meg) cartridge tapes of Katmai seismic data.

The Sun WS system is an example of the decreasing cost in hardware and software development, owing to the use of preexisting documented software. The availability of Sunpick for X-windows, XPICK from the University of Alaska, and the portability of UNIX software should result in lower software development costs for future real-time seismic-data-acquisition systems. Another advantage of documented software, and software used by other institutions, is the potentially lower maintenance costs of software. Both systems obviate the need for full-time computer specialists for programming and software maintenance. The Sun WS system is the system we would consider selecting for a seismic network with 16 or more channels of data.

The widespread availability of PC/AT computers (and clones) in developing countries makes The PC/AT the ideal seismic-data-acquisition and analysis tool for volcanologists from such countries. With data-analysis software written by Carlos Valdes (Valdes, 1989) and the DOS format of data files, digital seismograms can be available to anyone with an IBM compatible computer and EGA graphics capability. Recent hardware and software development for the PC/AT system and faster computers indicate a potential for recording and processing data from as many as 128 channels.

CONCLUSION

Our experience with both the PC/AT and Sun WS seismic-data-acquisition systems indicates that either system is appropriate for use with small seismic networks. Both have their advantages and disadvantages. The less costly PC/AT system is relatively simple to install and maintain and utilizes PC hardware available throughout the world. The disadvantage of a PC/AT-based system lies primarily with the limitations of DOS 3.3 and earlier versions. The Sun WS offers the advantages of UNIX and the availability of more than one type of data-analysis software, but currently uses a more expensive Data Sampler and is somewhat more difficult to implement and more costly to maintain. An ideal system would be one that utilizes the best features of both systems. The PC/AT system would be ideal for the task of acquiring digital data, and a UNIX type workstation that supports X-windows would excel in routine data analysis. Whatever system is chosen, it should be one that minimizes the need for expensive hardware, high-cost maintenance of hardware and software, burdensome programming costs, and potentially expensive changes in computer operating systems.

ACKNOWLEDGMENTS

We are indebted to Willie H.K. Lee, Carlos Valdes, and Peter Ward for their effort in developing software for PC/AT and Sun workstations. The results from both seismic-data-acquisition systems would not have been possible without the work on the CVO seismic network by Tom Murray, Bruce Furukawa, and other CVO staff. We also appreciate the work of the University of Washington staff who maintained the UWGP portion of the seismic network at Mount St. Helens, and the University's seismic analysis staff for seismic information.

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6. Methods Used to Monitor Deformation of the Crater Floor and Lava Dome at Mount St. Helens, Washington

By Eugene Y. Iwatsubo *and* Donald A. Swanson

ABSTRACT

The lava dome at Mount St. Helens grew episodically between October 1980 and October 1986, and throughout this period, many techniques and procedures were established to help monitor, study, and predict dome-building episodes. These included measurement of displacements on radial cracks and thrust faults on the crater floor and dome, leveling the crater floor, and repeated occupation of trilateration and distance-measuring networks on the crater floor and dome. Displacement meters were also installed to continually monitor radial cracks on the crater floor and dome. Distance-measuring networks became one of the most reliable methods used for predicting dome-building episodes. New and old methods have been adopted to establish and measure such networks. The use of both distances and angles has allowed us to locate stations in a coordinate system that offers a three-dimensional view of ground deformation in the crater.

INTRODUCTION

Many methods have been used at Mount St. Helens to monitor the deformation of the dome and adjacent crater floor. These methods range from simply using a steel tape to measure distances across cracks and thrust faults (Chadwick and others, 1983; Chadwick and Swanson, 1989) to the use of an electronic distance meter (EDM) and continuously monitoring displacement meters (Iwatsubo, Ewert, and Murray, chapter 9). As the

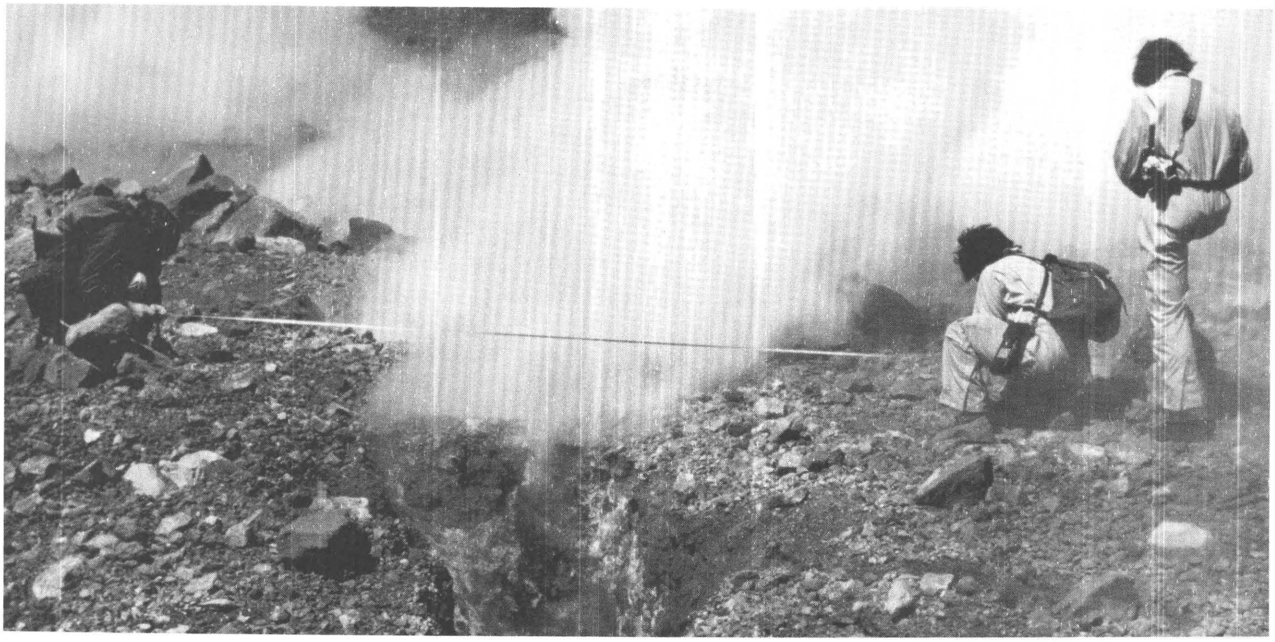


Figure 6.1. CVO scientists measuring distance across a radial crack on crater floor. Cracks would widen as magma intruded beneath lava dome. By measuring accelerating widening of crack, we were able to predict dome-building episodes.

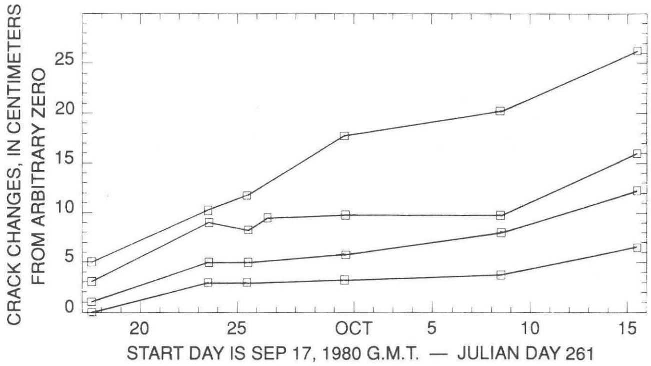


Figure 6.2. Widening of four radial cracks prior to October 1980 explosive episode. On October 15 (the day before the explosive episode), many new cracks had formed and were observed by field crews.

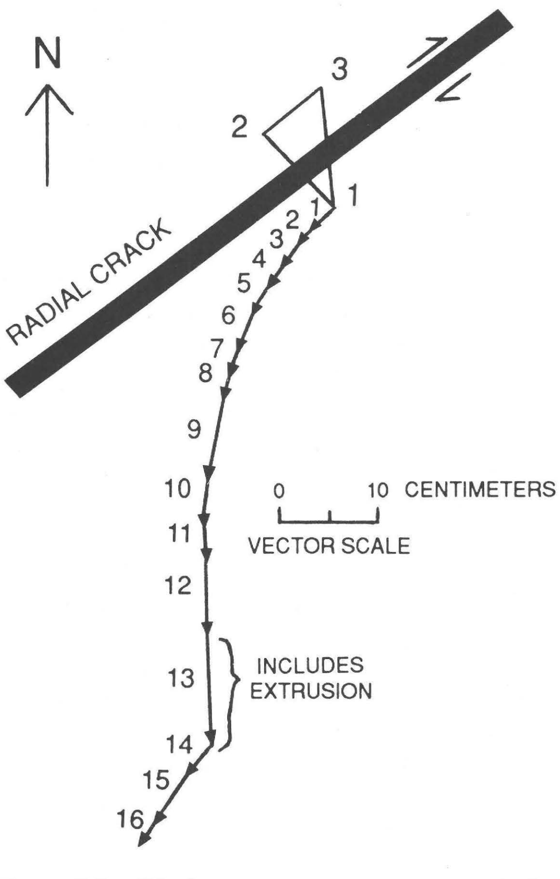


Figure 6.3. Displacement vectors for "Christina's radial," a crack located adjacent to lava dome on crater floor. Vectors show both widening and strike-slip displacements, owing to combined extension and movement of a thrust plate bounded by crack. Just before and during extrusion of September 6, 1981 (vector 13), sense of movement was mainly extensional (from Chadwick and Swanson, 1989).

dome grew and changed, so did the methods used to monitor and predict its activity. Many of the techniques described in this paper helped to predict dome-building episodes (Swanson and others, 1983).

Many of the techniques we used were adapted from elsewhere and modified to fit our needs. The principles of monitoring volcanic activity by measuring horizontal deformation had proved useful in Japan and Hawaii (Yokoyama and others, 1981; Kinoshita and others, 1974) for many years before 1980. Before and after the May 1980 eruption, we monitored the outer flanks of Mount St. Helens using these adopted techniques (Lipman and others, 1981; Swanson and others, 1981; Iwatsubo, Topinka, and Swanson, chapter 8). In 1981, when we recognized that the dome deformed in response to magma intrusion, we established distance-measuring networks inside the crater to monitor the dome. This has become one of our best tools for predicting eruptive episodes at Mount St. Helens.

HISTORY

In mid-September 1980, cracks started forming in the crater floor radially from the vent, which was plugged by a small dome that formed in August. Pieces of reinforcing rod (rebar) were driven into the ground on both sides of the cracks to form "crack stations," and the distances between rebar stakes were measured with a steel tape (fig. 6.1). Our intention was to monitor these cracks for any type of movement; prediction of future eruptive activity on the basis of such movement was considered unlikely. However, prior to the October 1980 explosive episode, the cracks widened at an accelerating rate in response to a rising magma body (fig. 6.2). On October 15, observers noted many new radial cracks that had formed since the previous visit on October 8. An explosive episode occurred on October 16–18, after which a new dome started to form; this dome, with subsequent additions, has survived to the present. Many new radial cracks formed on the crater floor as the dome continued to grow. Crack stations were established to monitor them (Swanson and others, 1981), and the crater-deformation program became firmly established.

Many useful data were obtained from the crack measurements. Distance changes across a crack were the most important of these, but displacement vectors could also be calculated for each station (fig. 6.3). We found that most cracks showed nearly pure dilational opening but that some cracks, which formed tear faults bounding thrust plates, showed both dilational and strike-slip components of displacement (Chadwick and Swanson, 1989).

Thrust faults in the crater floor were first observed during the December 1980 dome-building episode.

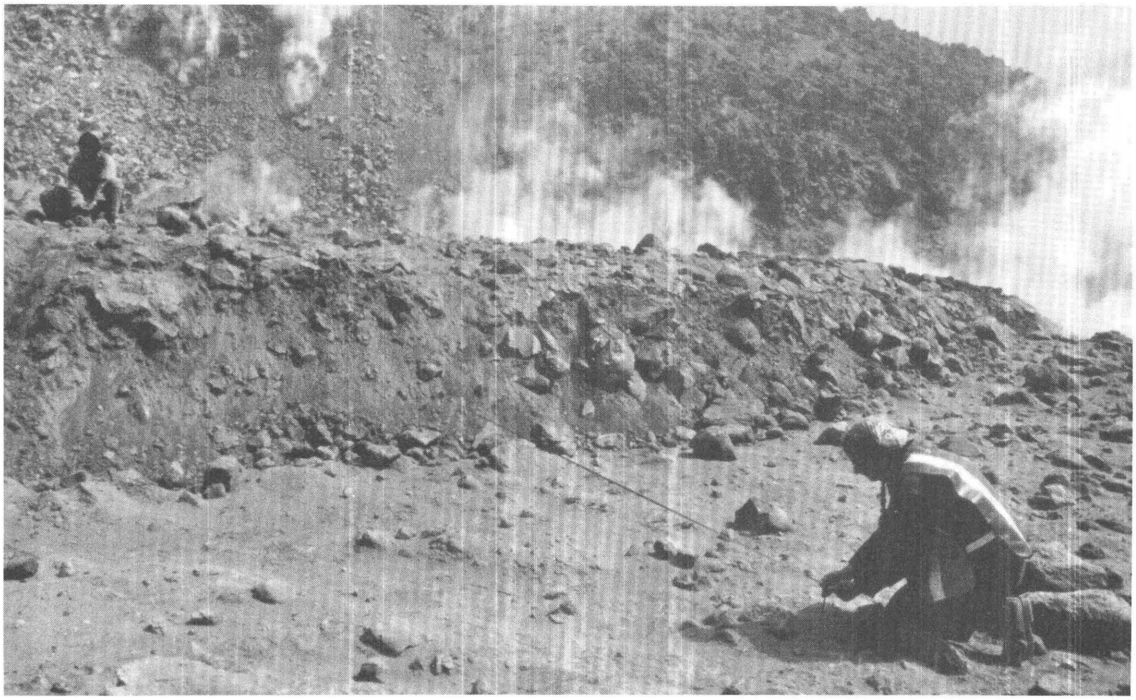


Figure 6.4. Measuring distance between rebar stakes at toe of a thrust fault. Near rebar is on lower plate of thrust, and far rebar is on upper plate. Upper plate of thrust overrode lower plate as an eruptive episode neared, and measured distance would consequently shorten. Rate of shortening would accelerate as magma neared surface of lava dome.

Thrust stations, established across the leading edge of the upper plate, were monitored in the same way as were the crack stations (fig. 6.4). As the upper plate of the thrust overrode the lower plate, measured distances shortened. The rate of shortening increased prior to dome-building episodes, just as did the rate of widening of cracks. The changing rates were used to predict the start of the next eruptive episode (Chadwick and others, 1983; Swanson and others, 1983). We also leveled between rebar stakes and determined that the upper plate was being uplifted as it thrust forward.

In May 1981 a stainless steel Parker-Kalon (PK) masonry nail was hammered into the lava at the base of the dome, and the distance to a rebar stake on the crater floor was measured with a steel tape. The taped distance shortened at an accelerating rate as the next eruptive episode neared (fig. 6.5). This was the first time we recognized that the dome itself was responding to the slow influx of new magma before an eruptive episode. The significance of this data set eventually led us into a new phase of monitoring.

A leveling network circling the dome was established in summer 1981 to determine the amount of uplift and subsidence of the crater floor. This type of monitoring yielded interesting results but was very time- and manpower-consuming, particularly given the helicopter logistics, uncertainties in weather, and volcanic hazards. One of the most severe problems was poor visibility in many parts of the crater owing to fume rising from fumaroles and to steam rising from the hot crater floor. The leveling data showed uplift of the crater floor centered around the dome prior to a dome-building episode. Leveling was completed before and after the June 1981 dome-building episode, and subsidence was observed along the whole line when compared to the pre-eruptive line. Subsidence was greatest nearest the dome and possibly resulted from (1) loss of volatile pressure acting against the crater floor, (2) loss of magma volume beneath the floor after extrusion, and (3) loading of the crater floor by the addition of the new magma. After 1981, we discontinued the leveling because it proved too time-consuming to be completed routinely for prediction purposes. Given more favorable circumstances, leveling would have been continued because of the unique data it provided.

In 1981, a trilateration network was established to monitor the crater floor north of the dome. Trilateration is a method that measures the length of triangle sides and can be used for establishing horizontal control (Sturgess and Carey, 1987); however, our intent was to calculate displacement vectors from the data. Trilateration was not conducted as a tool for predicting eruptive episodes, but

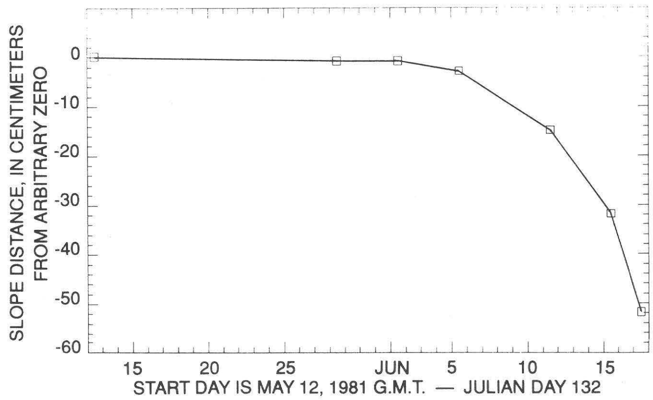


Figure 6.5. Movement of southeast lobe of lava dome relative to crater floor, May-June 1981. Taped distance between dome and crater floor shortened as eruptive episode neared. This was the first indication that the dome as well as crater floor responded to rising magma. Taped distance was approximately 18 m.

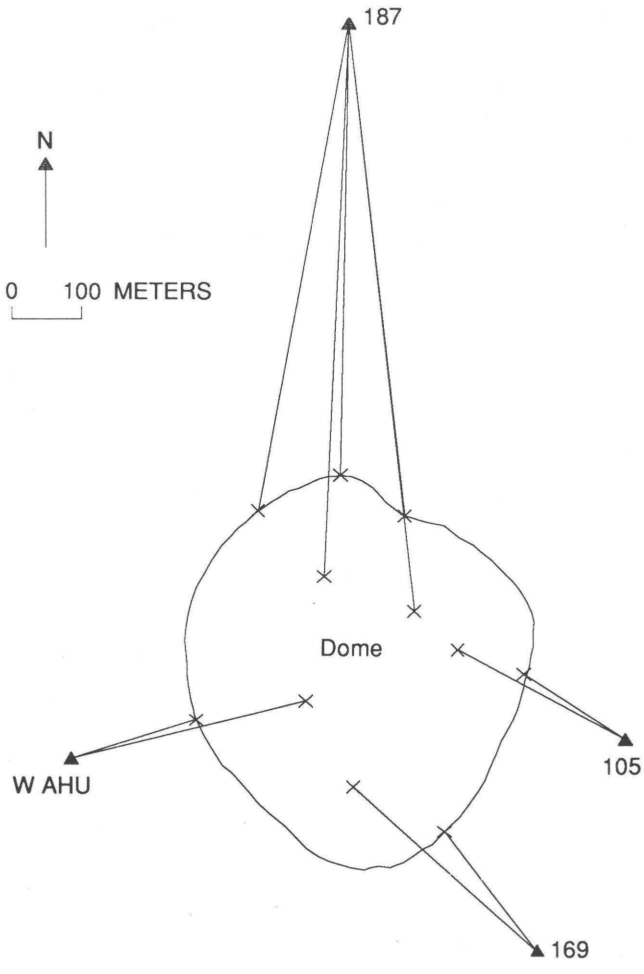


Figure 6.6. Sketch map showing instrument sites and targets inside crater and on dome in 1981. This was the first complete network using an EDM to monitor the dome. The longest measurement was 1,000 m.

instead was a research experiment. The results added to our understanding of the processes that were occurring on the dome and crater floor. Comparing the leveling and trilateration data, it was clear that horizontal displacements dominated vertical displacements during the same time period. For example, one station on the crater floor moved 50 cm horizontally but only a few millimeters vertically. The trilateration data also showed that horizontal displacement of the crater floor was cumulative. Once a station moved, it remained there rather than returning to its previous position.

By the end of summer 1981 we felt relatively at ease climbing the dome, and so we began an intensive monitoring program of the dome itself, in part spurred by the data in figure 6.5. In October 1981, plastic highway reflectors screwed on boards were placed at various locations on the dome. Instrument stations were established on the crater floor and distances to the targets were measured with an EDM. The first crater EDM network is shown in figure 6.6.

A theodolite was used to measure zenith angles to the same EDM targets. Combined with the EDM data, horizontal and vertical components of displacement *directed toward* the EDM site were calculated for each target. Horizontal angles were measured only to selected targets to observe the changes in horizontal spacing of two or more targets as the dome grew. In retrospect, horizontal angles should have been measured to every station on the dome and referenced to a known point. Coordinates for the targets could have been established at a later date if this had been done. Some horizontal angles referenced to points on the crater rim showed relative horizontal movement of the dome, but coordinates could not be calculated from these data.

During the March 19, 1982, eruptive episode (Waitt and others, 1983), all cracks and thrust faults on the crater floor were buried by pumice or stripped away, thereby ending one major phase of monitoring. New EDM networks were established around the dome, and monitoring continued. With no cracks and thrust faults to measure, EDM measurements became the primary method of monitoring dome deformation and are still used today.

A triangulation network on the north side of the dome was implemented in 1983, during a year-long period of slow, continual dome growth. Triangulation is the method where one side of a triangle (baseline) and at least two interior angles are measured to calculate a location for a station (Shafer, 1987). The purpose of this network was to monitor the inaccessible parts of the dome where it was impossible to place targets for EDM measurements. Horizontal and vertical components could be calculated for the triangulation data (fig. 6.7) and were a key part in determining where the dome was most active on the north side. Other parts of the dome were monitored with an EDM and theodolite.

A new dimension was added to our monitoring program in 1984 when Peter Otway of the New Zealand Department of Scientific and Industrial Research (DSIR) introduced the use of coordinates based on the state plane-coordinate system. Initially, triangulation was attempted from two instrument stations at Kid and Sugar Bowl (fig. 6.8), respectively. Zenith and horizontal angles were measured to dome targets and coordinates were calculated. This method was time- consuming and not cost-effective. Standard surveying methods were then adopted to use both EDM and theodolite measurements to locate targets. As EDM measurements and zenith angles were already being measured, only horizontal angles referenced to a known point had to be measured to enable us to make the coordinate calculations.

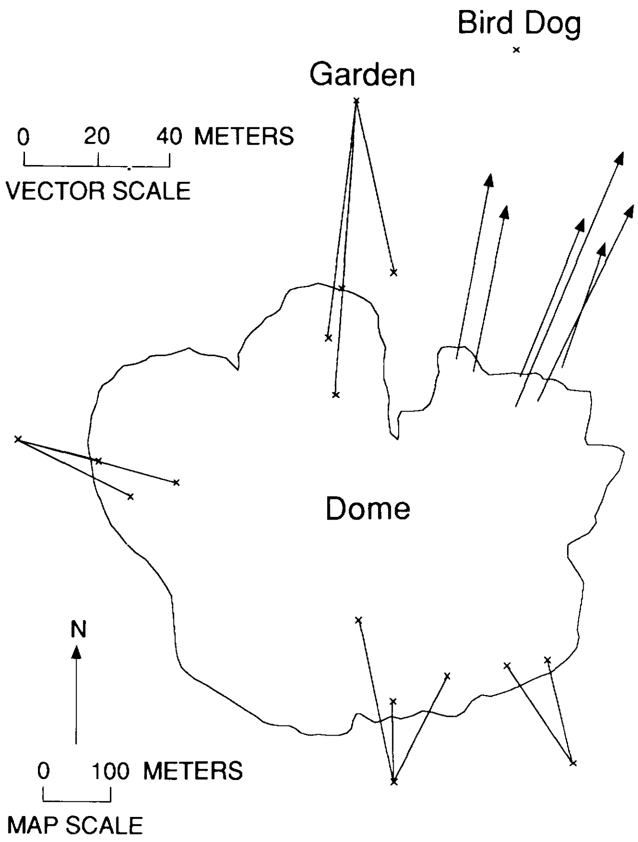


Figure 6.7. Horizontal displacements determined by triangulation for stations on northeast part of dome. Contour is schematic. Time period for these measurements was mid-July to late September 1983, during a period of prolonged dome growth chiefly concentrated in northeast part of dome. Two triangulation instrument stations were Garden and Bird Dog. Targets on nearby vertical faces of dome were marked by paint bombs dropped from open door of a helicopter. Other parts of the dome were monitored by EDM and theodolite; small x's identify instrument and target stations.

As the dome continued to spread, the available working space on the crater floor between the dome and the crater walls narrowed. On every side except the north, it became increasingly dangerous to work in the crater owing to rockfalls off the unstable crater walls in summer and snow avalanches in winter. Permanent snow and ice fields mixed with rock-avalanche debris formed on the east, west, and south parts of the crater floor, effectively precluding surveying from these areas. In 1985, because of the growing lack of working space on the crater floor, we transferred most of our monitoring activities onto the dome itself. Only the north side of the dome continued to be monitored from the crater floor. EDM networks were established at various locations on the dome. Owing to limited helicopter landing areas on top of the dome, some instrument stations could be occupied only during winter months when snow covered the rocky, irregular surface. In order to obtain deformation data from the dome in summer, a single instrument station, Shoestring Notch, was established on the southeast crater rim (fig. 6.8, 6.9*B*). Shoestring Notch could not be occupied in the winter, because conditions were often too hazardous in the notch; however, we were

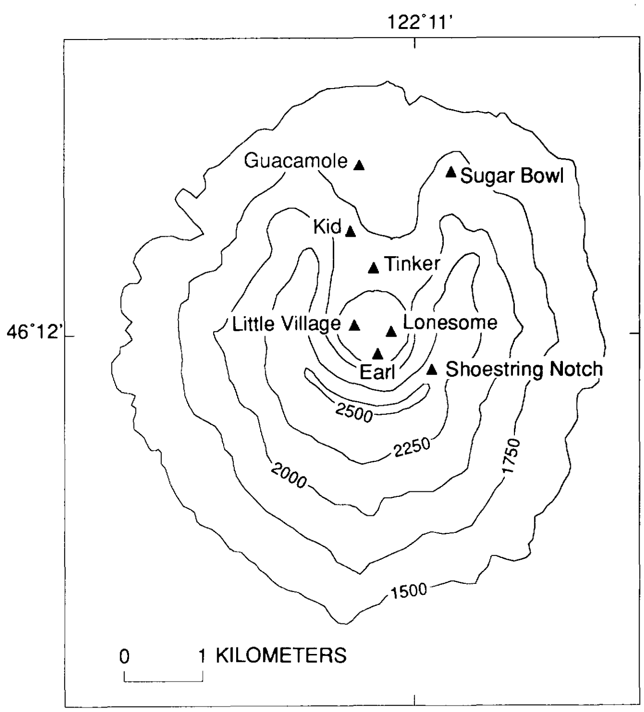


Figure 6.8. Critical stations on rim and inside crater of Mount St. Helens. Kid and Sugar Bowl were two principal triangulation instrument stations in 1984. Shoestring Notch, on crater rim, was used during summer months of 1985–88 to monitor parts of dome. Guacamole, Sugar Bowl, and Shoestring Notch are all horizontal reference marks used from various crater instrument stations in 1990. Guacamole is referenced from Tinker and Little Village, Sugar Bowl is referenced from Lonesome, and Shoestring Notch is referenced from Earl. Contours are in meters.

generally able to work on top of the dome during winter. Thus we had two monitoring networks, one for summer and one for winter (fig. 6.9).

In 1989, owing to a shrinking budget and lack of volcanic activity, the Shoestring Notch measurements were discontinued. To compensate, one more instrument station on top of the dome was established to monitor the south part of the dome, and landing sites for summer operation have been found or constructed.

MONITORING METHODS

Crack and Thrust Fault Stations

Monitoring of cracks and thrust faults is relatively simple and inexpensive, requiring only rebar and a sturdy 25-m steel tape measure. We cut rebar into stakes 40–50 cm long and drive them into the ground, leaving enough of the rebar exposed to provide ground clearance when the tape is stretched between them. Many rebars, particularly if not driven in far enough, can be hit and disturbed by rocks cascading off the dome or crater wall. Some pieces of rebar have had to be replaced because they were literally eaten away by corrosion from the bottom up, owing to warm acidic gas and water in the ground, until only the portion above the surface remained.

Displacement meters have been installed to monitor several cracks on both the crater floor and dome. The cost is much greater owing to the meter itself, and digital telemetry or an on-site recorder. More time and care are needed to establish such a site, but continuous measurement data can be obtained. Iwatsubo, Ewert, and Murray (chapter 9) describe how displacement meters are used to monitor cracks on the crater floor and dome.

When establishing a crack or thrust station with rebar, it is essential that consistency be maintained in procedures for numbering stakes and reading the distance between the rebars. We have been confused often enough

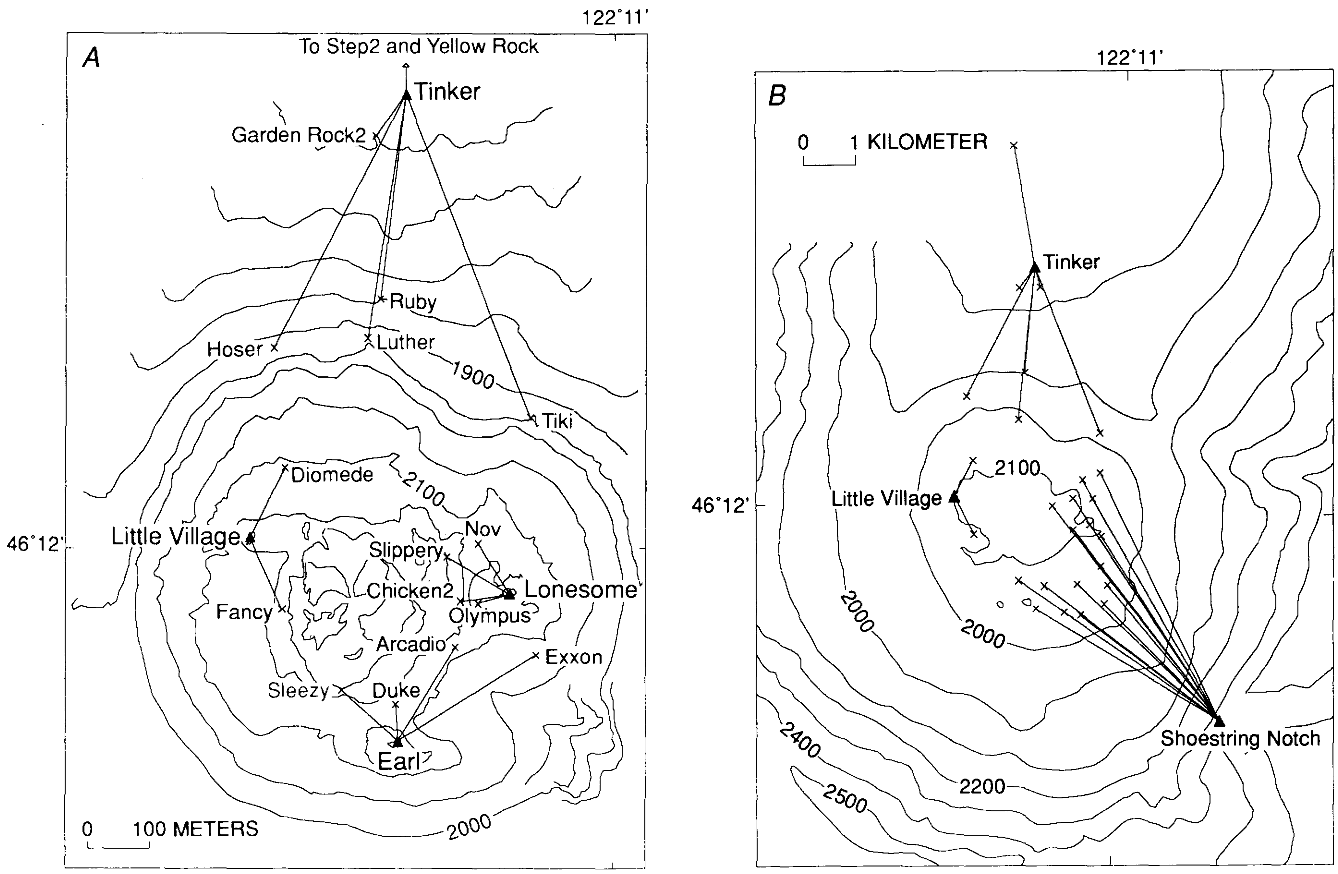


Figure 6.9 Schematic maps of Mount St. Helens. *A*, Digitized, schematic map showing crater EDM network in 1990. Distance to Yellow Rock is 374 m and to Step2 is 1,621 m. Prior to 1990, this was the winter monitoring network on the dome, and instead of Earl instrument station, we had shots from Lonesome to Earl area. *B*, Summer EDM network shown with Shoestring Notch as main instrument station to monitor southeastern part of dome. Contour intervals are in meters. All station locations were plotted by coordinates calculated from field observations. Instrument stations are identified by solid triangles.

to stress this point! Three rebars forming a triangle spanning the crack or thrust fault is typical. A braced quadrilateral would be more precise but is not warranted in our situation. We set up a crack station by placing one rebar (designated #1) on one side of the crack (or on the upper plate of a thrust fault) and two on the other side (#2 and #3), numbered in clockwise fashion. By measuring distances between 1 and 2 and between 1 and 3, widening or closing of the crack or thrust fault can be monitored. The 2–3 distance measurement serves as a baseline and check on measuring precision (1–2 mm). With the combined three measurements, vector displacements can be calculated for rebar 1 relative to rebars 2 and 3. For the index point for both ends of the tape, we generally center-punch the top of the rebar and use this mark. One person holds the zero mark of the tape over the center mark of one rebar, and the tape is stretched tight and read over the center mark of the other rebar.

Leveling, Trilateration, and Triangulation

Leveling and trilateration were time- and manpower-intensive. Three to four people were needed for

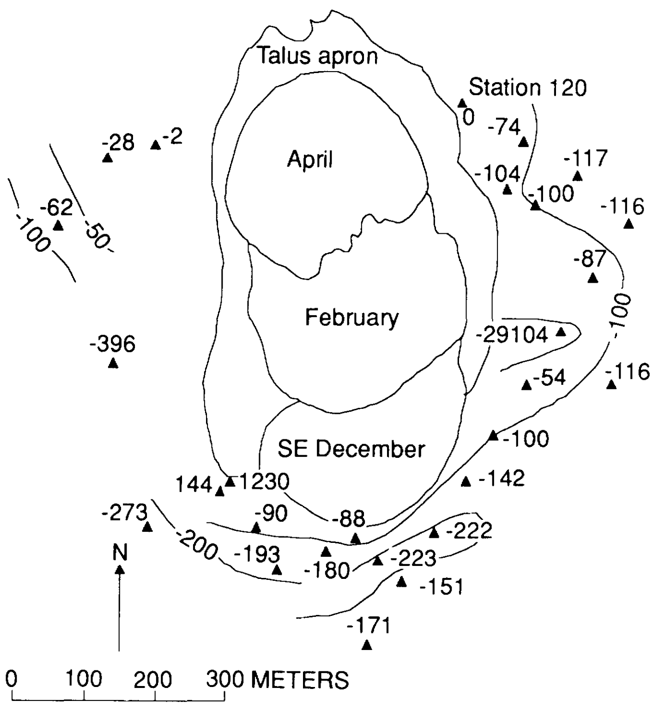


Figure 6.10. Vertical displacements in millimeters, determined by leveling before and after June 18–20, 1981, dome-building episode. Contour lines are drawn at -50, -100, and -200 mm. Station 120 was reference fencepost and was monitored by vertical angles from north crater floor. Anomalous, positive displacements are located on thrust faults that uplifted during this episode. "SE December," "February," and "April" identify lobes of dome extruded respectively in December 1980 and February and April 1981.

leveling, and at least four or five for trilateration. All leveling and trilateration stations were either steel fenceposts 1.5 m long that were marked with metal identification tags, or thrust-fault rebar stakes. The distance between leveling marks was approximately 50–100 m. We used two fiberglass, collapsible, 4-m leveling rods, and a Lietz B4 automatic level. The leveling was referenced to a fencepost on the east crater floor; its movement was monitored by measuring vertical angles from the crater floor north of the dome. Vertical displacements for the June 18–20, 1981, dome-building episode are shown in figure 6.10. For this episode, the reference fencepost was station 120; it rose 75 mm from April 14 to June 15 before the episode but had returned back to its April 14 elevation by June 24 following the extrusion.

The trilateration instrument stations were located approximately 700 m north of the dome and were assumed to be stable. A distance was measured between the two instrument stations to establish a baseline. The movement of the instrument stations was checked by measurements from Harrys Ridge north of the dome (Iwatsubo, Topinka, and Swanson, chapter 8). The EDM was set up over one instrument fencepost while people held prisms on the target fenceposts. The instrument was then moved to the second instrument station and the distances to all the targets were measured. The large displacements observed during the September 1981 episode (fig. 6.11) offset any minor movement that might have occurred at the instrument stations.

In 1983, a triangulation network was established to monitor the dome. Two instrument stations on the crater floor were established and targets on the dome were marked by fluorescent paint dropped in plastic bags from the door of a helicopter hovering above inaccessible areas of the dome. The length and azimuth of the baseline between the two instrument stations were measured. At the first instrument station, zenith and horizontal angles (referenced to the second instrument station) were measured to all the targets. The theodolite was then quickly moved to the second instrument site and the procedure repeated. The data using this method were not as accurate as those acquired with the EDM, partly owing to the difficulty of pointing the theodolite at the same part of the spattered paint-bomb targets from both instrument stations. But over time, reliable trends and vector displacements were determined.

These methods were of limited use during winter months, because of snow cover. Trilateration could be completed if snow accumulation was less than about 1 m, the typical height of the fenceposts above the ground surface, but leveling could be accomplished only when the ground was snow free. Triangulation was also discontinued because snow covered the inaccessible targets and could not be removed.

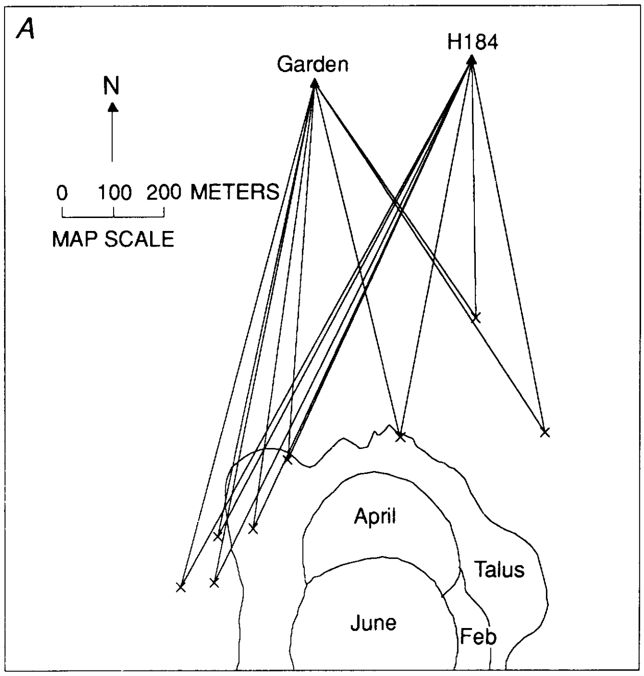
EDM Networks

Since the first crater EDM network was set up, there have always been at least three instrument stations to monitor as much of the dome as possible. From each instrument site, the distances and angles to several (2–8) targets on the dome and crater floor were measured with an EDM and a theodolite. For example, in 1990 there were four instrument stations and approximately 19 reflector targets (fig. 6.9*A*). The configuration of the network and number of targets changed as both instrument and target stations were destroyed by rockfalls or dome growth.

In 1985, we began monitoring the dome from Shoestring Notch during the summer months. Monitoring from Shoestring Notch required that we modify our data-collecting technique. Rebar stakes visible from Shoestring Notch were established high on the southeast half of the dome. The west and north sectors of the dome could not be seen from Shoestring Notch but could be monitored by the EDM networks owing to favorable helicopter landing sites on the dome and crater floor (fig. 6.9*B*). Approximately 15–20 rebar stations were established for the Shoestring Notch measurements. The rebar stakes were painted fluorescent orange to make them visible from Shoestring Notch through the telescope of the theodolite. With an instrument person and a recorder at Shoestring Notch, one person on the dome held a reflector on each rebar while an EDM measurement was taken, then quickly moved to the next rebar until all the distance measurements were completed. Radio communication was essential for this type of survey. Zenith and horizontal angles were then measured to the top of every rebar: no person had to be present at the rebars during the angle measurements. Horizontal angles were referenced to a known mark on the crater floor.

Instrument and target stations

Instrument stations are established by driving rebar stakes, 40–50 cm long, into the ground as far as possible or until 5–10 cm is remaining above the ground surface. PK nails, 5 cm long, are used to install stations on large boulders. To center over the same point each time, the center of the rebar is marked with a center punch; PK nails are commercially purchased with pre-punched heads. Most of the instrument rebar we used had a diameter of 0.38 in. (1 cm), but now a larger diameter 0.5 in. (1.3 cm) rebar is being used to take advantage of small aluminum caps (commercially available) that are



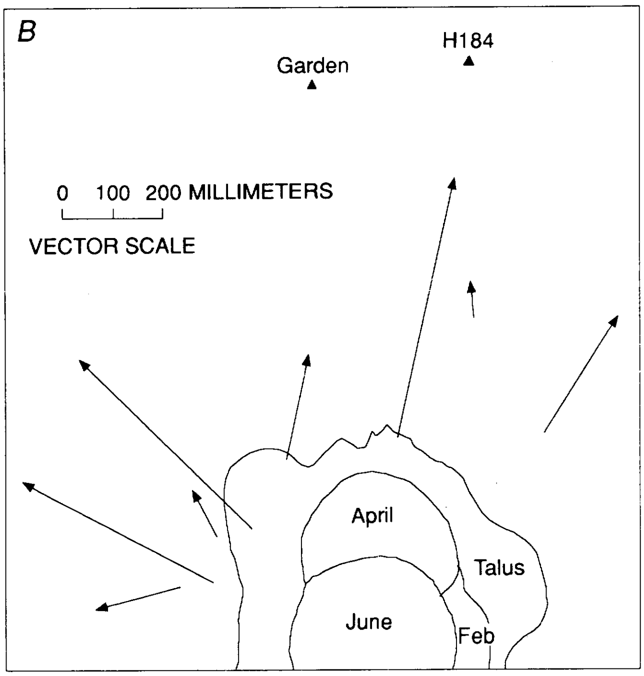


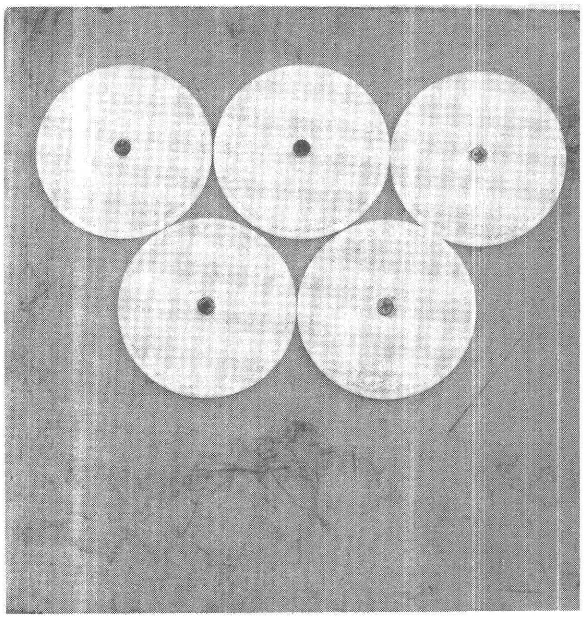
Figure 6.11. Trilateration data spanning September 6, 1981, dome building episode. *A*, Network shown with those stations that we were able to measure from both instrument stations. Normally, there are many more targets, but adverse conditions limited data. *B*, Displacement vectors calculated from measurements. Changes in slope distance and displacement vectors are in millimeters. Slope distance changes were cumulative and permanent. "Feb," "April," and "June" identify lobes extruded in February, April, and June 1981.

pre-marked and fit snugly on the heavier rebar (fig. 6.12). The caps can also be stamped for identification.

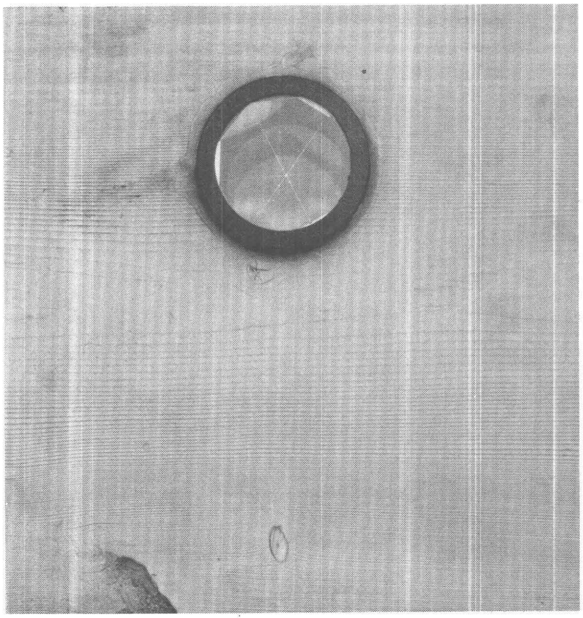
Initially, target stations consisted of a cluster of plastic highway reflectors (each reflector is 8 cm in diameter) mounted on 30-cm square boards (figure 6.13*A*) and placed on the dome and crater floor. The boards, painted fluorescent orange for visibility before attaching the reflectors, were supported by short pieces of rebar driven into the dome, by PK nails and stainless steel wire, or by a combination of rebar, nails, and wire. "Whatever works" was our guiding principle. The crater-floor targets were mounted on fenceposts driven into the ground. Highway reflectors are inexpensive and work for short EDM distances (<200 m). As the dome grew, however, the distances increased and better reflectors were needed.

One type of alternate reflector was a single corner-cube glass prism (7 cm diameter) mounted through a hole drilled in the target board. The prisms allowed longer distances to be measured, but were expensive ($100–$150), particularly given the short life expectancy of the targets owing to rockfalls, dome growth, and etching of glass (see "Target and Reflector Problems" below). Consequently we tested a lower cost ($45–$60) glass retroreflector that proved sufficient for our needs. This type of reflector consists of three mirrors glued together orthogonally to emulate the corner of a cube. These glass reflectors are fixed to the board in the same fashion as that used for the corner-cube prism (fig. 6.13*B*). The cost is lower, therefore allowing more targets to be placed on the dome. The retroreflectors are

Figure 6.12. Rebar (0.5 in., 1.3 cm diameter) with aluminum cap used as instrument stations on dome and crater floor. Aluminum caps can be stamped with station identifications. The caps were commercially purchased.



A



B

Figure 6.13. *A*, Target board with five plastic highway reflectors mounted on it. We point to the center of middle reflector on top row to measure angles. *B*, Target board with a glass retroreflector mounted in it. A hole is drilled through board and reflector is then fitted and glued with silicone seal to board.

Figure 6.14. Scientists measuring distances and angles on top of dome. Lietz Red 1A EDM is mounted on top of T2 theodolite.

not of the quality or accuracy of the glass corner-cube prisms, but the large movements occurring on the dome make these disadvantages insignificant.

EDM and Theodolite

In October 1981, we first used an EDM, a Hewlett-Packard (HP) model 3808A infrared medium-range instrument (Iwatsubo and Swanson, chapter 10), to measure distances from the crater floor to the dome. Zenith angles are measured with an old style (inverse reading) Wild T2 theodolite. The HP3808A was the smallest EDM available to us in 1981, but its size and bulk made it difficult to carry and use in the crater. The HP3808A could measure long distances but required up to 1 minute per measurement. Because of the slow measurement rate, changing steam conditions on the dome often made shots difficult to complete. In addition, to measure angles the HP3808A had to be removed from the tripod so that the theodolite could be mounted. When measurements were taken repeatedly at the same instrument station, it was difficult and time-consuming to continually switch instruments. This was a problem in particular during times when rates of movement were several centimeters or more per hour.

In 1982, a Lietz Red 1A EDM was purchased specifically for use in the crater. This is a relatively small EDM that could be mounted directly on top of the theodolite using a yoke mount (fig. 6.14; table 6.1). The size and weight of the Lietz allowed crews to walk from instrument site to instrument site; as a result, considerable helicopter time was saved, with the important bonus that the crater floor and dome could be observed in more detail than previously during the course of a survey. The Lietz performed well for as long as we used it, but in 1988 a Geotronics Geodimeter 210 was purchased. The Geodimeter 210 is even smaller and lighter than the Lietz Red 1A and is more precise (table 6.1). The Geodimeter 210 mounts on the telescope of the theodolite for easy use.

Single endpoint temperature and pressure are recorded at the instrument station for all measurements. Temperature, pressure, and humidity are the atmospheric parameters involved in slope-distance corrections. For the crater networks, we use a mercury-filled, hand-held thermometer for air temperature because the lines are so

Table 6.1. Specifications for the Lietz Red 1A and Geodimeter 210 EDM's.

Specification		Lietz	Geodimeter
Range:	1 Prism	1.4 km	2.3 km
	3 Prism	2.0 km	4.0 km
Accuracy:		±(5 mm + 5 ppm)	±(5 mm + 5 ppm)[1]
			±(5 mm + 3 ppm)[2]
Weight[3]:		3.5 kg	1.4 kg
Dimensions:		160×90×180 mm	175×85×85 mm
Temperature range:		-20°C to +50°C	-20°C to +50°C

[1]For a standard single measurement.
[2]For arithmetic mean value (every measurement display is an updated mean).
[3]Weight includes internal battery.

short that temperature has little effect on the corrected distance. A Thommens altimeter/barometer is used to measure pressure. Humidity is not recorded, because of its negligible effect.

Tripods and Setups

There are two common methods for centering tripods over a mark, (1) a tribrach with an optical plummet and (2) a telescoping centering rod. Each has its own advantages and disadvantages. The type of monitoring that is required could decide the choice of tripod and centering method. Regardless of which type is chosen, it is critical to check and keep the tripod leveling system true. Both systems are equally easy to check and adjust, and a procedure for doing so should become part of a routine maintenance schedule.

Tribrachs and standard tripods

A tribrach with an optical plummet (hereafter referred to as a tribrach) requires a tripod with a flat head and a 5/8×11 threaded screw (standard tripod). The advantages of a tribrach and standard tripod are that (1) most theodolites and EDM yokes will fit into a tribrach, and (2) the standard tripod can be set up close to the ground. This is useful when work needs to be done in high winds or over a large rock in which the station is set. Not only are winds less severe near the ground surface, but instruments are easier to shield and can be made more stable because the tripod legs can be spread wide apart.

The disadvantages of the tribrach and standard tripod are the requirement to measure the height of instrument (HI) above the station mark and to correct for different HI's during routine monitoring. If a method is established to measure the HI the same way each time, and everyone complies, problems will be minimized. However, errors can be introduced if individuals measure the HI inconsistently.

While monitoring the dome, it is important to examine raw data in the field to see if there have been significant changes since the last measurement. This practice also provides a check for gross measurement errors. If a tribrach is used and no attempt is made to establish a constant HI for each instrument station, comparing raw data on site will be complicated. Measured slope distances and zenith angles are both dependent on the HI. If the setup is at a different HI each time, the raw slope distance and zenith angle will differ even if the target has not moved. To compare successive measurements, the data must be reduced to either a horizontal or mark-to-mark distance. This can be accomplished on site if a programmable calculator or small computer is used in the field. This procedure takes time and could be a critical factor when weather and eruptive conditions change rapidly.

The better method is to consistently use the same HI each time at a given instrument station. However, this also is difficult and time-consuming with a tribrach setup. One easy way to accomplish this is to always use the same tripod with fully extended legs and mark where the legs should be placed. Alternatively, cement pads with small holes for the legs can be used to position the tripod in the same location for each setup. We have successfully used this technique, which we borrowed from colleagues at the Hawaiian Volcano Observatory, for some stations at Mount St. Helens (Iwatsubo, Topinka, and Swanson, chapter 8).

Centering-rod tripod

Centering-rod tripods simplify routine monitoring and have become our preferred method. The centering-rod tripod system is easy and fast to set up using the telescoping centering rod (stem). Every instrument station has a fixed stem height, and the tripod is set up at this stem height for each occupation. Because the stem height is always the same, raw slope distances can be compared because atmospheric corrections have little effect on the short lines measured (generally <400 m). There is no tape-measuring error with a centering rod, but errors can be introduced by an incorrect reading of the stem height.

There are two major disadvantages of centering-rod tripods. Centering rods allow the tripod to be lowered only to the minimum length of the stem, which is 1 meter. The instrument may therefore sit too high for working in windy conditions or over a high rock. The second disadvantage is that centering-rod tripods have a unique head that connects to the stem and requires special adapters (about $125 apiece) for mounting standard surveying equipment. This is no problem if all the pieces are together and present, but if an adapter is forgotten or lost, little or no work can be accomplished. It is wise to carry a spare adapter plate in the field.

Equipment Maintenance and Calibration

Equipment maintenance and calibration are important and should be part of a routine schedule. Tribrachs, centering-rod tripods, and standard tripods can be tested and adjusted by the user. EDM's should be calibrated at base lines established by agencies such as the National Geodetic Survey; however, they can also be checked in areas where there are no calibrated base lines. The accuracy of the EDM will not be known, but its precision will be, and precision is the key factor for routine monitoring. If the EDM measures the base line with precision, the data in the field are believable. Another check on an EDM is to measure its modulation frequency (the frequency that is used to measure distances). This frequency can be found in the manufacturer's manual. It is important to use a frequency counter that is one order of magnitude higher than the modulation frequency to ensure correct measurements. These counters are expensive and are not standard equipment; CVO does not have one. If there is a discrepancy between base-line or frequency measurements, the EDM must be checked and calibrated at the factory.

Theodolites are the only instruments that must be tested by the factory or authorized dealer. The amount and conditions of use should determine the schedule for calibration and cleaning of both the EDM and theodolite.

The procedure for checking and adjusting tribrachs or centering rods is simple and should be done often. Instructions are usually included with the instrument manual, or a general surveying reference (Brinker and Minnick, 1987) can be used. Routine fieldwork is hard on equipment. Bumping and shaking while riding in a vehicle or helicopter can cause surveying equipment to go out of adjustment. If the centering method is out of adjustment, the data will be affected. Once at Mount St. Helens, the crater centering-rod tripod came out of adjustment, and this was not immediately noticed. The data collected during that time period showed significant scatter and caused concern over the erratic behavior of the dome. After the centering rod was adjusted, the data smoothed out and showed that no actual deformation had occurred.

Target and Reflector Problems

The main reflector problem encountered over the years has been etching and sandblasting of both plastic and glass reflectors. Hydrofluoric acid mixed with steam can badly etch glass in as short a time as one week. Other volcanic gases deposit sublimates that also take their toll. Windblown ash is a strong abrasive. These factors must be taken into account when placing targets on the dome. If there is much gas present, the target will not last long. We have learned to avoid areas that are frequently near or downwind from fumaroles, even if the fumes seem weak. Even with such precautions, reflectors placed in areas apparently free of gases and protected from winds and steam commonly became etched within one week to one month. For these reasons, it is wise to place targets in more different locations than are absolutely necessary.

Rockfalls from higher on the dome, and spalling of rock faces holding targets, have caused the demise of many targets. It is not uncommon to lose 90 percent of the targets before and during a dome-building episode.

During winter months, problems develop when snow and ice cover the reflectors. From 1981 to 1984, we went out frequently to monitor the dome, even during winter. Cold temperatures do not allow melting of snow or ice on the targets and require someone to visit and clean every obscured reflector. Even if the reflector is ice free, steam can often condense on the reflector, and someone has to continually wipe it dry until the measurement is completed. This is time-consuming and often exciting (due to rockfalls off the dome or to icy conditions) for the person doing the cleaning. In the late 1980's eruptive activity slowed, and crews no longer go out as often, and then only during good weather; consequently reflectors are often snow free.

Steamy conditions also hinder the ability to complete a measurement. No infrared EDM can measure through steam. This has been a problem since the first network was established, particularly during winter months. It is common during winter to wait an hour or more for the steam to clear in order to complete a measurement. Prior to dome-building episodes the data are critical, and such time delays, although frustrating, are deemed worthwhile.

If angles are to be measured, be consistent in where the reference point on the target is. If prisms are used, use the center of the prism or prisms as the reference point for all angles. This will simplify the procedure and is easy to remember.

COORDINATES

The coordinate system we use is based on the state plane-coordinate system converted to meters. The initial known points were located by colleagues of the National Mapping Division as part of the control for producing topographic maps of the dome and crater. All instrument stations, reference marks, and targets have x (easting) and y (northing) coordinates, plus an elevation. Coordinates are calculated each time a target is measured and can be compared with the previous measurement to create a displacement vector. Prior to dome-building episodes, these vectors can indicate the location of the pressure source within or at the base of the dome.

Network Setup

We establish a network using coordinates by starting with two nominally stable points, one instrument and one reference mark, each with known longitudes, latitudes, and elevations. The longitude and latitude are converted to *x* and *y* coordinates respectively, which are easier to manipulate for routine data reduction. The conversion is made by a commercially purchased software package (Department of Commerce, National Geodetic Survey Division). Where it is not possible to use two known points, an alternative method is to pick two prominent points from a map and establish longitudes, latitudes, and elevations. All subsequent locations will be relative to these starting points. The starting points may not have exact locations, but all calculated locations will be internally consistent.

When establishing the network, we try to limit the number of reference marks. The ideal situation would be a single reference mark for all of the instrument stations. The best type of reference marks that we use are steel towers that were installed for other EDM measurements around Mount St. Helens (Swanson and others, 1981; Iwatsubo, Topinka, and Swanson, chapter 8). We also use steel fenceposts and antenna poles. Anything that is uniquely recognizable can be used, taking into account summer haze and winter snow (see figure 6.8 for horizontal references used in 1990).

One of the most important requirements for using a coordinate system is to locate instrument and reference marks on a yearly basis. This is especially critical if stations are located on possibly active or unstable sites, such as the dome or crater floor. All of the dome's instrument stations are located at least annually, even when no eruptive activity has taken place. When eruptive activity occurs, we try to relocate each instrument station on the dome. This always creates an offset in the coordinate data, but it is necessary. One way to prevent the offset is to locate the instrument station during each occupation. This is fine in theory but not so easy in practice. Two ways could be used to locate the instrument station: (1) measure a distance and zenith angle to a known point, and a horizontal angle between that point and one other known mark, and (2) locate the station from some other instrument station, as a regular target would be located. In order to use the first method without a reflector person, a reflector must be attached to a known tower, pole, or fencepost. At Mount St. Helens, this type of station is typically located on the crater rim for visibility. During summer months it is possible to measure the distance, but in winter, rime and snow often cover the reflector. It is not cost-effective to fly to and clean the reflector for each visit. The cost prohibits the second method as well. A special trip would have to be made each time. The best that we can achieve is to locate each instrument and reference mark at least once a year, or whenever it is made necessary by significant movement of the dome.

SOFTWARE AND NOTES

Reduction of EDM data can be done with programs written in-house or purchased commercially. Most of our data reduction and plotting programs have been written in-house. We have progressed from data reduction by hand, to an HP-41C hand-held computer, to a VAX minicomputer, and finally to a PC computer. The advantage of in-house programming is the ability to custom design programs and to allow for growth. As we gain experience, new knowledge can be applied to expanding and improving existing programs.

Slope distances corrected for atmospheric parameters form the base from which horizontal and mark-to-mark distances are calculated. We always enter the atmospheric parameters into the formula given by the manufacturer of the EDM, rather than using the atmospheric or environmental correction charts that come with the instrument, as the charts are not accurate enough for most applications and the formula is more consistent. To calculate mark-to-mark or horizontal distances, either zenith or vertical angles must be measured or station elevations must be known.

Programs were initially written to reduce data to a slope distance at a fixed stem height, using only instrument temperature and pressure for atmospheric corrections. This approach worked until the fixed stem height had to be changed for several measurements. A program was then written to convert the slope distance from a different stem height to the slope distance at the correct stem height. This conversion program was critical when it became necessary to monitor the dome from Shoestring Notch on the crater rim. At Shoestring Notch, a centering-rod tripod was first used to establish a stem height. But because of usually windy conditions, it was necessary to use a standard tripod and tribrach to set up close to the ground, and consequently a different HI was used each time. The conversion program was the only way to compare slope-distance changes.

After years of dealing with the problems of EDM data, we recommend reducing data to mark-to-mark distances. We routinely measure zenith angles, and it is a simple matter to calculate mark-to-mark distances. There is no need for conversion programs, and any tripod

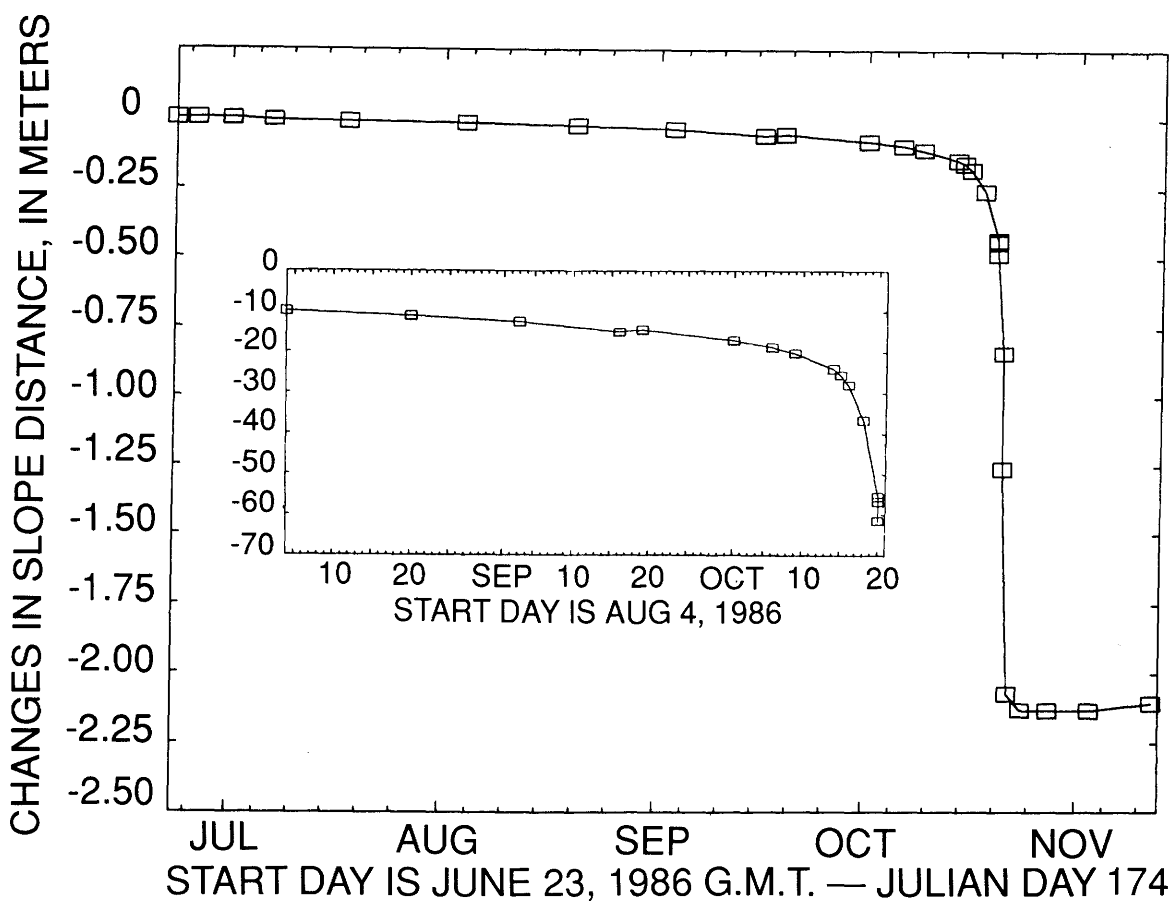


Figure 6.15. Distance changes for a typical dome station during quiet and eruptive periods. This station, located on northwest side of dome, was measured from an instrument station on north crater floor. Inset is a closer view of data leading up to October 1986 dome-building episode. By observing curve as episode nears, onset of activity can be predicted. A new lobe on dome was first observed on the morning of October 22 (vertical line).

system can be used to obtain the raw data. When it is possible to measure only a slope distance but no zenith angle, mark-to-mark distances can still be calculated if there has been no large-scale deformation. Because of the short distances (200–400 m), the zenith-angle difference needed to change the mark-to-mark distance by 1 mm is approximately 2.5 minutes of arc for an 84-degree zenith angle (average zenith angle at Mount St. Helens). The typical error for zenith angles in the crater is less than 15 seconds of arc, so the 2.5 minutes is well above our noise level.

Computer files are created to store the reduced data. Saving all pertinent raw data will save time in reentering numbers if new calculations need to be made. Raw slope distances, zenith angles, temperatures, pressures, and instrument and reflector heights will allow fast reduction of the data at a later date. We did not store these in the computer for several years, but as we learned more, reprocessing of some data was required, and all the raw data had to be reentered into the computer. Now, all pertinent raw data are stored along with the reduced data. We have three data files for each target: (1) a file containing the raw, reduced distance data and associated changes, (2) a file containing vertical and horizontal components and daily rates of change calculated from the slope distance and zenith angle, and (3) a file containing calculated coordinates, elevations, and changes associated with these data. It was necessary to create three files, because all of the data would not fit into one or two large files.

Plotting the data presented a totally different problem. When we converted all data processing to computers, there was no commercially available package that would plot time-series data with adequate tick marks and labeling of days, months, or years. An in-house plotting program was written to plot slope-distance changes versus time (fig. 6.15). As other types of data were produced, plotting programs were adapted to accommodate them. The coordinate system has allowed stations to be plotted on digitized maps (fig. 6.9). All the stations were located from coordinates calculated from field observations.

We have learned to keep good field notes on any changes that are made to instrument and target stations. In later years, these notes will become invaluable. If data are to be stored in computers, we try to add all or as many of the field notes as possible. The better the documentation, the easier it will be for the person who will have the responsibility to write a report.

DISCUSSION AND SUMMARY

The ability to reoccupy stations is a critical factor in determining the equipment used and precision required. The accuracy of the EDM should meet the resolution that the monitoring requires. It is better and more versatile to use a more accurate EDM. If targets are to be measured frequently, the precision need not be as tight as for those stations that are measured only periodically. Frequent measurements allow trends in the data to be established and lessen the effect of a few bad points. These guidelines are important to follow, because deviations from ongoing trends normally imply changes in the volcano. We never trust single measurements but instead always look for patterns and remeasure as soon as possible.

Consistency is important for methods used in the field and in the office. We have learned, the hard way, that inconsistency will ultimately lead to more work. Try to make methods simple without compromising the data that to be collected.

Once equipment and field procedures are established, data processing and storing become important. For historical and research purposes, we advise keeping complete field notes on any changes and anything different that was done in the field. We also advise establishing a method for data reduction that fits the needs of the office and that people are comfortable with. It is a waste of time and money to purchase or design powerful software when all that is needed is to reduce a slope distance. Perhaps in the future these powerful software packages will be useful, but for inexperienced workers they can lead to confusion and frustration.

Establishing and implementing a small deformation network has been successful in the crater and on the dome of Mount St. Helens. Techniques ranging from simple measurements with a steel tape to networks using electronic distance-measuring instruments have helped to predict all but one of the dome-building episodes. The above description of the methods used at Mount St. Helens is intended to be used as a guide. Every volcano will have certain aspects that are unique to it. We hope that our descriptions are general enough to be helpful and that they can be changed and adapted to meet the different needs of researchers at other volcanoes.

ACKNOWLEDGMENTS

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7. Electronic Tiltmeters for Volcano Monitoring: Lessons from Mount St. Helens

By Daniel Dzurisin

Abstract

The recent proliferation of electronic tiltmeters suitable for volcano monitoring presents both an opportunity and a challenge to volcanologists charged with providing timely warnings of impending eruptions. On one hand, tiltmeters are valuable monitoring tools because they are widely available, relatively inexpensive, easy to install and operate, and capable of continuously monitoring ground deformation in remote and hazardous areas. On the other hand, tiltmeters have several characteristics that can introduce misinformation and confusion into real or perceived volcanic emergencies unless considerable caution is used in the installation and maintenance of the tiltmeters and in the interpretation of tiltmeter data. Most tiltmeters are short-baseline instruments that measure tilt over horizontal dimensions of a few centimeters to a few meters—several orders of magnitude smaller than the scale of ground deformation associated with most volcanic activity. Local effects caused by such factors as ground slope or soil characteristics can overwhelm larger-scale effects of volcanic deformation. Therefore, it is imperative to verify tiltmeter data and relate it to the larger-scale deformation field by making geodetic measurements that span the entire area of interest. Other characteristics of tiltmeters that affect their applicability to volcano monitoring include secular drift, trade-offs between resolution, repeatability, and range, and susceptibility to environmental factors such as temperature, site preparation, precipitation, freeze-thaw cycles, and ground-water changes. Coupled with the fact that the pattern of ground tilt associated with volcanic unrest can be extremely variable in space and time, both at any one volcano and from one volcano to another, these factors make the interpretation of tiltmeter data extremely difficult in a crisis situation.

Several steps can be taken to mitigate these problems. First, tiltmeters with specifications (resolution, repeatability, range, drift characteristics) that are appropriate for the specific application should be selected. Ideally, the magnitude and dimension of ground deformation should be determined by geodetic measurements before tiltmeters are installed. Second, all reasonable effort should be made to couple tiltmeters to the ground in a stable and meaningful way, and to shield them from extraneous environmental effects. The best approach to each installation depends on the resources available, logistical constraints, and field conditions, but in general subsurface installations in bedrock or well-drained sediments are preferable. In order to determine both the spatial and temporal patterns of ground tilting, no fewer than three tiltmeter stations should be established in a network that spans the area of concern. Stations on the upper flanks of a restless volcano or elsewhere where large tilts are expected should take precedence, because at such sites environmental factors are less likely to overwhelm long-wavelength crustal tilts caused by the unrest. If possible, two tiltmeters should be installed at each station for redundancy, and any difference between the two tilt records must be weighed heavily in assessing the reliability of the measurements. A third important step is to acquire enough baseline data from each tiltmeter station to fully characterize its response to environmental factors, so that extraneous effects can be recognized and factored into interpretations of volcanic unrest. A fourth essential step is to interpret data from each tiltmeter only within the context of all available information that addresses the current state of the volcano, the trend of recent changes, and the range of likely outcomes of the unrest. This context should include (1) knowledge of the volcano's recent eruptive history based on historical records and stratigraphic studies, (2) the temporal and spatial patterns of ground deformation determined from tiltmeter data, leveling surveys, EDM measurements, or other geodetic techniques, and (3) other monitoring information including visual observations, seismic information, and volcanic gas measurements. Toward this end, collective sites should be chosen for various types of measurements in order to develop a common data base for comparison.

Experience shows that the same tilt pattern measured by different methods at different places or at different times can have vastly different implications for the outcome of volcanic unrest. In view of the high stakes involved in predicting eruptions of explosive volcanoes in populated areas, it is incumbent on volcanologists to base their predictions on the most complete and reliable data set possible. Electronic tiltmeters can make a unique and valuable contribution to such a data set, but only if

they are installed, operated, and interpreted in a careful and responsible manner.

INTRODUCTION

During the past decade, several manufacturers have introduced relatively inexpensive electronic tiltmeters that are suitable for monitoring ground deformation associated with volcanic unrest. When combined with modern radio telemetry and recording systems, these instruments are capable of recording ground tilts at remote or hazardous sites on a virtually continuous basis, thereby complementing various types of geodetic surveys and contributing to eruption predictions (for example, Dzurisin and others, 1983a). My personal experience with electronic tiltmeters at the Hawaiian Volcano Observatory (HVO) and the Cascades Volcano Observatory (CVO) illustrates the utility of electronic tiltmeters for monitoring volcanic unrest, but also highlights several pitfalls that deserve careful consideration. Recently, I have grown increasingly concerned that the easy availability of inexpensive tiltmeters plus the widely publicized fact that tiltmeter data have contributed to successful predictions of dome-building episodes at Mount St. Helens (Swanson and others, 1983; Dzurisin and others, 1983a) might set the stage for inappropriate applications of tiltmeters at other hazardous volcanoes, with potentially tragic consequences.

My goal here is to encourage the prudent use of tiltmeters by describing their strengths and weaknesses as revealed by experience at HVO and CVO from 1976 to 1989, with emphasis on applications at Mount St. Helens since 1980. This paper is more nearly a scientific essay than a research report. Its recommendations are supported by a combination of data and experience, but most of them are generalizations that must be adapted to specific situations. Nonetheless, I believe its message is an important one for volcanologists attempting to deal with hazardous volcanoes: Tiltmeters are valuable tools when used properly, but like any tool they can be dangerous and should be handled with care.

Types of Electronic Tiltmeters

Tiltmeters are available in assorted shapes, sizes, and price ranges that are suited to a wide variety of applications. They range from relatively simple designs used as security devices in executive briefcases to sophisticated instruments capable of recording the effects of solid Earth tides or providing inertial guidance for aircraft and missiles. For volcano applications, the most common types use a fluid to measure tilt changes along a baseline that ranges from a few centimeters to a few meters in length.

Water-tube tiltmeters are fluid-filled U-shaped tubes, typically a few meters long. As the tube tilts, the fluid (usually water) rises relative to one end of the tube and drops relative to the other end. The change in water level can be measured manually or sensed electronically and converted to an equivalent tilt change. A state-of-the-art, half-filled, water-tube tiltmeter developed by R. Bilham features a 1-km baseline, extreme precision (resolution of one part in 10^{10}), and very low long-term drift rate (Agnew, 1986). It is relatively easy to install and has been used successfully to monitor uplift of the resurgent dome at Long Valley caldera in east-central California.

Bubble tiltmeters use the motion of a bubble in a fluid to accomplish the same task. Typically, a bubble a few millimeters in diameter floats in an electrolytic fluid sealed in a vial a few centimeters across. Motion of the bubble caused by tilting of the vial is measured electronically by electrodes that project into the fluid (Westphal and others, 1983). Tilt along a single axis can be measured using a cylindrical vial, and tilt along two axes can be measured using a disk-shaped vial.

Mercury tiltmeters employ a pool of mercury as a capacitance plate in an LC resonant bridge circuit; tilting of the opposite plate relative to the surface of the mercury causes a capacitance change that can be measured electronically.

Because the bubble tiltmeter is the most commonly used type at CVO and other volcano observatories, the following sections were written with bubble tiltmeters in mind. However, most of the ideas apply equally well to other types, including more specialized designs not mentioned above.

Choosing an Appropriate Tiltmeter

Resolution, Repeatability, Range, and Cost

The selection of a tiltmeter inevitably will involve trade-offs among resolution, repeatability, range, and cost. The **resolution** of a tilt sensor is the smallest tilt increment that produces a measurable change in sensor output. **Repeatability** measures the range of outputs produced by the same input following tilt excursions; it differs from resolution because most tilt sensors are subject to hysteresis. Thus, a tilt sensor might be capable of resolving tilt changes as small as 0.1 microradian, but with a repeatability of only 1.0 microradian. The **range** of a tilt sensor is the maximum tilt change that it can measure reliably; a related concept is **linearity**, which measures a sensor's nonproportional response to tilt changes near the limits of its range. Most tiltmeters used for volcano monitoring have ranges of 1 to 60 degrees and linearities of 1 to 5 percent. In general, better resolution correlates with narrower range, better linearity, and increased cost.

The most precise tiltmeter (that is, the one with the smallest resolution and repeatability) that is affordable may not be the best choice, because better resolution and repeatability generally mean narrower range. It accomplishes little to resolve a tilt change of 0.1 microradians through a range of 100 microradians if diurnal fluctuations or volcanic unrest cause tilts of several hundred microradians or more (1 microradian = 0.206 arc-seconds = 5.730×10^{-5} degrees). Conversely, it is futile to monitor microradian-scale tilt changes with a tiltmeter designed to resolve changes of a few arc-seconds through a range of several degrees.

Ideally, the magnitude and dimension of ground deformation should be determined first by surveying techniques such as trilateration or leveling, as discussed elsewhere in this volume. This is not always feasible or advisable in a volcanic emergency. In such cases, I recommend tiltmeters with at least 10-microradian resolution and repeatability over as wide a range as possible (usually a few thousand microradians). Experience shows that most volcanic eruptions cause tilts of at least tens of microradians within a few kilometers of the vent, so sub-microradian resolution is not required. This is particularly true if the tiltmeter installation is subject to diurnal tilt changes larger than 1 microradian, which is common. An exception might be a deep installation (deeper than 2 m) relatively far from the vent, where diurnal effects are negligible and volcano-related tilts are expected to be small. Such installations are particularly useful for monitoring deep-seated magma reservoirs, which can cause relatively small tilts over broad areas. For such applications, choose a tiltmeter capable of resolving 1 microradian or less, and bury it at least 2 m deep to reduce diurnal and seasonal effects.

More likely to be encountered near the vent of a restless volcano are very large tilts that are detectable with virtually any commercially available tiltmeter. In this case, range is more important than resolution. During several dome-building episodes at Mount St. Helens, tilts greater than 10,000 microradians have been measured on the flanks of the lava dome, while on the crater floor a few hundred meters away, measured tilts have been less than 1,000 microradians (figs. 7.1, 7.2). On the dome, most tiltmeters with microradian-scale resolution would be beyond their useful ranges during the most critical part of the precursory period before dome-building episodes, while on the crater floor tiltmeters with very wide ranges would be incapable of resolving small tilt changes to provide a useful record of the event.

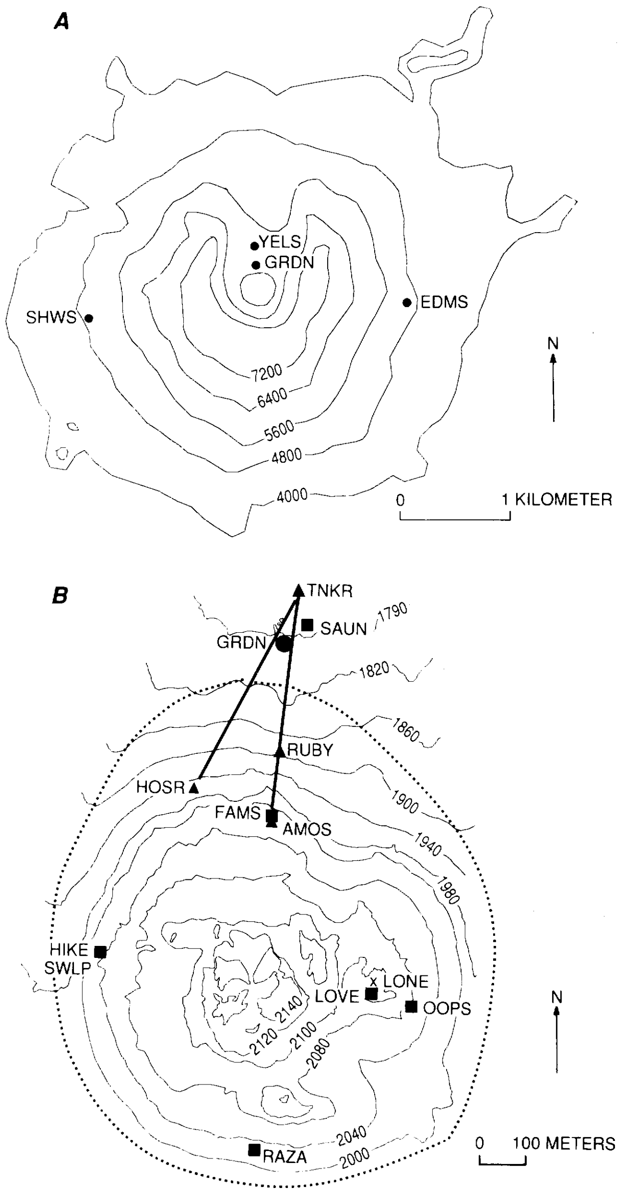

Figure 7.1. *A*, Generalized outline of Mount St. Helens with locations of seismometers mentioned in text: YELS, Yellow Rock; GRDN, Garden; SHWS, St. Helens West; EDMS, East Dome. Approximate outline of lava dome is indicated by circular contour at center. Contours are in feet. *B*, Generalized outline of lava dome and crater floor at Mount St. Helens, with locations of EDM stations (triangles), tiltmeters (squares), a seismometer (circle), and a gas sensor (x) mentioned in text: TNKR, Tinker EDM station; SAUN, Sauna tiltmeter; GRDN, Garden seismometer and tiltmeter (located together and indicated by circle only); RUBY, Ruby EDM station and tiltmeter (located together and indicated by triangle only); FAMS, Famous tiltmeter; AMOS, Amos EDM station; HOSR, Hoser EDM station; LONE, Lonesome gas sensor; OOPS, Oops tiltmeter; LOVE, Lovelorn tiltmeter; RAZA, Raza tiltmeter; SWLP, Sweet tiltmeter; HIKE, Hike tiltmeter. The October 1986 lobe is outlined by several closed contours midway between HIKE and LONE; bold dotted line indicates approximate base of dome. Contours are in meters.

At CVO, we solve this problem by installing two single-axis tiltmeters at each station on the dome: a high-gain instrument with a resolution of about 5 microradians and range of ±1 degree (17,450 microradians; approximate cost $2,000), and a low-gain instrument with a resolution of about 1 arc-minute (350 microradians) and a range of about 1 radian (±60 degrees) (cost, $100). We use single-axis tiltmeters to reduce cost and because the most important component of tilt for purposes of eruption prediction and hazard assessment at Mount St. Helens is radially outward from the center of the dome. The high-gain instruments are sensitive enough to detect precursory swelling of the dome several weeks before the culmination of dome-building episodes, but they are sometimes beyond their useful range during the last few days of most intense activity. By that time, the low-gain instruments are capable of tracking the intense deformation that occurs just before magma reaches the surface of the dome. Combining data from both types of tiltmeters provides a relatively complete record of ground tilt from the inception of precursory activity through the most intense period of dome building and, unless the station is destroyed by explosions or rockfalls, during the period of structural adjustment to the newly extruded lobe (fig. 7.3).

On the crater floor near the base of the dome, ground tilts associated with dome-building episodes are typically one to three orders of magnitude smaller than on the dome itself. Accordingly, we install two-axis tiltmeters on the crater floor that are more sensitive than the instruments used on the dome, and we attempt to shield them more thoroughly from environmental effects (see below). Close to the dome (within 700 m of the vent), we use sensors with ±1.0 microradian resolution and 10 degree range; farther from the dome, we use models with 0.1 microradian resolution and ±1 degree range. The approximate cost for each model is $3,000.

Two-axis tiltmeters provide directional information that helps to locate the deformation source, which in this case is consistently beneath the center of

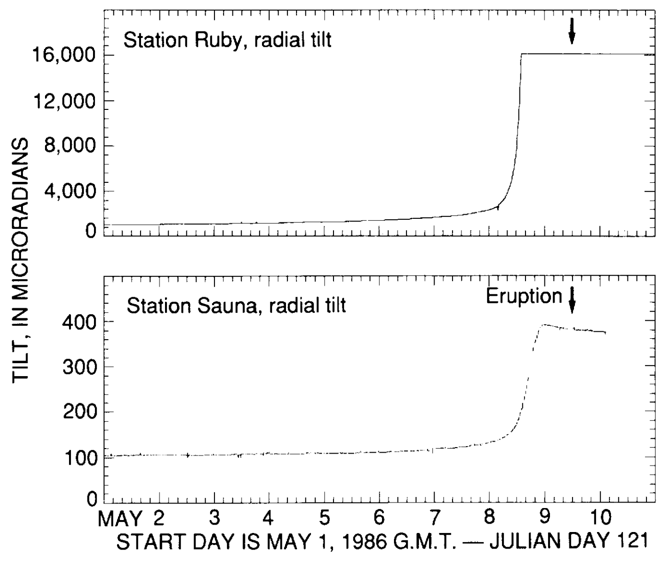

Figure 7.2. Tilt records from stations on north flank of dome (top) and crater floor north of dome (bottom) for May 1–10, 1986, which included the May 1986 dome-building episode. Net tilt change on dome was more than 40 times as large as that on crater floor, although stations were only about 300 m apart. Arrows indicate onset of extrusion.

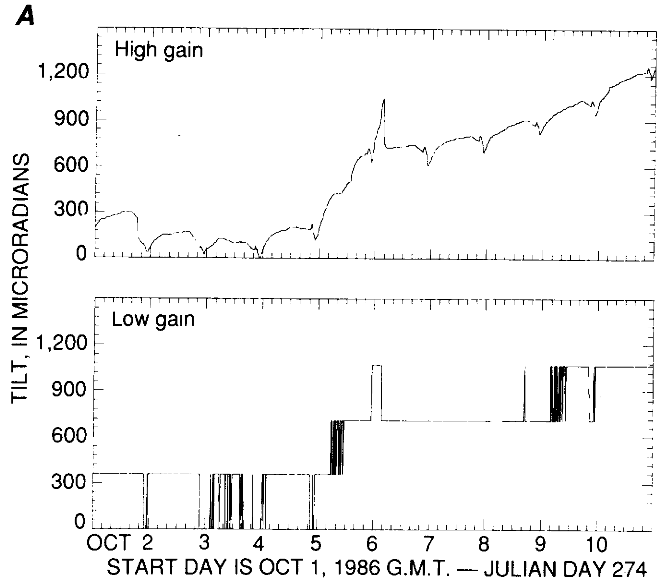

Figure 7.3. *A*, Records from a high-gain (top) and a low-gain (bottom) tiltmeter at station Sweet on west flank of dome for October 1–10, 1986. Difference in gains between the two tiltmeters was approximately a factor of 100 (3.6 microradians/count for the high-gain tiltmeter versus 355 microradians/count for the low-gain tiltmeter). Diurnal pattern in high-gain record is caused primarily by temperature fluctuations. Discrete steps in low-gain record occur because tiltmeter does not respond to tilt changes smaller than 355 microradians. More than two weeks before beginning of extrusion on October 21–22, precursory tilt was well resolved by high-gain instrument but barely detected by low-gain instrument. *B*, Records from the same tiltmeters for October 11–20, 1986. The two records are similar during this period of slowly accelerating deformation of dome. Both tiltmeters were offset by similar amounts by a magnitude 3 earthquake on October 20 (arrows). *C*, Records from the two tiltmeters at Sweet for October 21–22, 1986. Note differing vertical scales. High-gain tiltmeter went off-scale early on October 21 after recording more than 20,000 microradians of outward tilt. Low-gain tiltmeter continued to operate for an additional 18 hours and recorded about 1.5 radians (87 degrees!) of outward tilt before going off-scale. Station was destroyed by a rockfall about 9 hours later. Extrusion probably began about 0800 G.m.t. on October 22 (arrows).

the dome. However, this is not always clear from the tiltmeter data alone, because local site effects often complicate the pattern of measured tilt changes. In theory it should also be possible to determine the depth of the pressure source using an array of several tiltmeters installed at various distances from the dome, but in practice this has not worked well at Mount St. Helens for at least two reasons. First, tilts associated with dome-building episodes are small enough on the crater floor to be partly obscured by spurious environmental effects. Second, except possibly for the very early stage of precursory activity, deformation of the dome and crater floor is strongly inelastic, anisotropic, and therefore difficult to model.

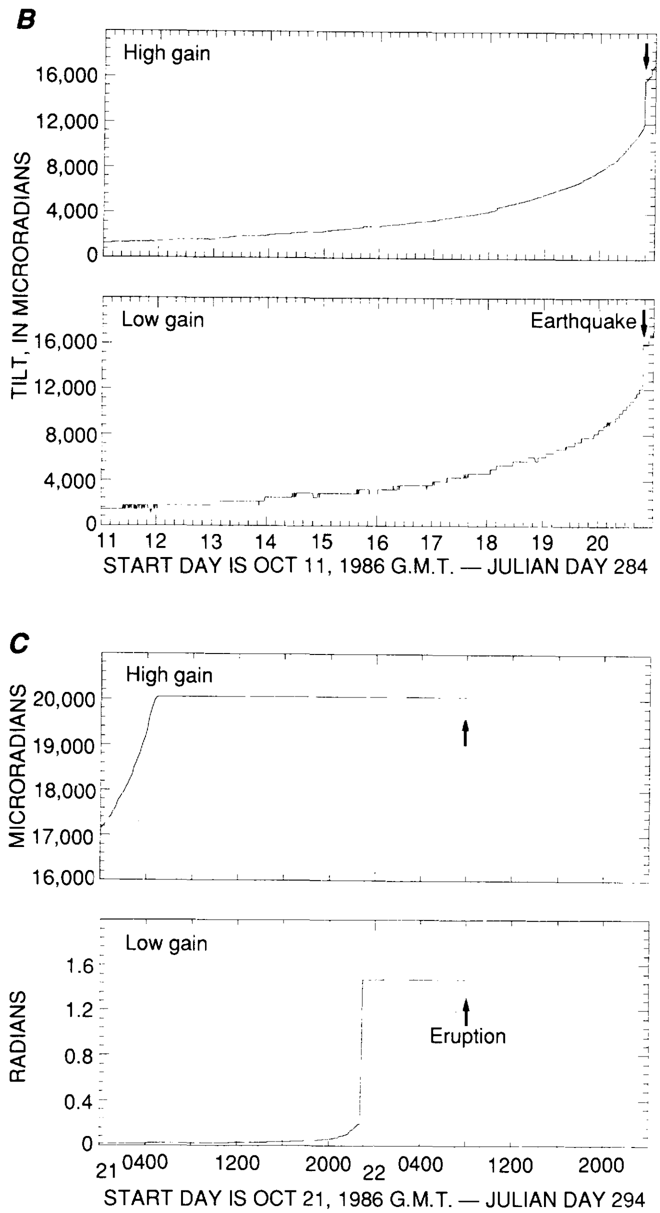

Figure 7.3. *Continued*

Platform Versus Borehole Models

It is worth noting that platform and borehole tiltmeters measure physically different quantities, although for most volcano monitoring applications the difference is negligible (C.E. Mortensen, written commun., 1989). If x and y are the horizontal axes, z is the vertical axis, u_x and u_y are the horizontal components of displacement, and u_z is the vertical component of displacement, then the horizontal tilts measured by a platform tiltmeter are given by

$$\frac{\partial u_z}{\partial x} \text{ and } \frac{\partial u_z}{\partial y},$$

whereas the vertical tilts measured by a borehole tiltmeter are given by

$$\frac{\partial u_x}{\partial z} \text{ and } \frac{\partial u_y}{\partial z}.$$

The horizontal and vertical tilts will differ if there is a significant stress gradient within the rock volume sensed by the tiltmeter, owing to deformation of the rock volume itself. This is particularly true if heterogeneities are present. However, for the case of zero stress, as at or near the surface where there can be no tractions, these tilts are equivalent.

Another consideration is that the platform configuration is first-order sensitive to temperature, while in the borehole configuration this is a second-order effect (C.E. Mortensen, written commun., 1989). This is because the platform configuration relies on mechanical elements such as screws for coarse leveling of the instrument, and the lengths of these elements are directly proportional to temperature. Therefore, any initial length difference in these elements will cause a first-order response to temperature fluctuations. In contrast, the borehole configuration is radially symmetric and therefore temperature fluctuations cause volumetric changes within the tiltmeter housing but no first-order tilt response (although the bubble itself is still temperature sensitive). In addition, borehole tiltmeters typically are installed deeper than platform models, where temperature fluctuations are smaller. To reduce temperature effects, platform tiltmeters can be temperature-compensated, or various temperature stabilizing approaches can be adopted. Nonetheless, for applications in which temperature sensitivity is a critical issue, the borehole configuration is preferred. In most applications at restless volcanoes, this is not a limiting factor, and the choice between borehole and platform configurations can be based on other considerations.

In my experience, the choice depends primarily on local conditions and on such factors as relative availability, price, and ease of installation. Borehole models are used more widely in Hawaii, while platform models are used almost exclusively at Mount St. Helens.

This is partly a historical accident and partly a consequence of differing local conditions. In Hawaii, the deformation field is usually broad enough that tiltmeters can be located in relatively safe areas that survive several eruptions. At Mount St. Helens, in contrast, measurable deformation occurs only on the lava dome and surrounding crater floor. Therefore, tiltmeters must be placed close to the vent in hazardous areas in order to be useful. As a result, most tiltmeter stations survive only a few eruptive episodes. Given the short life expectancy of tiltmeters at St. Helens, we have opted for platform models that are easier to install and adjust, and also generally less expensive, than borehole models.

Another consideration is the nature of surficial material at prospective tiltmeter sites. In Hawaii, borehole tiltmeters can be installed in young basalt flows or soil, whereas at Mount St. Helens the crater floor is composed of heterogeneous debris from eruptions, lahars, and rockfalls. Digging or augering in such material is very difficult. In addition, for several years after the 1980 eruptions, this material was still too hot for subsurface tiltmeter installations. Therefore, we decided to use platform models installed at the ground surface. More recently, a lens of permanent snow and ice intercalated with rockfall talus has accumulated on the south crater floor, making that area unsuitable for surface installations. Experience at Long Valley caldera shows that borehole tiltmeters work very well under snowpack (Mortensen and Hopkins, 1987), but such installations are not feasible in the crater at Mount St. Helens, where the lens of snow and talus is locally more than 100 m thick and growing.

In my experience, the difference between platform and borehole tiltmeters is less important than the manner in which each type is installed and coupled to the ground. A carefully installed platform tiltmeter that is shielded from most environmental effects and well coupled to the volcano-related deformation field is better than a poorly installed borehole tiltmeter, as vice versa.

Single-Axis Versus Two-Axis Types

Two-axis tiltmeters provide useful information on the location of the deformation source, and therefore are preferable to single-axis types in most cases. A two-axis tiltmeter determines the vector to the deformation source, whereas a single-axis tiltmeter measures only one component of the tilt vector. Measurements from several two-axis instruments indicating tilt vectors that are demonstrably radial to a possible vent might have very different implications for volcano hazards than measurements from single-axis instruments that are sensitive only to the radial tilt component. In the first case, the source of the deformation is indicated to be near the vent, but in the second case the source is unknown and might be completely unrelated to the vent (perhaps each station is unstable and tilting in some random direction, and the radial tilt components fortuitously define a consistent pattern). Redundancy is another advantage of two-axis tiltmeters, which use a separate sensor and amplifier for each axis (useful information can be obtained even if one axis fails). To take advantage of this feature, the sensor axes can be rotated approximately 45 degrees from the radial direction, so both axes are sensitive to radial tilt changes.

A possible exception to the general preference for two-axis tiltmeters is the case of a known vent such as the lava dome at Mount St. Helens, where in order to reduce cost we have opted for single-axis tiltmeters oriented radial to the center of the dome. The same compromise might be considered for monitoring the flanks of a restless stratovolcano, where the probable location of the vent is known. However, the increased cost of two-axis instruments is usually outweighed by the additional information they provide.

When *Not* to Use Tiltmeters

It is important to remember that electronic tiltmeters generate a nearly continuous stream of data that must be recorded, processed, interpreted, and archived—and that recording, processing, interpreting, and archiving zeroes is a very time-consuming and unrewarding task. In addition, routine maintenance and repair of tiltmeters (and associated telemetry or data logging systems) can be an onerous job, particularly during periods of bad weather when access to the stations is difficult or impossible. This is especially true at remote volcanoes, where access may be difficult even under the best conditions. Accordingly, it is seldom a wise use of limited resources to install tiltmeters on dormant or long-inactive volcanoes in anticipation of the time when the volcano might become restless. In such cases it is usually adequate to monitor earthquake activity with a modest seismic network and to make repeated geodetic surveys on the volcano, either according to a predetermined schedule or as dictated by seismicity or other signs of unrest.

This is the approach that CVO has taken to monitoring the currently dormant volcanoes of the Cascade Range (that is, all except for Mount St. Helens). Earthquake activity near each of these potentially active cones is monitored by regional seismic networks that are capable of detecting and locating earthquakes larger than some threshold magnitude that varies from volcano to volcano (generally magnitude 2.5). In addition, CVO has installed baseline geodetic networks on most of the potentially active cones (Chadwick and others, 1985; Dzurisin and others, 1982, 1983b; Iwatsubo and others, 1988; Yamashita and

Doukas, 1987; Iwatsubo and Swanson, chapter 10). These networks will be remeasured every few years or as conditions warrant. We made a conscious decision not to install tiltmeters or other continuously recording devices, because in view of the long recurrence intervals between past eruptions (centuries to millennia), we judged the cost of installation and maintenance, both in dollars and manpower, to be too high to justify the effort.

Even if tiltmeters are affordable, they are usually a poor choice for monitoring dormant volcanoes. This is because, although tiltmeters are well suited to measuring short-term tilts, they also are subject to long-term drift from a variety of sources, which can confuse assessments of volcanic unrest. The causes of long-term drift include aging of electronic components, adjustments of the ground to the installation process or to the presence of the station, and seasonal or secular environmental factors (fig. 7.4). Especially over time scales longer than a few months, tilt changes indicated by electronic tiltmeters must be verified by geodetic surveys. Therefore, continuous seismic monitoring and periodic geodetic surveys are adequate at most dormant volcanoes; tiltmeters should be considered only after the beginning of unrest, and then only to monitor relatively short-term changes.

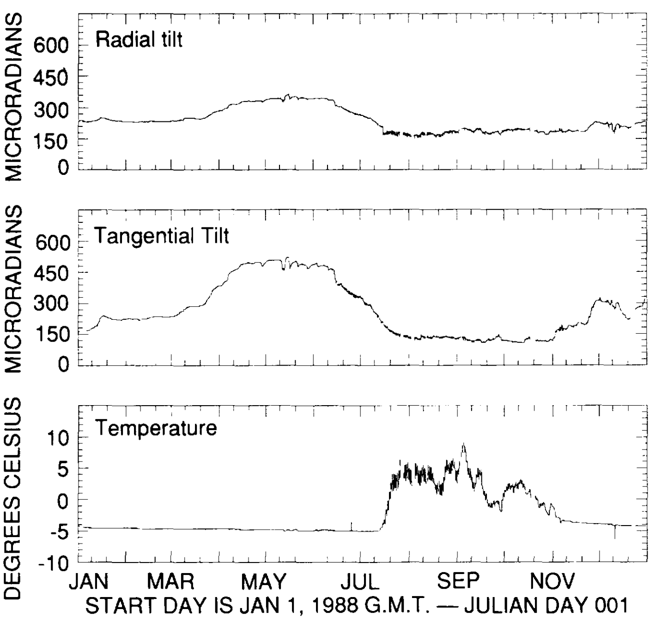

Figure 7.4. Tilt and temperature records for 1988 from a tiltmeter mounted on a large boulder on crater floor north of dome. Note relatively large reversible tilt change (several hundred microradians) caused by precipitation and snow loading while station was buried under snow from January through early July. When station emerged from under snow in mid-July, long-period tilt changes virtually stopped and diurnal effects became apparent.

Types of Tiltmeter Installations

General Considerations

In order to provide useful information for volcano monitoring, tiltmeters must be coupled to the ground in such a way as to provide a representative measure of the spatially-averaged deformation field in the surrounding area. Although this problem may seem straightforward at first, in practice it is usually the single greatest obstacle that must be overcome in order to obtain meaningful tiltmeter data. Many sophisticated and expensive tiltmeters have been operated at poorly designed installations, recording countless bits of precise but useless information on site-specific ground movements. Even when considerable time, money, and effort are invested in more elaborate tiltmeter installations, some of them inevitably prove to be inadequate. Experience shows that no single recipe can be trusted to consistently produce high-quality tiltmeter installations: What works well in one place or at one time may fail miserably in another. Only a long record of high-quality baseline data can demonstrate the reliability of a given installation.

Theoretical discussions of potential topographic and thermal effects on tiltmeters are given by Harrison (1976) and Harrison and Herbst (1977). Those authors argue that, in order to reduce such effects, tiltmeters should be installed as deep as possible at sites that are topographically symmetric.

In my experience, healthy doses of common sense and perspiration provide a good start toward effective tiltmeter installations. The more effort expended on the installation, the better it is likely to be. There is no substitute for hard work, whether it is spent digging a hole to shield the tiltmeter from environmental effects or pouring concrete to produce a massive foundation. In general, the deeper the installation, the better. High-precision borehole tiltmeters installed 30-100 m beneath the surface will resolve the daily solid-earth tides (a few parts in 10^7) with virtually no other diurnal effects and seasonal effects of only a few microradians (Meertens, 1987; Meertens and others, 1989).

Near-surface installations are quicker and easier, but they are subject to large environmental effects. Diurnal tilts of several hundred microradians are common at surface installations exposed to outdoor temperature fluctuations (figs. 7.5, 7.6). For comparison, the magnitude of diurnal tilt caused by solid-earth tides is approximately 0.1 microradians at temperate latitudes. Indoor installations below ground level are a good choice if the area is not subject to heavy vehicular or foot traffic. In such cases, the tiltmeter should be mechanically isolated from the surrounding building, which may deform to a surprising degree in response to thermoelastic effects. If drilling or augering is an option, the tiltmeter should be placed at least 2 m below the ground surface and the hole should be backfilled to insulate the tiltmeter from diurnal and seasonal temperature changes. I prefer installations in bedrock wherever possible, but another school of thought recommends well-drained sediments such as dry sand or gravel. In the latter case, choose an area that is relatively level and isolate the tiltmeter from at least the upper few decimeters of substrate, to minimize the effects of near-surface creep and freeze-thaw cycles. In practice, the choice is often dictated by local conditions: On many stratovolcanoes, exposed bedrock is scarce because most of the surface is covered by loose fragmental material. In all cases, be flexible. Choose what seems to be the best installation option in the area of interest and then make the best installation possible, given the time and resources available—then distrust the site until it proves itself to be reliable.

Surface Installations

The simplest approach is to install a platform tiltmeter on a boulder or concrete platform that is partly buried below ground level and seemingly well coupled to the ground. I prefer boulders that "ring" when struck with a hammer, but this test is arbitrary, depends on the nature of rock available, and is scant assurance of stability. This method was used with good results for several tiltmeter installations on the crater floor at Mount St. Helens during the early 1980's, when dome-building episodes were frequent and the average lifetime of most stations was only a few months. Tiltmeters were placed on ceramic tiles cemented to large (up to several meters in diameter), relatively flat boulders that were mostly buried in ash. The meters were covered to protect them from ash and the elements, and the required batteries and telemetry system (Murray, chapter 2) were housed nearby in a sturdy container. Starting in 1985, similar installations were made in the summit area of the dome, where the tiltmeters were placed on boulders buried in tephra or on recently extruded bedrock. The main advantage of this method is ease of installation, but a major disadvantage is susceptibility to large environmental effects (typical diurnal variations are several hundred microradians). Accordingly, such installations are appropriate only when time is limited, other approaches are not feasible, or the expected tilt signal is very large.

Another approach to installing tiltmeters that has worked well at Mount St. Helens is to attach them to steep cliffs on the flanks of the lava dome. The initial motivation for such installations was to protect the meters from ballistic ejecta during small explosions on the dome. This was accomplished by bolting a sturdy

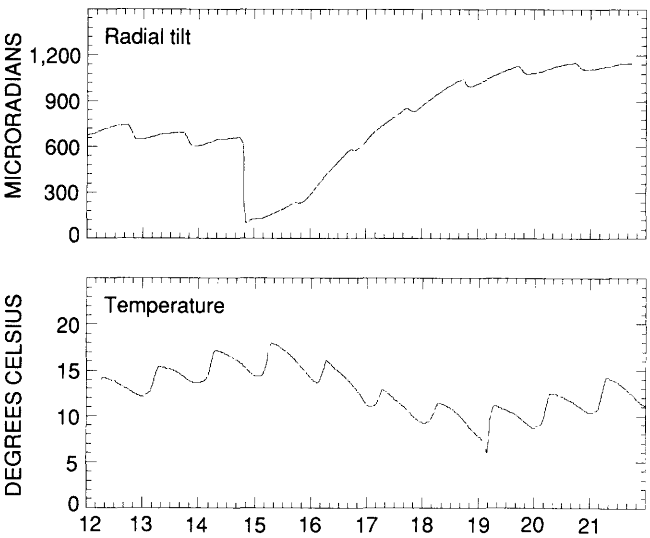

Figure 7.5. Tilt and temperature records for a 10-day period in September 1989 from station Oops, a surface tiltmeter installation on east flank of dome. Diurnal effects such as these can be modeled and removed from tiltmeter data, but it is better not to remove such effects and to compare tilt and temperature records visually. During quiescent periods, diurnal changes are welcome evidence that station is operating normally. Before most eruptions, diurnal effects are overwhelmed by precursory ground deformation as magma forces its way to the surface.

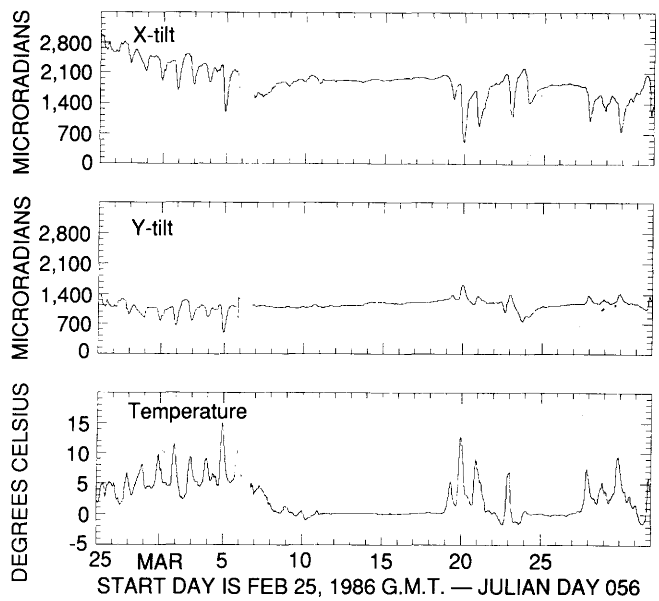

Figure 7.6. Tilt and temperature records from station Lovelorn, located on a boulder that was partly embedded in tephra on surface of dome. Diurnal tilt changes of several hundred microradians per day occurred whenever station was exposed to atmosphere, but they virtually stopped while station was buried under snow during March 6–18 and March 24–26.

aluminum housing to a cliff or by using a portable electric jackhammer and generator to make an opening in the cliff face large enough to house one high-gain and one low-gain tiltmeter. We continue to use this approach even when explosions are infrequent, because on the upper flanks of the dome steep cliffs are more common than large, stable boulders suitable for the type of installation described above. Diurnal effects at cliff sites are comparable to those at boulder sites, typically a few hundred microradians per day.

Subsurface Installations

Whenever possible, tiltmeters should be buried at least 2 m below the ground surface to reduce environmental effects. At bedrock sites, a relatively small diameter hole can be drilled for a borehole tiltmeter, or a larger hole can be drilled for a platform tiltmeter. At Long Valley caldera, we drilled five 20-cm-diameter holes 5–10 m deep in bedrock, and cemented a platform tiltmeter to the bottom of each hole. Using a detachable metal rod, each tiltmeter was lowered to the bottom of a hole where a specially designed leveling mechanism at the base of the tiltmeter was embedded in wet cement. Coarse leveling was accomplished by measuring the output of the tiltmeter at this stage and positioning it with the rod. After the cement hardened, final adjustments were made using a tool attached to the rod, while the bottom of the hole was illuminated with reflected sunlight. The procedure was tedious but usually required less than an hour.

If bedrock is unavailable or badly fractured, holes should be drilled and cased in dry sandy sediment or tephra; clay and water-saturated material should be avoided. To allow for removal or coarse releveling of the tiltmeter, it can be carefully packed near the bottom of the hole with well-sorted sand rather than being cemented permanently in place.

Another approach to burying the tiltmeter in soil or fragmental material is to excavate a large hole, drive rods and pour concrete at the bottom, and install the tiltmeter on the concrete pad. One formula that has worked for us is to dig a cylindrical hole about 2 m deep and 1 m in diameter, and case the lower 1 m with corrugated metal drain pipe. Drive at least three metal rods into soil at the bottom of the hole, at least 2 m deep but preferably until they can be driven no farther. Metal fence posts or sections of 3/8-inch or 1/2-inch-diameter rebar are widely available and suitable for this purpose. If necessary, cut the rods off 5–10 cm above the bottom of the hole and encase them in a concrete pad at least 50 cm across and 10 cm thick. Install the tiltmeter on the pad, cover it, and fill the drain pipe with insulating material that can be removed for easy maintenance of the tiltmeter (a sturdy bag full of plastic foam pellets works well). Cover the top of the drain pipe with a lid or plate and bury it under 1 m of soil. If vandalism is a problem, the entire installation except for a telemetry antenna can be buried or otherwise hidden from view.

Installations similar to this have been used by staff of the Rabaul Volcano Observatory (RVO) in Papua New Guinea and by the USGS Volcano Crisis Assistance Team (VCAT; Lockhart, Murray, and Furukawa, chapter 3) in Central America. Most of these stations have performed well after an initial settling period, but a few have had to be replaced owing to unacceptably large diurnal or ground water effects.

At Mount St. Helens, CVO uses a similar approach to install tiltmeters and other monitoring instrumentation on the 1980 crater floor. Instead of drain pipe, we use rectangular fiberglass vaults about 3 m × 1.5 m × 1.5 m high. The vaults are custom made for CVO at a cost of about $600 each; similar vaults can be fabricated wherever fiberglass technology is available. At Mount St. Helens, the vaults were buried by tunneling into a small ridge or levee, which has the advantage of providing easy access to the front entrance. The vaults are floorless, so rods can be driven and a concrete pad poured to accommodate tiltmeters, seismometers, and other instruments. By burying the tops of the vaults under 1–2 m of crater fill, we have reduced diurnal tilt changes from hundreds of microradians at surface installations to a few microradians in the vaults (fig. 7.7), while typical seasonal effects are reduced from hundreds of microradians to tens of microradians.

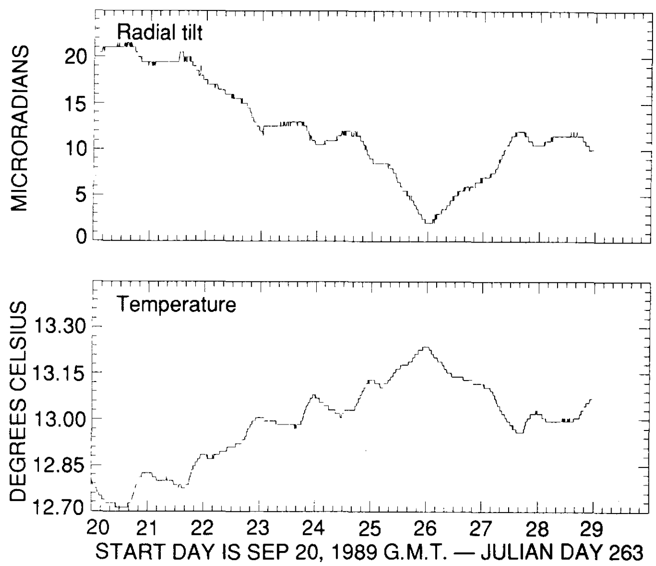

Figure 7.7. Tilt and temperature records from Garden Vault, an instrument enclosure buried about 1 m beneath crater floor north of dome. Note that diurnal effects are greatly reduced relative to those at typical surface installations (compare with figs. 7.5, 7.6).

Sources of Extraneous Tilt Signals

Even if an appropriate tiltmeter has been selected and carefully installed, it still may be subject to several signal sources that are unrelated to volcanic activity. As noted above, diurnal and seasonal temperature changes can cause tilt signals as large as several hundred microradians in surface installations. Temperature-sensitive components in the tiltmeter or telemetry system may be a factor, but I suspect that thermal strains in the tiltmeter or its housing are the dominant cause in most cases. The best solution is to insulate the tiltmeter from thermal effects by burying it as deeply as possible. Thermoelastic strains caused by heating and cooling of the ground surface can be transmitted to the tiltmeter through the surrounding rock or soil mass and therefore are difficult to eliminate (C.E. Mortensen, written commun., 1989). In most volcano-monitoring applications, such effects are believed to be negligibly small.

Another common source of extraneous tilt signals is precipitation. At Mount St. Helens, most of the annual precipitation falls as snow during the period from October to May, but brief periods of heavy precipitation occur throughout the year. Particularly during heavy snowfall or rainfall, tiltmeters in the crater commonly record rapid tilt changes (fig. 7.8) that define no coherent pattern of tilting throughout the crater, even though the general direction of tilting at each site may be consistent from storm to storm. Stations on the dome are usually less susceptible than stations on the crater floor, presumably because the dome is mechanically stronger and better drained than crater-fill material. To minimize precipitation effects, install tiltmeters on bedrock or in well-drained granular material, and record precipitation at one or more tiltmeter sites for comparison with the tiltmeter data.

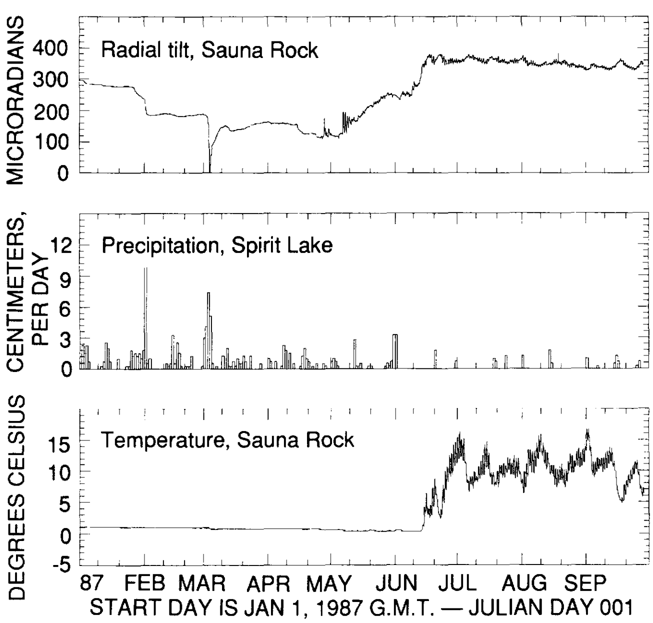

Figure 7.8. Tilt, precipitation, and temperature records from January 1987 through September 1987. Tilt and temperature data are from a station on crater floor near north base of dome; precipitation record is from a station near Spirit Lake, about 10 km north of dome. Note relatively large tilt changes (100–200 microradians) during periods of heavy snowfall on February 1 and March 1–4, and also during spring snowmelt in May and early June. Starting in mid-June when station melted out of snow and precipitation became much less frequent, tilt record was relatively flat except for minor diurnal effects.

Extraneous tilt signals also can be caused by changes in the local ground-water table during periods of heavy precipitation or rapid snowmelt. This is the case at Yellowstone Caldera, where tilts of several microradians were detected during periods of rapid spring snowmelt by high-precision tiltmeters installed in 30-m-deep boreholes (Meertens, 1987; Meertens and others, 1989). The larger the water-table fluctuation, the larger the effect on the tiltmeters. Similar effects have been noted at Long Valley Caldera, where spring snowmelt in the Sierra Nevada and resulting ground-water flow through porous materials flooring the caldera cause tilt excursions that are clearly recorded by an array of tiltmeters in shallow boreholes (Mortensen and Hopkins, 1987). Record water-table changes near the tiltmeter array if possible, but in any event be aware of such changes and their possible effects on tiltmeters.

Many other processes can cause tilt signals that are not directly related to volcanic activity, including regional strain or large earthquakes, landslides, and human or animal activity. These are too numerous and varied to discuss here.

TILTMETERS USED TO AID ERUPTION PREDICTION: A CASE HISTORY

The October 1986 dome-building episode at Mount St. Helens illustrates the use of electronic tiltmeters as part of CVO's integrated volcano-monitoring effort, which has led to successful predictions of numerous eruptive episodes since May 1980 (Swanson and others, 1983, 1987; Swanson and Holcomb, 1990). Following the May 1986 dome-building episode, which was preceded by a series of small explosions that destroyed most of the monitoring stations on the dome and surrounding crater floor, the dome entered a typical period of post-eruptive quiescence. From June through August 1986, all monitored parameters, including seismic activity, ground deformation, and gas emission, were at background levels. The only change noted in the crater was slow gravitational spreading of the dome as indicated by electronic distance meter (EDM) measurements (fig. 7.9).

The first hint of further unrest was noted in mid-September 1986, when a subtle increase in the number of small earthquakes occurring beneath the dome was accompanied by tilt changes of a few hundred microradians (only slightly larger than diurnal effects) at two of four tiltmeter stations on the flanks of the dome (fig. 7.10). As described above, each tiltmeter station contained two single-axis tiltmeters oriented radial to the center of the dome. The radial tilt components measured in mid-September and throughout the rest of the precursory period were directed outward from the center of the dome, consistent with swelling and endogenous growth. Additional flurries of small earthquakes that culminated on October 1 and October 5 were accompanied by further small tilt changes at stations Famous and Sweet; the latter event was the most pronounced to date (fig. 7.11).

Following the October 5 event, there was a brief lull in earthquake activity but Famous and Sweet continued to tilt outward at a slowly increasing rate. EDM measurements showed that deformation of the dome, particularly the west flank where Sweet tiltmeter was located, had begun to accelerate (fig. 7.9). On October 16, new cracks were noted on the dome and in snow mantling the west crater floor. On that date, seismic activity beneath the dome and tilt rates at Sweet and Famous were steadily increasing (figs. 7.12, 7.13). Comparison of the EDM and seismic data with patterns from previous dome-building episodes indicated that another episode was likely to begin within three weeks, and a public advisory to that effect was issued on October 16.

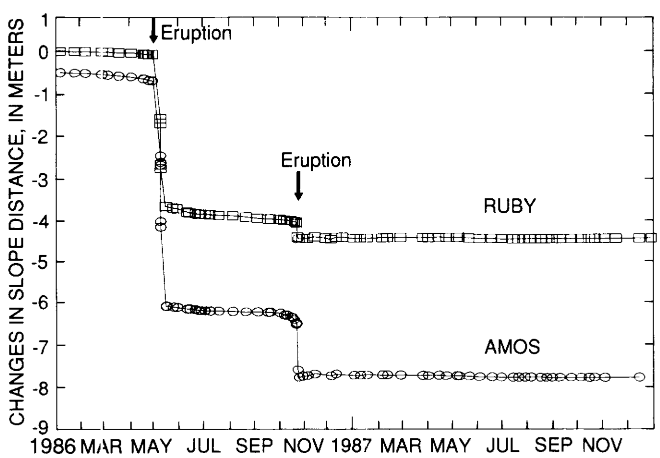

Figure 7.9. Line-length changes from EDM station Tinker to two reflectors on north flank of dome from January 1986 to December 1987, which included dome-building episodes in May 1986 and October 1986. For each line, an arbitrary nominal length was subtracted from measured line-lengths.

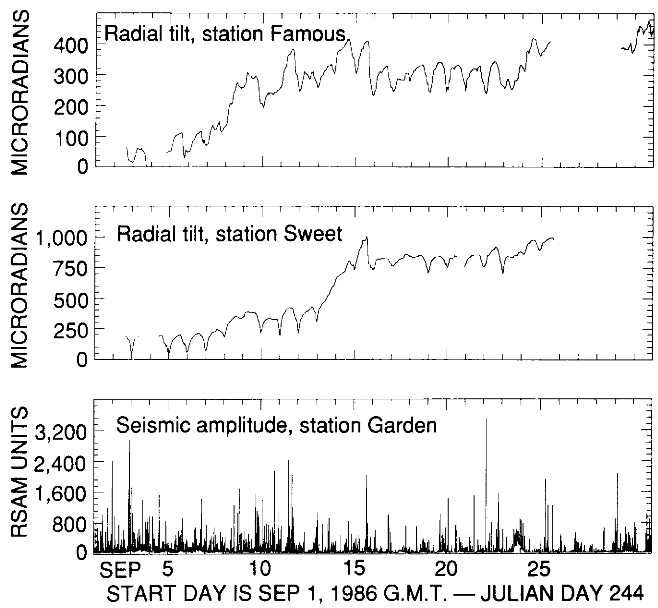

Figure 7.10. Tilt records from two high gain tiltmeters on the dome (top, middle) and an RSAM (Real time Seismic Amplitude Measurement; Endo and Murray, 1991) record from Garden seismometer, each for September 1–30, 1986. RSAM provides a measure of seismic activity based on numerical integration of electrical output of a seismometer. Vertical scale for RSAM record is arbitrary; values shown are 10-minute averages. A small flurry of shallow earthquakes beneath the dome on September 15 was accompanied by small tilt changes at Famous and Sweet, but was too small to be evident on RSAM record.

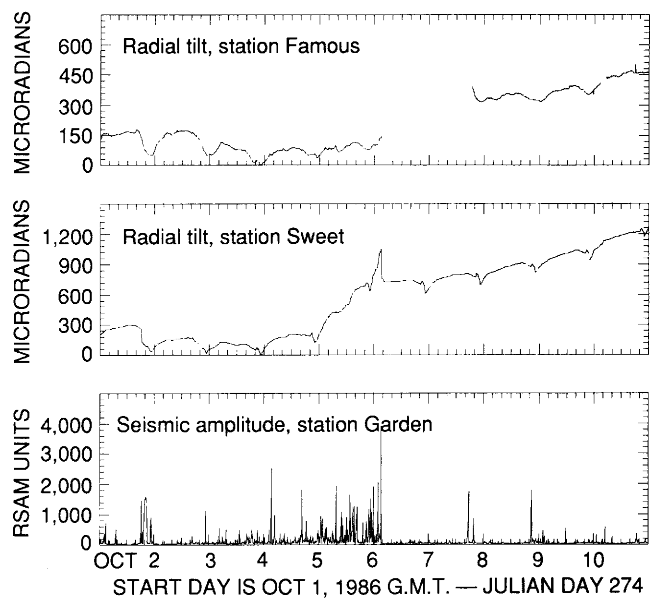

Figure 7.11. Tilt records from two stations, Famous and Sweet, and an RSAM record (10-minute average) from Garden seismometer for October 1–10, 1986. A pronounced flurry of small earthquakes beneath dome that culminated on October 5 was accompanied by onset of slow but steady tilting at Famous and Sweet. Note differing vertical scales for tiltmeter data; RSAM scale is arbitrary.

By October 18, EDM measurements and the tiltmeter data from Sweet indicated that the most rapid swelling was occurring on the north and west flanks of the dome, while tiltmeters at stations Raza and Oops indicated that the south and east flanks of the dome also had started to tilt outward (figs. 7.9, 7.13). An updated advisory issued on October 19 narrowed the prediction window from 3 weeks to 2–10 days. New cracks were noted on the dome and crater floor on October 20, when another advisory was issued to narrow the prediction window to "within the next 5 days, most likely within the next 3 days." The predictions were based most directly on the EDM data and seismicity, which indicated rapidly accelerating deformation according to a pattern that had generally repeated itself during each previous dome-building episode. The pattern of tilt changes was less useful for detailed predictions because it was less repeatable from episode to episode. Several factors contributed to this shortcoming, including (1) extreme deformation of the dome that changed pattern from episode to episode; (2) destruction of many tiltmeters by eruptive activity, which precluded long-term records from the same sites; and (3) the very short base line of tiltmeters relative to EDM lines, which makes tilt measurements more sensitive to local deformation. On the other hand, tiltmeters played a strong supporting role in the predictions by providing real-time deformation data at night and during periods of bad weather, when visual observations and EDM measurements were not feasible.

By October 21, seismic activity beneath the dome was very intense (numerous M 2–3 earthquakes), severe disruption of the dome was obvious to observers in the crater (many new cracks and frequent rockfalls), the high-gain tiltmeter at Sweet was off-scale, and the flux of sulfur dioxide measured above the dome had increased above background levels (figs. 7.14–7.16). The Sweet low-gain tiltmeter recorded almost 90 degrees(!) of outward tilt before it was destroyed late on October 21, while the other tiltmeter stations recorded lesser amounts of tilt that were generally consistent with EDM measurements to nearby reflectors. In anticipation of outward tilting during dome building, the Sweet low-gain tiltmeter had been adjusted during installation to make use of most of its range of ±60 degrees (120 degrees total).

Extrusion of a new lobe probably began during the night of October 21, as suggested by (1) a change in the character of seismic events to predominantly rockfall signals, (2) destruction of Sweet tiltmeter station, (3) a temporary reversal in the tilt trend at Raza, (4) the onset of more rapid tilting at Famous and Oops (possibly an accommodation to extrusion), and (5) a sudden increase in the flux of volcanic gases measured by a continuously recording sensor on the dome (Sutton and others, chapter 18; fig. 7.16). A new and growing lobe was first observed on October 22, eventually from a safe vantage point on the dome itself. An advisory issued on October 22 reported the beginning of extrusion and noted that,

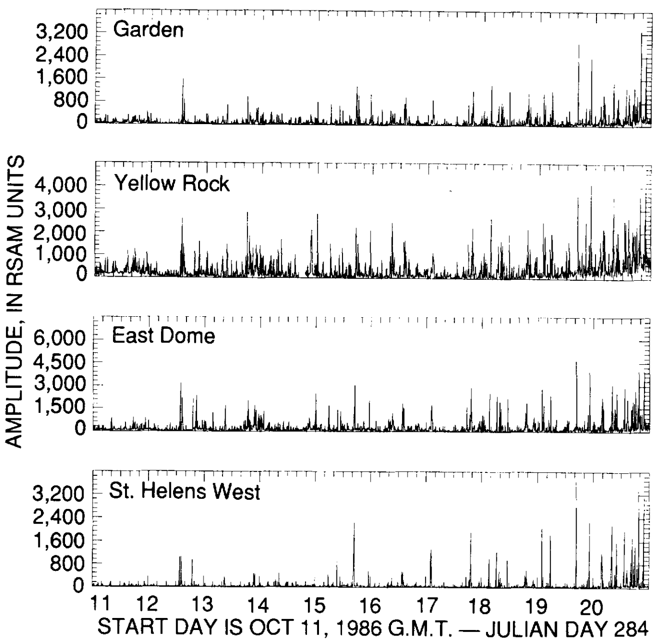

Figure 7.12. RSAM records (10-minute averages) from four seismometers at Mount St. Helens for October 11–20, 1986. Seismic activity increased steadily during this period, accompanied by inflation of the dome at an increasing rate.

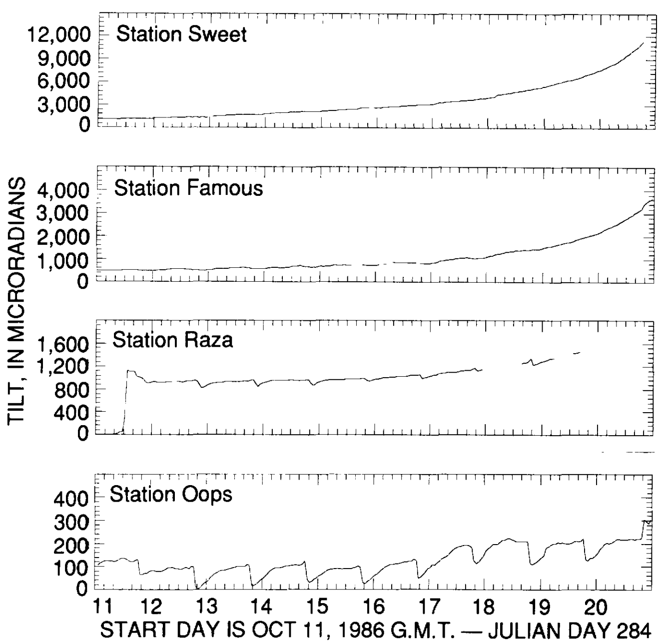

Figure 7.13. Records from four tiltmeters on the dome for October 11–20, 1986. See figure 1 for locations of tiltmeters. Note differing vertical scales. Offset at RAZA on October 11 was caused by a local earthquake during early phase of precursory activity.

although seismic activity remained high, the new lobe appeared to be stable and therefore collapse of the lobe or other part of the dome was unlikely. On October 27, a final advisory reported that seismicity, deformation, and gas emission had decreased markedly, and therefore hazards had returned to their pre-eruption levels.

Each of the data sets mentioned above provided valuable information concerning the October 1986 eruptive episode, but it was the thorough integration of all the information that contributed most to our successful predictions and scientific understanding of the event. By studying in real time plots such as those in figure 7.16, which combines five separate data sets ranging from EDM surveys every few days to seismic amplitude measurements every minute, the CVO staff was able to track the situation as it unfolded, assess the associated hazards, and communicate our conclusions to appropriate public officials in a timely fashion. Clearly, this would not have been possible if only one or two types of data had been available, or if the various data sets had been interpreted independently. Consider, for example, what conclusion might have been drawn from the tiltmeter data alone (fig. 7.15). Late on October 21, one tiltmeter station had literally fallen over (Sweet), another was temporarily tilting inward toward the center of the dome (Raza), and two others had not yet started to tilt rapidly outward. Based on this confusing pattern of tilt changes alone, no specific prediction would have been possible. However, on the basis of a variety of seismic, deformation, and volcanic gas data, CVO was able to issue three increasingly specific and accurate predictions of the onset of extrusive activity.

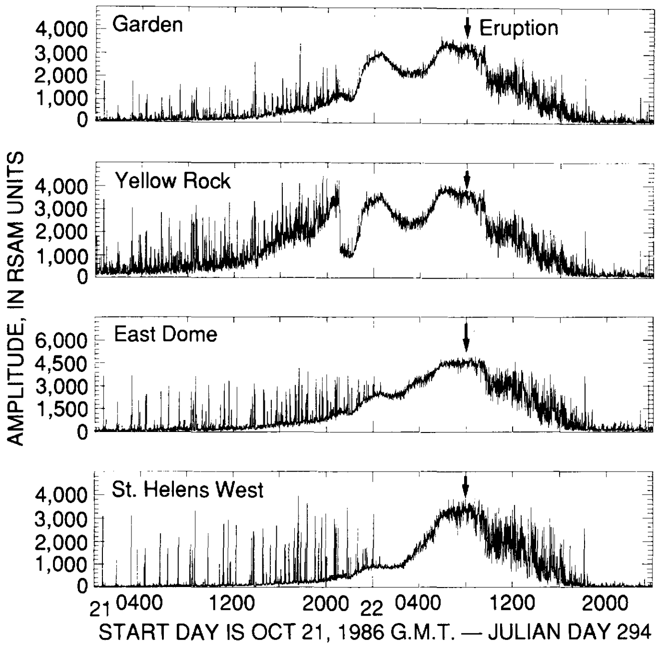

Figure 7.14. One-minute RSAM data for period of most intense activity on October 21–22, 1986. Extrusion probably began at about 0800 G.m.t. on October 22 (arrows). Offset in Yellow Rock record at about 2030 G.m.t. on October 20 was caused by a gain change. Reduced scatter in RSAM data from all four stations from about 0000 to 0800 on October 21 indicates a change in character of seismic activity from numerous discrete earthquakes that produce RSAM spikes to virtually continuous small earthquakes that maintain RSAM value at a high level.

RECOMMENDATIONS

1. **Be skeptical.** Don't believe tiltmeter data unless compelled to do so by reliable information. Resist the temptation to interpret tiltmeter data until adequate base-line information is available for each station. Remember that substantial ground tilt can be caused by site responses to installation of the tiltmeter, diurnal variations, seasonal variations, precipitation, freeze/thaw cycles, ground-water changes, and other factors unrelated to volcanic activity.

2. **Never believe a single tiltmeter.** Design your tiltmeter network with enough redundancy to compensate for unreliable stations that are likely to exist, regardless of the amount of effort expended during installation. For

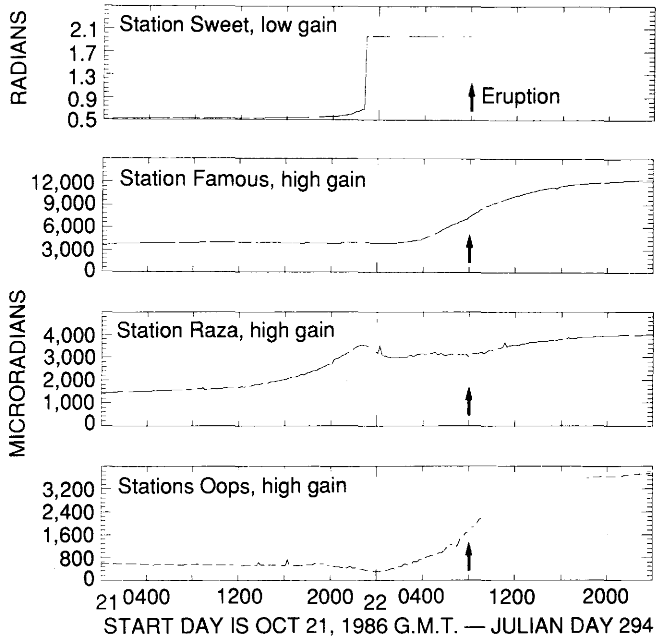

Figure 7.15. Tiltmeter records for October 20–21, 1986. Low-gain tiltmeter record at Sweet went off-scale early on October 21 after recording more than 20,000 microradians of outward tilt change. Low-gain instrument continued to operate for another 18 hours. It recorded nearly 90 degrees of outward tilt before going off-scale late on October 21 and then being destroyed on October 22. Extrusion probably began at about 0800 G.m.t. on October 22 (arrows).

the foreseeable future, the cornerstones of volcano monitoring and eruption prediction will continue to be seismology and geodesy. With limited resources, priority should be given to seismic and ground deformation techniques that are reasonably assured of yielding unambiguous data for interpretation.

3. **Never believe a single data set.** Interpret tiltmeter data only within the context of other monitoring information and in light of the recent eruptive history of the volcano. Eruption prediction is a young and largely intuitive endeavor. Experience is the best teacher, and the more information that can be brought to bear on the problem, the better.

4. **Be conscious of the social and economic impact of your work.** Impacts can be either positive (reduction of damage to life or property) or negative (hardships caused by unnecessary evacuation or decrease in property values), but in either case they are likely to be substantial. For your own peace of mind, be very sure of your information before reaching a conclusion that may have a direct impact on local residents.

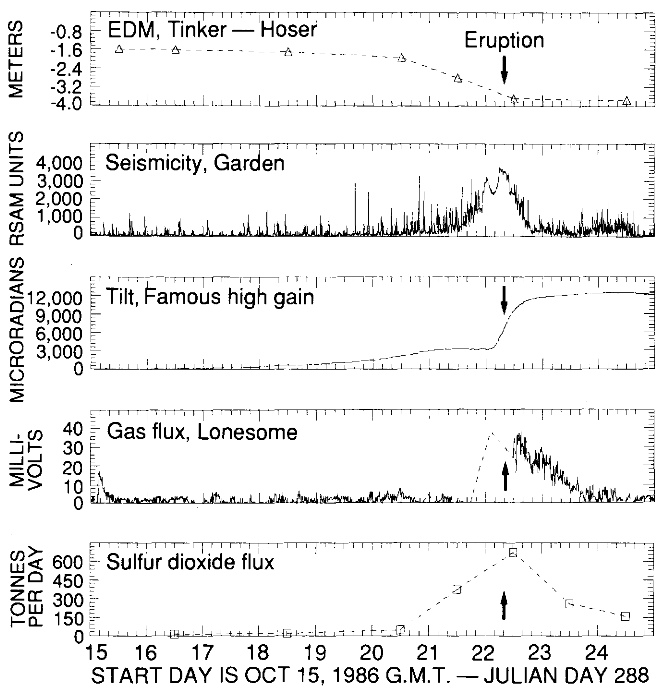

Figure 7.16. Comparison of EDM, RSAM, tiltmeter, and gas flux data for October 15–24, 1986. See figure 1*B* for locations of measurement stations. RSAM values in second plot represent 10-minute averages of RSAM signal; vertical scale is arbitrary. Fourth plot shows flux of volcanic gases measured continuously by a sensor at LONE on dome (Sutton and others, chapter 18). Bottom plot shows flux of sulfur dioxide measured above dome at 1- to 2-day intervals using a COSPEC spectrometer mounted in a fixed wing aircraft. Extrusion probably began at about 0800 G.m.t. on October 22 (arrows).

ACKNOWLEDGMENTS

Andy Lockhart and Carl Mortensen shared their considerable experience with tiltmeters; Barry Voight and the editors, Don Swanson and John Ewert, made helpful suggestions. Jim Savage and colleagues in the Tectonophysics Branch contributed a healthy dose of skepticism concerning tiltmeters, for which I am grateful. Tom Murray and Gene Iwatsubo developed computer software used to generate the figures.

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8. Slope-Distance Measurements to the Flanks of Mount St. Helens, Late 1980 through 1989

By Eugene Y. Iwatsubo, Lyn Topinka, *and* Donald A. Swanson

ABSTRACT

A slope-distance monitoring network on the flanks of Mount St. Helens was established one month before the major eruption of May 18, 1980. By 1990, the network has expanded to include 6 instrument and 13 reflector stations designed in a star-shaped configuration. The instrument and reflector stations are steel towers 3–4 m high cemented in the ground. The towers are designed to allow measurements to be taken during winter months when snow covers ground marks. For atmospheric corrections, measurements of temperature and pressure at the instrument station only (without corresponding measurements at the reflector station) have proved adequate for the precision required. Prior to dome-building episodes, measurements taken from a station as far as 8 km away can be used as a predictive tool. Seasonal variations are possibly observed on some lines. Taken as a whole, the data obtained from measurements to the flanks after May 18, 1980, show no correlation with eruptive activity.

INTRODUCTION

Following the eruption on May 18, 1980, slope-distance monitoring of the flanks of Mount St. Helens was resumed and expanded to a network of 7 instrument and 12 reflector stations (Swanson and others, 1981). One pre-1980 instrument station was occupied for a short period but was abandoned in late 1980, leaving six permanent instrument stations. A thirteenth reflector tower was established in November 1983.

The purpose of this network is to detect a large influx of magma into the present conduit system. From late 1980 through 1989, 1 explosive episode and 16 dome-building episodes have occurred. Although the amount of deformation has been large, this movement has been localized at or very near the dome; at times, only sections of the dome were affected by magmatic intrusion. Detectable changes in line length to the flanks of the volcano were not associated with any of the episodes; thus no significant volume (several million cubic meters or more) of magma has intruded the conduit system at a shallow depth of about 1 km since the eruption of May 18, 1980. An even larger influx of magma would have to be introduced at the 7–10 km depth, the depth of the reservoir inferred from seismic and petrologic studies of the May 18 eruption (Scandone and Malone, 1985; Carey and Sigurdsson, 1985; Rutherford and others, 1985), before measurable line-length changes would be detected by the outer-flank network.

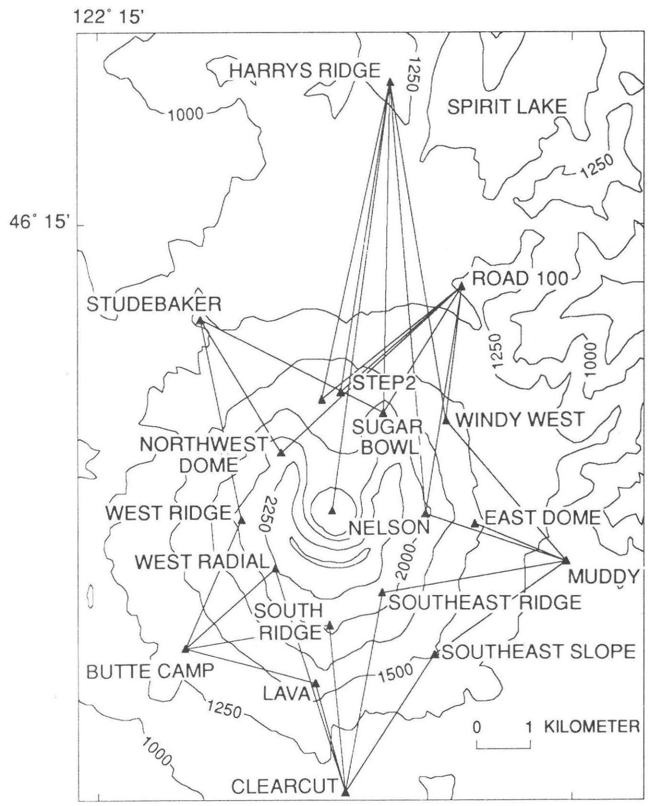

Figure 8.1. Slope-distance monitoring network established at Mount St. Helens. Line from Harrys Ridge to dome and crater floor actually represents several lines to closely spaced targets. Contours in meters.

NETWORK

The slope-distance network on the flanks of Mount St. Helens, called the outer net, is shown in figure 8.1. A star-shaped configuration was used to obtain coverage around the volcano (Iwatsubo and Swanson, chapter 10). Twenty-eight lines make up the outer net, with distances ranging from 2 to 8.5 km. Several additional lines from Harrys Ridge measure distances to targets mounted on the dome and crater floor.

Instrument stations used soon after May 18, 1980, consisted of two lengths of reinforcing rod (rebar) cemented into the ground close to one another; one was for the electronic distance meter (EDM) to measure distances, and the other for the theodolite to measure angles. Because of the danger imposed by the major explosive episodes that followed the May 18 eruption (the last one occurring in October 1980), both measurements were taken simultaneously to minimize the time spent at each site. Unfortunately, because of volcanic activity or weather, some measurements were taken in haste and important information, such as height of instrument (HI), was not recorded.

To resolve the HI problem, a method of tripod setup developed at the Hawaiian Volcano Observatory (HVO) was used. Three cement pads were positioned around each rebar to mark where the tripod legs should be placed. Small holes were chipped into the cement and painted for easy recognition. The tripod legs, always fully extended, were fit into the holes, thereby assuring that the tripod was at the same height each time. An optical-plummet tribrach was used to center each instrument over its rebar. This cement-pad method allowed an easy and quick setup.

The reflector stations from May to September 1980 consisted of a cluster of plastic highway reflectors mounted on boards bolted to steel fenceposts driven into the ground. The reflectors were typically 1–1.5 m above the ground surface. For several longer instrument-to-reflector distances, standard glass corner-cube prisms

A

B

Figure 8.2. *A*, Instrument tower with EDM mounted on top tower plate. *B*, Reflector tower with prisms mounted near its top. Tower heights range from 3 to 4 m. Each leg is cemented into ground. Instrument tower has a walkway for easy access to all sides of tower. Temperature pole is supported by walkway and one leg of tower.

were mounted on the fenceposts, replacing the plastic reflectors. Blowing ash often sandblasted the reflectors, but the plastic reflectors were inexpensive and easy to replace. The reflectors performed well during summer months but would have been buried under snow during winter months.

In September 1980, steel towers (fig. 8.2) were installed by a local power company at all instrument and reflector stations (Swanson and others, 1981) to monitor the network throughout the year, especially during winter months. These towers stand 3–4 m above the ground and allow the instrument and reflectors to be almost always above the snow (fig. 8.3). Measurement stations for all distances and angles were then transferred from the ground marks to the towers and used throughout the year.

Each reflector tower has glass corner-cube prisms mounted near its top to raise them above the snow and blowing ash (fig. 8.2*B*). Each tower has one or two prisms, depending on how many instrument stations measure to it. Although the prisms were relatively high above the ground, loose blowing ash etched some reflectors and was a minor problem for several years after the towers were installed. Most reflector prisms have been replaced once since 1980, and a few have been replaced twice. Ice is the major problem during winter months. The glass prisms are typically ice covered and need cleaning before a measurement can be made, and it is not uncommon to have up to 1 m of rime on the towers (fig. 8.4) that has to be chopped off with an axe before the prism can be cleaned.

Instability can be a problem with the towers. The problem is most severe at those towers installed on thick unconsolidated deposits from the May 18 eruption, where settling has occurred over several years (fig. 8.5, lines ROADSGB, HARYSSGB, and HARYSSTP). Step tower, located at the north entrance to the crater on loose debris-avalanche material, had to be moved in 1986 because the narrow ridge it was on was eroding. Sugar Bowl tower now has one free-standing leg, because pumice and ash has been eroded by the wind from the base of that leg. Towers located on other sections of the volcano, where the 1980 deposits are thin, appear to be stable.

EQUIPMENT

The EDM used for the outer net measurements is a Keufel & Esser Rangemaster III, capable of measuring up to 60 km using 30 prisms at an accuracy of ±(5 mm +

A

B

Figure 8.3. *A*, Instrument station Clearcut in summer, and *B*, winter monitoring conditions. Steel towers enable occupation of network all year long. Snow accumulations rarely cover instrument towers and never reflector towers.

1 ppm). The Rangemaster III draws 5 amperes (amp) of current and requires a large 12-volt battery. Car batteries can be used but are extremely heavy. We use a 24 amp-hour, sealed, gelled-electrolyte, rechargeable battery (dimensions are 17×16×12.5 cm; weight is 8.65 kg) packaged inside a fiberglass box with a handle for easy use. We always carry two batteries into the field and typically use both during the survey. The EDM's light source, a helium-neon gas laser, is visible, and the return signal from the reflector can be seen. The visible beam is very useful in locating targets that are a long distance away or in marginal weather conditions.

The Rangemaster III is yoke mounted using an optical-plummet tribrach. The tribrach, yoke, and EDM are mounted directly to the top of the steel instrument tower (fig. 8.2*A*). The top plate of each instrument tower has a hole drilled in the center so that the tribrach can be mounted. A tapered bolt is used to insure that the instrument is always centered in the hole.

Air temperature and barometric pressure are atmospheric parameters measured to correct the slope distance. Air temperature is measured 7–8 m above the ground surface. A calibrated temperature sensor (Iwatsubo and Swanson, chapter 10) is mounted inside a streamlined shield that fits atop sections of steel pipe used to raise the shield. The sensor is mounted inside a 46-cm-long, 3.7-cm-diameter tube that is nested inside a larger 8.5-cm-diameter tube. Phenolic tubing is used, because of its property of distributing radiant heat over the whole surface of the tube. A fitted tail or rudder is at the rear of the tube (fig. 8.6). A short piece of solid brass stock (7 cm long, 1.3 cm diameter) attached to the middle of the outer tube perpendicular to its long axis fits into the top section of the steel pipe (inner diameter of 1.5 cm) and allows the shield to spin. The whole design acts as a weather vane, so as the wind direction changes, the shield pivots to allow air to always flow through the tubes and past the sensor. The steel pipe holding the shield is supported at its bottom by the walkway around the tower and is tied to a tower leg for stability (fig. 8.2*A*).

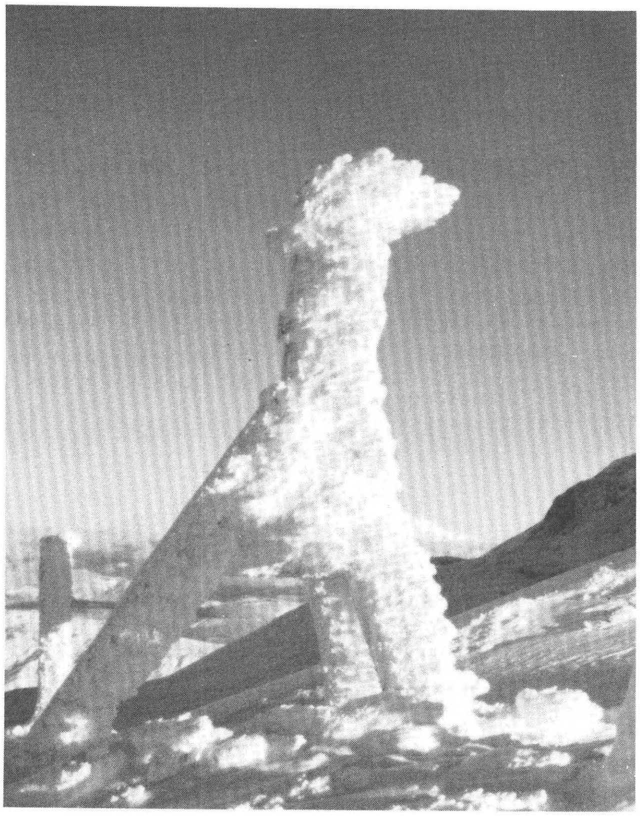

Figure 8.4. Rime collecting and covering reflector tower and prism is a problem during winter months. This tower had to be cleared of all ice and prisms cleaned before a measurement could be made.

From 1980 to 1986, barometric pressure was measured using a Wallace & Tiernan altimeter. In 1987, we switched to the AIR-HB-1A hand-held barometer/altimeter (Iwatsubo and Swanson, chapter 10) for a more accurate measurement. Humidity is not measured.

A Wild T2 theodolite is used to measure zenith and horizontal angles. The theodolite mounts directly to the top plate using the same tapered bolt as that for the EDM. Zenith angles are measured to the same prism used for the EDM measurement. The distance is always measured first. Thus, where there is more than one prism per tower, the visible laser of the EDM allows us to observe which prism is the correct one, thereby avoiding confusion when the angles are measured.

DATA

Single-endpoint atmospheric data are collected only at the instrument station, because it is not economically feasible to fly to each reflector station and measure atmospheric conditions. Comparison of slope distances calculated by using atmospheric data measured at one endpoint with those measured at both endpoints shows that although the corrected slope distance differs, the changes in slope distance remain approximately the same, especially when the elevation difference between the instrument and reflector is less than about 300 m (Hawaiian Volcano Observatory, unpublished data, 1989). In other words, the accuracy differs but the precision is about the same.

Single-endpoint atmospheric data can be adequate for monitoring purposes, but it is imperative that many slope-distance measurements be taken to establish the precision associated with each individual line. At Mount St. Helens, many single-endpoint measurements are used

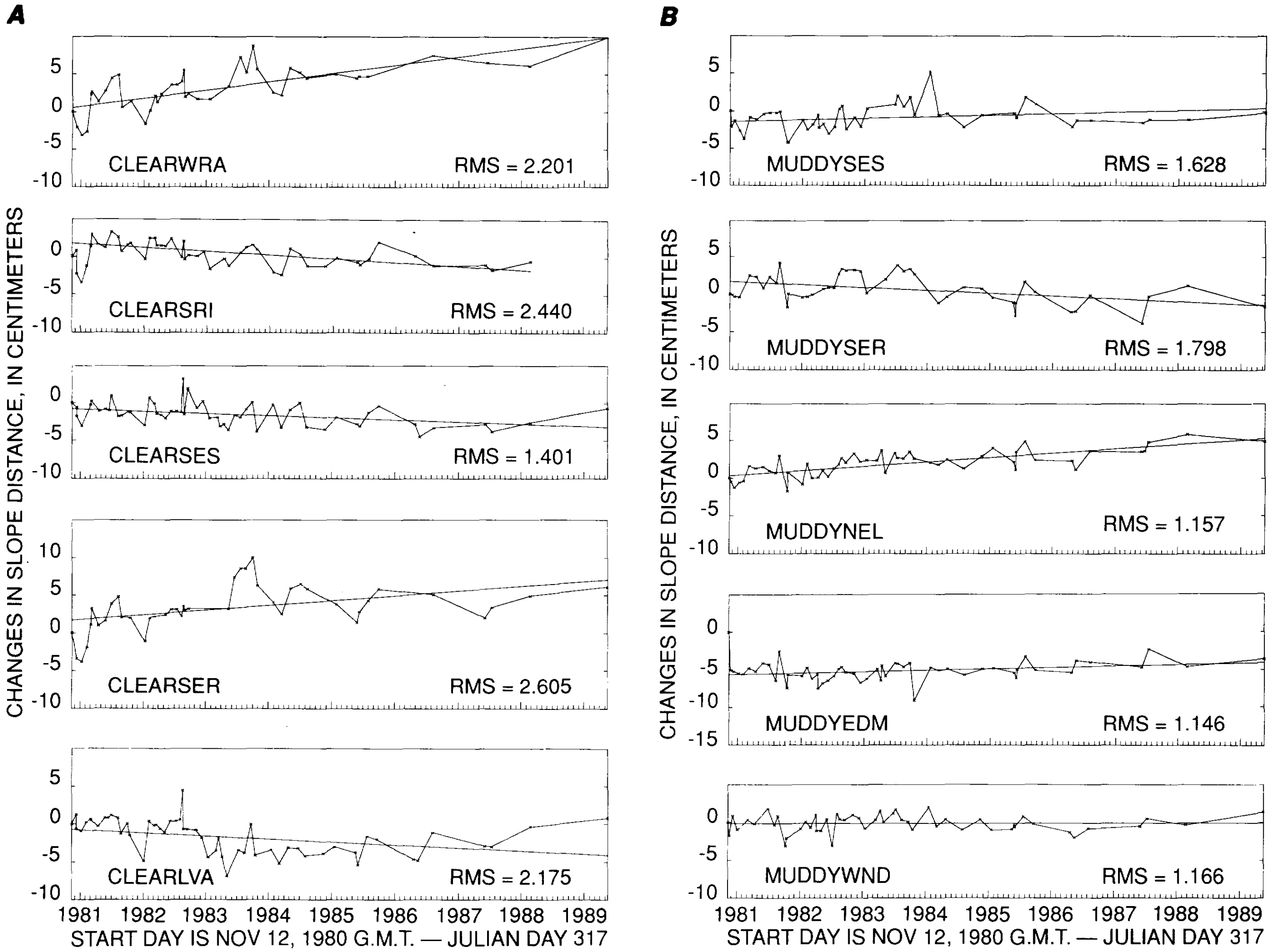

Figure 8.5. Cumulative slope-distance changes of lines measured from *A*, Clearcut; *B*, Muddy; *C*, Road 100; *D*, Harrys Ridge; *E*, Studebaker; and *F*, Butte Camp instrument stations. A best fit line is drawn through data, and root-mean-square error (RMS, in centimeters) around line is indicated in each plot.

to establish trends and errors (fig. 8.5). Errors related to setup procedures, atmospheric conditions, and measurements on steep slopes (average elevation difference between instrument and reflector station is 617±286 m) can be as much as several centimeters.

The cumulative slope-distance changes for all 28 lines (lines to Step are included although the station was moved in 1986) are plotted in figure 8.5. The straight line is a least-squares regression and the root-mean-square (RMS) error is given in centimeters. Table 8.1 lists other statistics. The standard deviations (S.D.), in meters and parts per million (ppm), are associated with the mean slope distance, and *n* is the number of measurements. The linear regression equation is

$$y = A + Bx.$$

The mean standard deviation for 25 of the lines is 0.0188±0.0044 m (4.9068±1.2544 ppm). The mean standard deviation does not include the lines measured to Step and Sugar Bowl towers, which were not stable throughout the period of measurement.

RELATION BETWEEN OBSERVED DEFORMATION AND VOLUME OF ERUPTED OR STORED MAGMA

A simplified Mogi (point-source) model (A. Okamura, written commun., 1990) was used to estimate the maximum expected horizontal displacement and its horizontal distance from the source for two volumes of magma, 2.5 and 5.0 × 10^6 m^3, added or subtracted at depths ranging from 1 to 5 km (table 8.2). The model assumes a volume change in an elastic, isotropic material. The depth range is that considered as likely for the shallow magma reservoir under Mount St. Helens. The average horizontal distance from the reflector towers

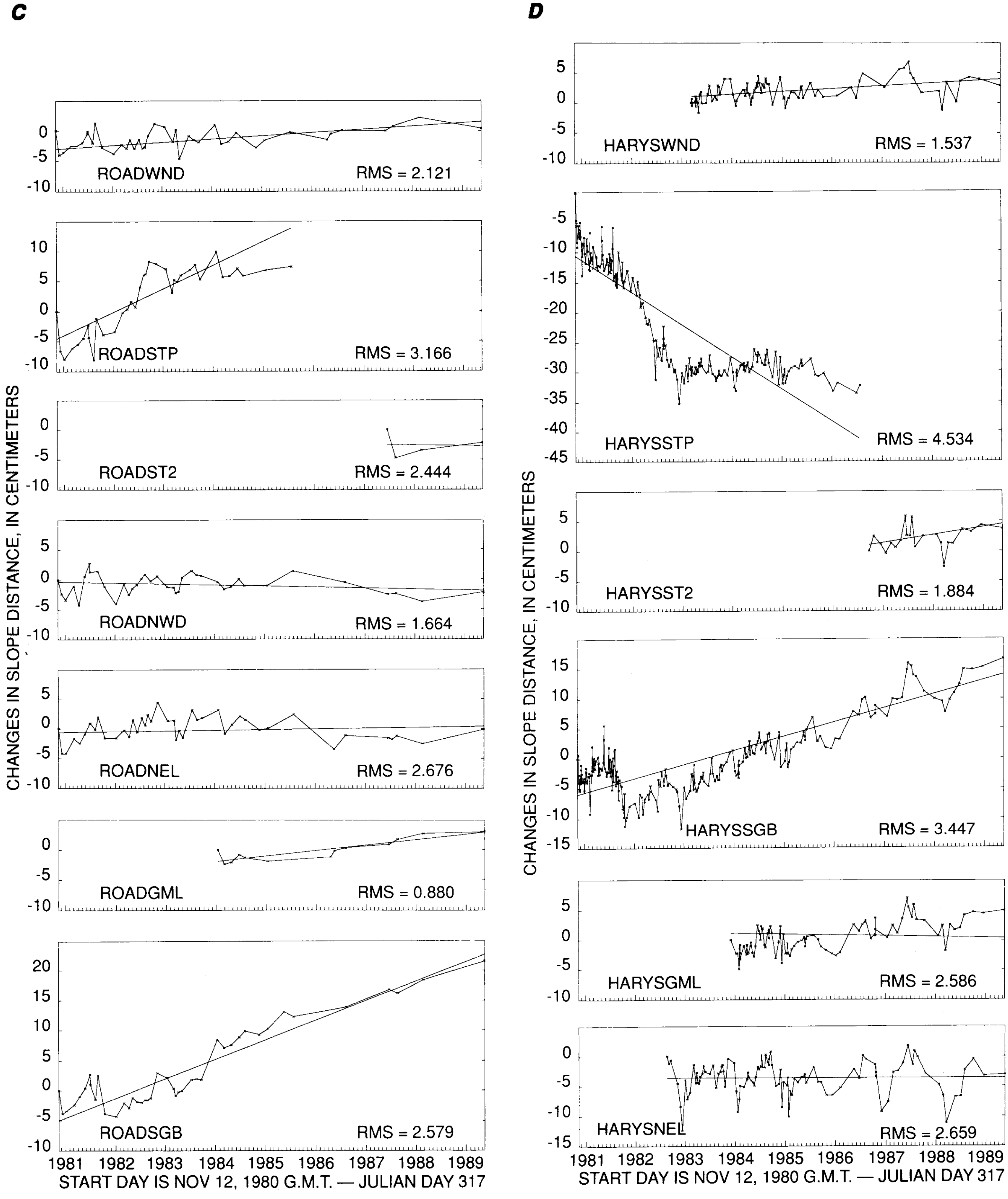

Figure 8.5.—*Continued*

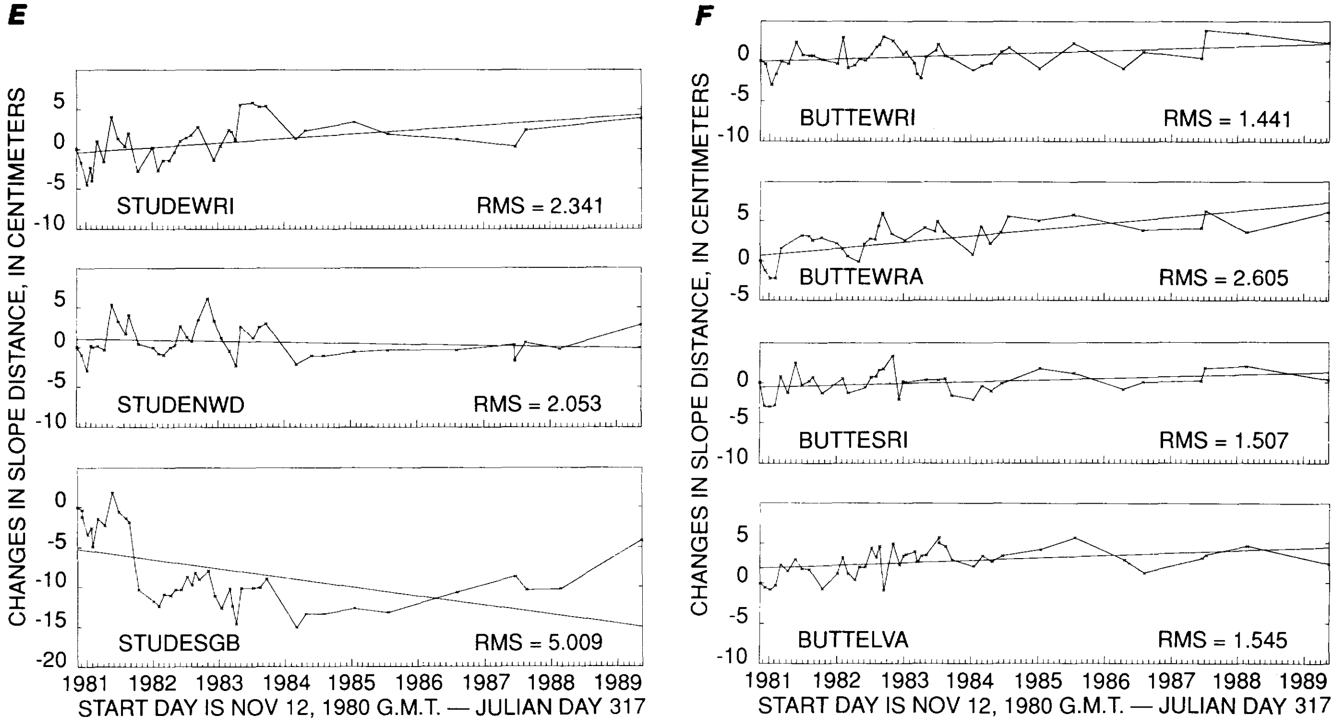

Figure 8.5.—*Continued*

to the center of the dome is 2.1 km, and the amount of horizontal displacement at this average distance is also shown in table 8.2 (TD).

The results of the calculations suggest that the outer net would detect displacement greater than those expected at the 2 S.D. level only for a volume change of more than 2.5×10^6 m^3 at a depth of about 1 km. A smaller volume or greater depth would not yield displacements greater than those expected at the 2 S.D. level. However, repeated measurements over a long time interval might result in a convincing trend even if the volume or depth were not adequate to satisfy formally the 2 S.D. confidence guideline.

The modeling results are marginally consistent with the volume of single dome-growth episodes. The average dome-growth episode produced a volume of about 3.6×10^6 m^3 (Swanson and Holcomb, 1990), and no deformation was detected by the outer net during the events. According to the model, this would imply withdrawal of magma from a reservoir at a depth greater than 1 km, which is within the range of 1–2 km estimated from seismic observations (Endo and others, 1990). Most likely the model is too idealized to be used in such a detailed manner, but at least it is consistent with observations. Another complication is the possibility that magma rose from greater depth to take the place of the magma erupted, thereby resulting in no net deformation related to a shallow source and deformation related to a deeper source that is too small to be detectable by the outer net.

A related finding is that the outer net did not detect any deformation resulting from the eruption of about 77×10^6 m^3 between October 1980 and October 1986 (Swanson and Holcomb, 1990). According to the point-source model, eruption of such a volume from a depth of 7 km should have resulted in about 6.6 cm of horizontal displacement at 2.1 km from the vent; from depths of 8, 9, and 10 km, the resulting displacement would have been 4.6 cm, 3.0 cm, and 2.4 cm, respectively. However, considerably less displacement than this was measured at most of the stations (fig. 8.5), and in fact nearly all of the measured changes are within the 2 S.D. confidence limits. Therefore, we can conclude that a volume of 77×10^6 m^3, equivalent to that of the dome, *could* have incrementally risen from a depth of 7 km or more without geodetic detection.

DISCUSSION

Several interesting results have been seen from monitoring the flanks of Mount St. Helens. There is a

Table 8.1. Statistics for outer net lines station symbols listed in figure 8.5.
[Average standard deviation (S.D.) is .0188±0.0044 m (4.91±1.25 ppm), excluding measurements to unstable Step and Sugarbowl towers. A and B, coefficients in linear regression equation (see text); n, number of measurements.]

Line	Mean slope distance (m)	S.D. (m)	S.D. (ppm)	A	B	*n*
CLEARLVA	2612.3518	0.0163	6.24	0.052843	-0.000011	55
CLEARWRA	5142.2053	0.0255	4.38	0.058339	0.000030	44
CLEARSRI	3787.7435	0.0207	5.46	-0.131858	-0.000013	50
CLEARSER	4567.9731	0.0245	5.36	0.019525	0.000018	41
SLEARSES	3229.0305	0.0143	4.43	0.009890	-0.000008	55
MUDDYSES	3155.5176	0.0167	5.29	0.015682	0.000006	49
MUDDYSER	3944.8057	0.0194	4.92	0.031095	-0.000010	44
MUDDYNEL	3133.9928	0.0165	5.26	0.012470	0.000016	52
MUDDYEDM	2073.8606	0.0119	5.74	-0.019293	0.000005	53
MUDDYWND	3559.6672	0.0115	3.23	-0.013443	0.000000	50
ROADWND	2921.7032	0.0158	5.41	0.100623	0.000015	42
ROADNEL	4558.1470	0.0198	4.34	0.113864	0.000003	43
ROADSGB	3240.9759	0.0695	21.44	0.049108	0.000089	42
ROADSTP	3392.5475	0.0545	16.06	0.032978	0.000092	37
ROADST2	3243.5133	0.0200	6.17	-0.025132	-0.000002	4
ROADGML	3823.3190	0.0177	4.63	-0.018813	0.000024	13
ROADNWD	5079.7687	0.0166	3.27	-0.019029	-0.000005	38
HARYSSGB	6679.5150	0.0648	9.70	-0.125063	0.000060	237
HARYSSTP	6346.4131	0.0916	14.43	-0.170432	-0.000148	215
HARRYSST2	6101.6053	0.0209	3.43	0.009628	0.000030	24
HARYSGML	6391.8993	0.0257	4.02	0.012151	0.000000	95
HARYSNEL	8529.7190	0.0265	3.11	-0.035903	0.000000	107
HARYSWND	7033.3793	0.0171	2.43	0.010598	0.000013	88
STUDESGB	4461.8031	0.0454	10.18	-0.177775	-0.000031	42
STUDENWD	3502.0822	0.0206	5.98	0.013641	-0.000003	41
STUDEWRI	4507.9884	0.0263	5.83	0.009424	0.000017	37
BUTTEWRI	2814.4481	0.0152	5.40	-0.001051	0.000007	44
BUTTEWRA	2585.6419	0.0216	8.35	0.111692	0.000022	35
BUTTESRI	3014.5021	0.0151	5.01	0.031401	0.000006	37
BUTTELVA	2717.0358	0.0138	5.08	0.012025	0.000008	44

hint of seasonal fluctuations affecting some slope distances but not others (fig. 8.5). For example, from the same instrument station, line MUDDYSER shows such fluctuations but line MUDDYWND does not. Elevation, line length, and site location have no apparent effect. We have no ready explanation, although we suspect that the fluctuations are caused by atmospheric rather than volcanic effects.

Since late 1980, no pattern of extension or contraction consistent throughout the network has been defined. Hence the few trends seen, such as those on the lines CLEARWRA, BUTTEWRA, BUTTESRI, and STUDEWRI, may be attributable to slight instability of the instrument or reflector towers, or to other local effects such as sliding, settling, or freeze-thaw activity. The lack of a consistent pattern contrasts with the general trend of inward collapse, possibly along a northwest-trending axis, that characterized the volcano in the summer and fall of 1980 (Swanson and others, 1981) and may have resulted from a response of the remaining shell of the volcano to the sudden formation of the deep crater on May 18, 1980.

Although not part of the network to monitor the flanks of the volcano, the measurements from Harrys Ridge to the dome (8 km) and crater floor are used to help predict dome-building episodes and provide an alternative indicator if volcanic conditions in the crater are considered too hazardous to work there. In 1984,

Table 8.2. Computed maximum horizontal displacement (HD) and horizontal distance (D) from the source for two increases in volume of magma at depth. TD, expected change at reflector towers (calculated for the average horizontal distance of the towers to the center of the dome, 2.1 km).

[Calculations based on point source embedded in an isotropic, homogeneous, elastic half-space.]

	2.5×10^6 m^3 volume increase			5.0×10^6 m^3 volume increase		
Depth (km)	D (km)	HD (cm)	TD (cm)	D (km)	HD (km)	TD (cm)
1	0.7	15.3	6.6	0.7	30.6	13.3
2	1.4	3.8	3.4	1.4	7.7	6.9
3	2.1	1.7	1.7	2.1	3.4	3.4
4	2.8	1.0	0.9	2.8	1.9	1.8
5	3.5	0.6	0.5	3.5	1.2	1.8

prior to the February and March dome-building episodes, a target on the north side of the dome was measured from both Harrys Ridge and Sauna instrument stations. Sauna was located approximately 280 m north of the dome and was part of the dome-deformation network in the crater (Iwatsubo and Swanson, chapter 6). Both lines reflect the same characteristics (fig. 8.7) and were used to help predict this dome-building episode. Moreover, the similarity of trends from both instrument stations indicates that Sauna, on the crater floor near the dome, was not moving significantly—a vital piece of information otherwise unavailable.

One benefit of the measurements from Harrys Ridge to the dome is that conditions outside the crater almost always allow landings at Harrys Ridge. In contrast, high, unpredictable winds in the crater sometimes make flying and landing in a helicopter hazardous. During periods before an eruptive episode, when work may be limited to Harrys Ridge owing to weather or safety considerations, these measurements help to define better the deformation cycle. An example is the February 1984 episode (fig. 8.7). The dome-building episode started on February 6. The Sauna-Funkier line was measured on February 5 and next on February 14, but the Harrys-Funkier line was measured at midday February 7, when windy conditions prohibited work in the crater, and again on March 3. The Harrys-Funkier distance on February 7, when compared to that of March 3, shows that deformation had virtually stopped by February 7. Therefore the change in the Sauna-Funkier distance measured between February 5 and February 14 must also have occurred before midday on February 7.

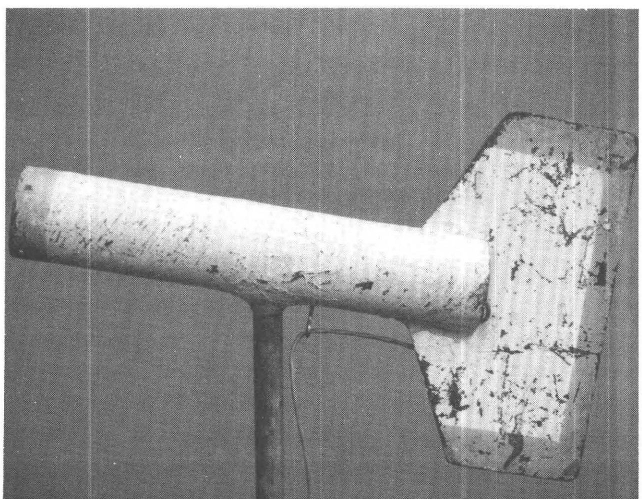

Figure 8.6. Side view of shield used to house temperature sensor. Shield spins on steel pipe like a weather vane, thereby allowing wind to pass through tube and temperature sensor. Shield is approximately 60 cm long.

CONCLUSIONS

Since late 1980, little or no detectable deformation has been measured on the flanks of Mount St. Helens. All eruptive activity and deformation has taken place on the lava dome.

Single-endpoint atmospheric data are adequate to detect large-scale deformation that may occur before an eruptive episode, as indicated by the measurements from

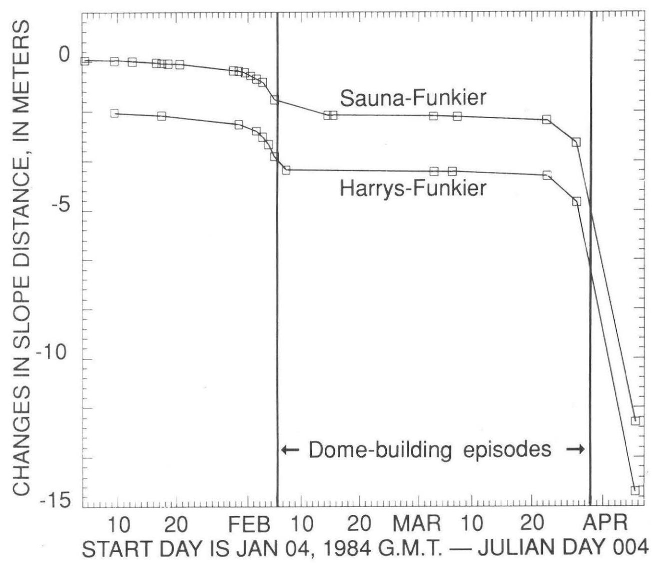

Figure 8.7. Cumulative slope-distance changes to dome target Funkier from two different instrument stations for February and March 1984 dome-growth episodes. Upper plot shows data measured from Sauna, 280 m north of dome on crater floor. Bottom plot shows data measured from Harrys Ridge, 8 km north of dome. Both lines were used to predict both episodes.

Harrys Ridge to points inside the crater. It is important to collect as many single-endpoint measurements as possible to help define errors and trends for each line. The data show random variations of about 5 ppm, which is considered to be within the expected errors defined by the long-term trends. Many lines at Mount St. Helens exhibit this type of behavior.

If a significant new influx of magma enters the system at a depth of about 1 km, movement of the flanks should indicate this inflation. What "significant" means in this context is not known well, other than that the new volume would probably have to be greater than 2.5×10^6 m^3, as judged from the simple point-source modeling. At greater depths a larger intrusion could go undetected by the outer net. Until intrusion occurs, we expect little or no slope-distance changes along the outer-flank lines.

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9. Monitoring Radial Crack Deformation by Displacement Meters

By Eugene Y. Iwatsubo, John W. Ewert, *and* Thomas L. Murray

ABSTRACT

Measurements of change in the width of cracks on the crater floor of Mount St. Helens, Washington, were a major tool used in predicting dome-building episodes during 1980–82. These measurements were made by field crews using a steel tape measure to determine the distance between lengths of reinforcing rod driven into the ground on opposite sides of cracks. In 1981, a telemetered, electronic tape measure was installed on the crater floor to monitor crack movement continuously. However, electronic and physical problems kept this and a second displacement meter from being viable predictive tools. In 1985, using new techniques and instrumentation, a third displacement meter was installed on the dome, and it successfully monitored the widening of a crack days before a dome-building episode. By 1989, there were two displacement meters of this type monitoring cracks on the dome.

INTRODUCTION

Beginning in September 1980, cracks that extended radially from the Mount St. Helens dome (fig. 9.1) formed in the crater floor. As magma ascended into the dome the crater floor deformed, creating segments or blocks bounded by cracks that either widened or, less commonly, narrowed before and during extrusive episodes (Chadwick and others, 1983; Chadwick and Swanson, 1989; Swanson and others, 1983). The rate of widening or narrowing of the cracks accelerated before extrusion occurred. Initially, a steel tape was used to measure changes in distance between reinforcing rod (rebar) stakes driven into the ground on either side of selected cracks (crack stations). This method became a reliable tool for predicting dome-building episodes at Mount St. Helens.

To monitor crack movement continuously, electronic tape measures (displacement meters) were installed to monitor displacements between rebar stakes. Measurements from the displacement meters are made every 10 minutes and telemetered to the Cascades Volcano Observatory (CVO). This paper discusses methods used to establish permanent displacement meters at Mount St. Helens. Although these methods deal with specific problems at Mount St. Helens, they could be adapted for use at other volcanoes that display similar deformation.

DEVELOPMENT OF THE METHOD

Data obtained by monitoring crack stations helped in predicting the October 1980 explosive episode (Swanson and others, 1981, 1983). With the success of this method, more crack stations were established on the crater floor to monitor deformation and aid in the prediction process.

Because measurements could only be taken when crews were in the crater, instrumentation was designed to measure and telemeter crack measurements to CVO. In June 1981, the first displacement meter was installed on the east crater floor. The displacement meter and electronics were housed inside a fiberglass box that was connected to a plastic pipe 10 cm in diameter and 12 m long. The displacement-meter wire (stainless steel) was strung through the plastic pipe to a fencepost on the other side of the crack. At this time, many of the cracks were hot and emitted steam and gas; where the wire crossed the crack, the plastic pipe was encased in a larger steel pipe for added protection.

A separate fiberglass box contained the telemetry unit. Measurements were telemetered to CVO at 10-minute intervals. Our intent was to observe movement of the blocks on either side of the crack before and during an eruptive episode, but condensation of water vapor and corrosion by gases caused the electronics in the meter to fail.

After modifying the electronics housing to be airtight, the displacement meter was once again installed across a crack. As a check on the displacement meter, a crack station was established and measured by field crews. Prior to the September 1981 episode, the telemetered data from the displacement meter indicated narrowing of the crack; field measurements confirmed this trend. It had been expected that the crack would widen as magma intruded, and the construction of the station was accordingly designed to accommodate widening, not narrowing. Consequently, as the crack continued to narrow, the stiff plastic pipe buckled and eventually broke the wire. As the pipe buckled and pulled on the wire, the displacement meter indicated widening, even though the crack itself was narrowing.

Following the March 1982 episode, the radial cracks on the crater floor were buried by pumice deposits (Waitt and others, 1983). Consequently no measurements of cracks were made until 1985, when we started to establish geodetic stations on the dome itself (Iwatsubo and Swanson, chapter 6). At this time a commercial displacement meter was purchased and installed (station Steger) next to an existing crack station (South August). This third installation was environmentally secure, and both the displacement meter and taped distances showed similar trends preceding the May 1985 episode (fig. 9.2). Except for minor modifications, this is the system configuration used in 1990.

EQUIPMENT

The primary equipment is the displacement meter itself. The displacement meter used in 1981 was designed and installed by Malcolm Johnston and Tom Murray and was described in the monthly report of the Cascades Volcano Observatory in June 1981. This meter used a spring, wheel, axle, stainless-steel wire, and a 360-degree potentiometer. The stainless-steel wire was strung from one end pier, across the crack, and into the electronics box containing the displacement meter. The wire was wound around the wheel and attached to a spring for tension. The wheel was welded to an axle that had one end connected to the wiper of the potentiometer. As the wire was pulled or wound, the wheel would rotate the axle and change the position of the wiper of the potentiometer. Five volts was applied across the potentiometer, and as the wire moved and rotated the potentiometer, the voltage would change correspondingly. The signal output of the displacement meter was digitally transmitted to CVO.

Beginning in 1985, with the installation of station Steger, a displacement meter purchased from Celesco has been used. The displacement meter, model PT101, has a

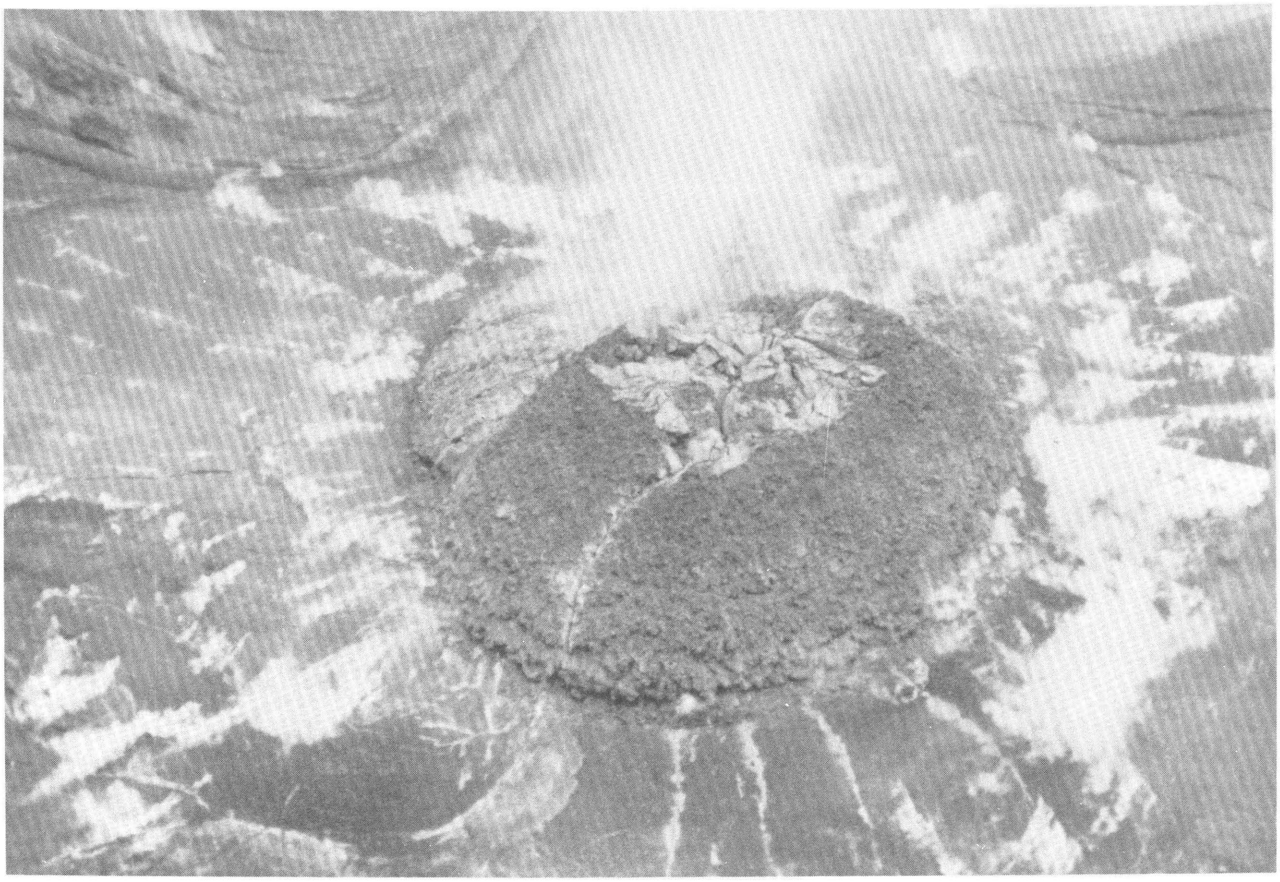


Figure 9.1. Dome of Mount St. Helens in December 1980, showing radial cracks that formed on crater floor adjacent to it.

3.8-m-long wire but can be purchased in lengths that range from 1 cm to 12.7 m. The PT101 has an operating temperature range of -17.7 to 93.3 °C, the thermal coefficient is reported as 0.0011 percent per °C, and the accuracy is 0.10 percent full-scale maximum. The dimensions of the meter are 19 × 13.5 × 11 cm. With a 3.8-m-long wire, the sensitivity of the meter is 1.4 mV/mm. The PT101 works on the same basic principle as the displacement meter built by Johnston and Murray.

Materials and Installation

Installation costs are minor compared to the cost of the meter ($500). All totaled, the materials used for installation and wire protection cost approximately $50. This section describes materials and methods used to install displacement meters at Mount St. Helens.

The displacement meter is mounted inside a surplus metal ammunition can (30 × 15.5 × 18 cm) with six holes drilled in it, one for the displacement-meter wire, one for the signal output, and four to bolt the meter to the can (fig. 9.3*A*). Silicone sealant is used around the screw holes to prevent water and fumarole gas from seeping into the ammunition can. The meter is powered by a single 12-volt alkaline lantern battery (or two 6-volt alkaline batteries), which also is inside the ammunition can. A 5-volt regulated reference supplies a constant voltage to the meter. The batteries power the 5-volt reference and displacement meter for one year.

The displacement-meter wire passes through a small hole drilled into the side of the ammunition can. To protect the wire from rubbing and breaking on the metal edge, it is strung through a hard rubber plug (a rubber eraser would also suffice) with a hole drilled through it. The plug is then placed inside the small hole and glued in place with silicone sealant (fig. 9.3*B*). This

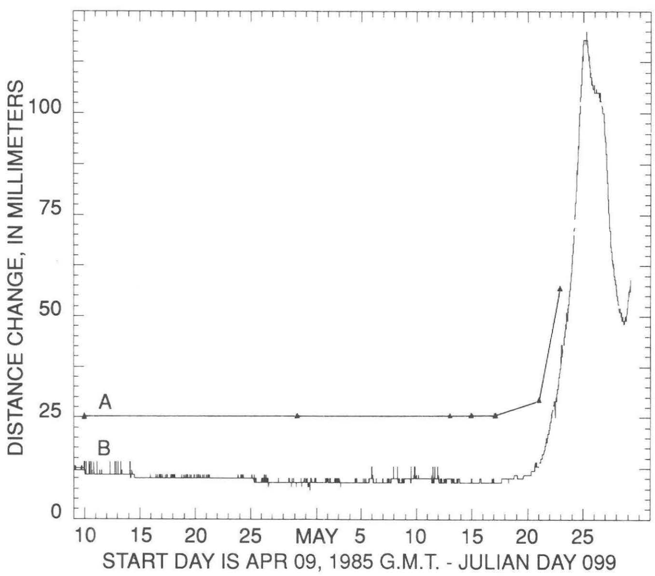
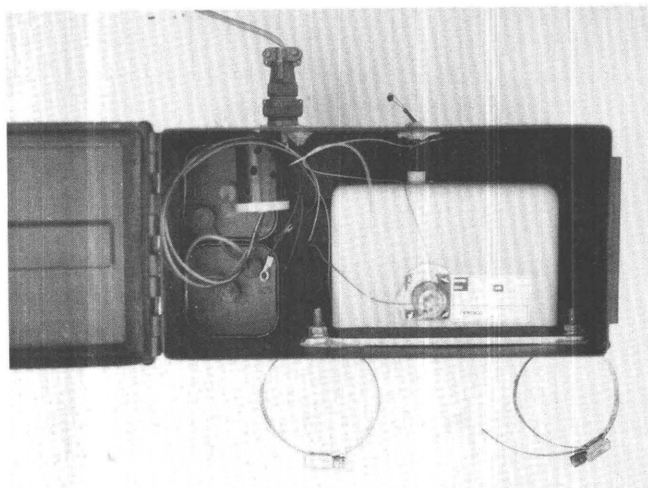
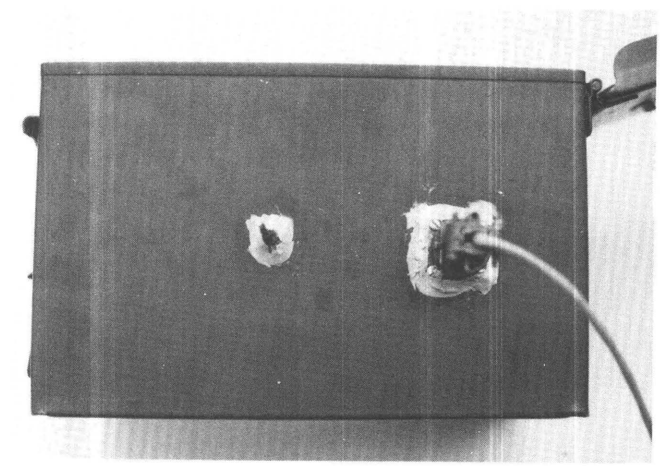


Figure 9.2. Taped (A) and telemetered (B) distance changes across South August crack, April–May 1985. Telemetered data from Steger displacement meter show start of deformation to be on May 18 and define a smooth curve as deformation increases. Tape measurements reflect same displacements, but could only be measured up to May 23. Downward inflections of Steger displacement data correspond to graben-forming events that occurred during extrusive episode, which began late on May 24. Vertical scale shows relative displacement from an arbitrary zero point.



A



B

Figure 9.3. *A*, Top view of inside of displacement meter housing (ammunition can). A 12-volt (two 6-volt batteries connected in series) battery is used to power 5-volt reference (small plastic container attached to wires). Holes are drilled in ammunition can for wire and to mount meter. Hose clamps are to connect housing to fenceposts. *B*, Closeup view of wire coming out of can. Rubber stopper (left side) with hole drilled in it for wire is glued in the hole with silicone sealant. Plug on right-hand side is signal output to telemetry unit.

allows the wire to move freely in and out, protects it from the metal edge, and maintains the environmental integrity of the ammunition can.

Three steel fenceposts are driven into the ground and cemented (if the fenceposts are not stable when driven in), two at the instrument end, and one on the other side of the crack for an end pier. The ammunition can is attached to the two fenceposts by two hose clamps mounted to the can (figs. 9.3, 9.4) and sits directly on the ground for added stability.

A path between the fenceposts is cleared so that the displacement-meter wire can stretch between end piers without touching the ground. We typically string a temporary wire between end piers, at the height of the actual wire, to act as a guide while clearing the path. This temporary wire shows where material needs to be removed or filled in and can be kicked or hit with debris without fear of damaging the instrument. After the path is cleared, the temporary wire is removed and the displacement-meter wire is strung.

Once strung, the wire must be protected from volcanic and environmental processes. Small explosions can impact the wire with ballistic ejecta 1 m or more in diameter, and snow accumulation (up to 10 m on the dome) during the winter months can pin the wire to the ground. To protect and give easy access to both the instrument and end piers, wooden boxes (61 cm square) with large slots to allow the wire free movement are constructed and placed over each end pier (fig. 9.4). To cover the boxes, we place a separate piece of wood on top of the box and hold it down with rocks.

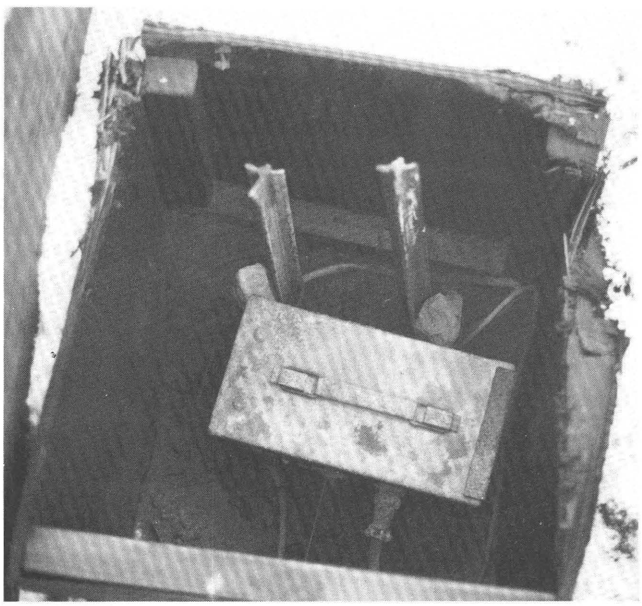


Figure 9.4. Displacement meter housing attached to fenceposts by two hose clamps (rocks are spacers between hose clamps and fenceposts). Wooden box allows easy access to wire and displacement meter. End pier has a similar box surrounding it. This box shows signs of the one winter it has survived.

In 1985, to protect the wire at station Steger, 0.5-in. (1.3 cm) plywood sheets were cut into 30.5-cm-wide strips and connected together to form an A-frame over the wire (fig. 9.5). The ends overlapped one another to allow the frames to slide if narrowing or widening of the crack occurred. Tephra and dome rocks were piled against the A-frame for additional lateral support. This method performed well until the meter was destroyed in the May 1985 eruptive episode. In August 1985, a displacement meter was installed on the dome at station Rainbow Warrior. An A-frame cover was again used to protect the wire, but by February 1986 10 m of snow had accumulated over the displacement meter and the A-frame was crushed, breaking the wire.

A second installation method was tested at station Rainbow Warrior. A trench was dug from fencepost to fencepost and a plywood box approximately 20.5 cm square and 10 m long (forming a tunnel) was placed in the trench. The wire was then strung through the tunnel and attached to the anchor pier. The top of the box, which was level with the ground surface, was covered with dirt for added protection. The wire was thus safe from snow and ballistics. This method would not have been used had previous crack information not indicated that widening of the crack would be the dominant sense of movement. The buried box method will not work for measuring large-scale contraction.

PROBLEMS

In 1981, the two major problems that affected displacement-meter operation resulted from gases and construction design. The first displacement meter failed because the electronics corroded from condensation of gases. An environmental housing was subsequently used. The second displacement meter failed because the protective wire casing was too stiff and could not accommodate narrowing of the crack. Since 1985, the displacement meters have been housed in ammunition cans because they are airtight, large enough to enclose both the meter and battery, and inexpensive. The problem of wire protection has been solved as discussed above.

A short time after station Steger was installed in 1985, we noticed that the telemetered data differed significantly from the taped data at South August crack station. The problem was found to be electronic; the 5-volt reference was drifting with time. The displacement-meter output signal is directly related to its input voltage, the 5-volt reference. In order to obtain true displacement readings, the 5-volt reference must be stable. A 5-volt reference is used because of the configuration of the digital telemetry. We now use a Precision Monolithic Incorporated, REF-02 5-volt reference.

The most common problem we have encountered has been broken wires. Wire breakage is typically caused by the condensation of corrosive gases on the wire—even stainless steel wire is not immune. Breakage owing to corrosion is not a problem in the summer months, when gases can vent from the monitored crack and mix freely with the atmosphere. The problem arises during winter months, when the stations are buried under deep snow.

A broken displacement meter can be difficult to repair. When the wire breaks, it often will snap back into the displacement-meter housing and (1) completely unwind from the wheels inside, (2) cause the tension to release, and (3) can damage the potentiometer. We obtained instructions from the manufacturer on how to rewind the wire and set the spring tension, and potentiometers can be purchased locally. Therefore we are able to repair the instruments when they break.

To protect the thin (0.038 mm), stranded, stainless steel wire of the displacement meter from corrosion during winter months, we attach a heavier (1 mm), solid stainless-steel wire to the end pier and stretch it across the hot crack to within 1–2 m of the displacement meter. The thinner wire of the displacement meter is then connected to the heavier wire. If the heavier wire is too long, the relatively weak spring in the displacement meter will not be able to hold it off the ground. In this case, the total length of the installation must be shortened until the spring holds the heavier wire above the ground.

The heavier wire increases the overall life expectancy of the installation, but the remaining thinner wire is still susceptible to corrosion over time. Prior to the use of the heavier wire, installations have lasted 2–3 months during winter, but with the heavier wire, installations lasted up to 6 months before the thinner wire broke. To improve the installations, we now replace the manufacturer's wire with nylon-coated, stranded stainless steel fishing line (purchased at a fishing shop). The diameter of the nylon-coated wire is a little larger than the wire supplied with the displacement meter but not enough to affect the sensitivity of the meter.

In addition to modifying the wire, we drill holes (2–3 cm) in the protective wood box and frame to help circulate air and to vent corrosive gases and steam away

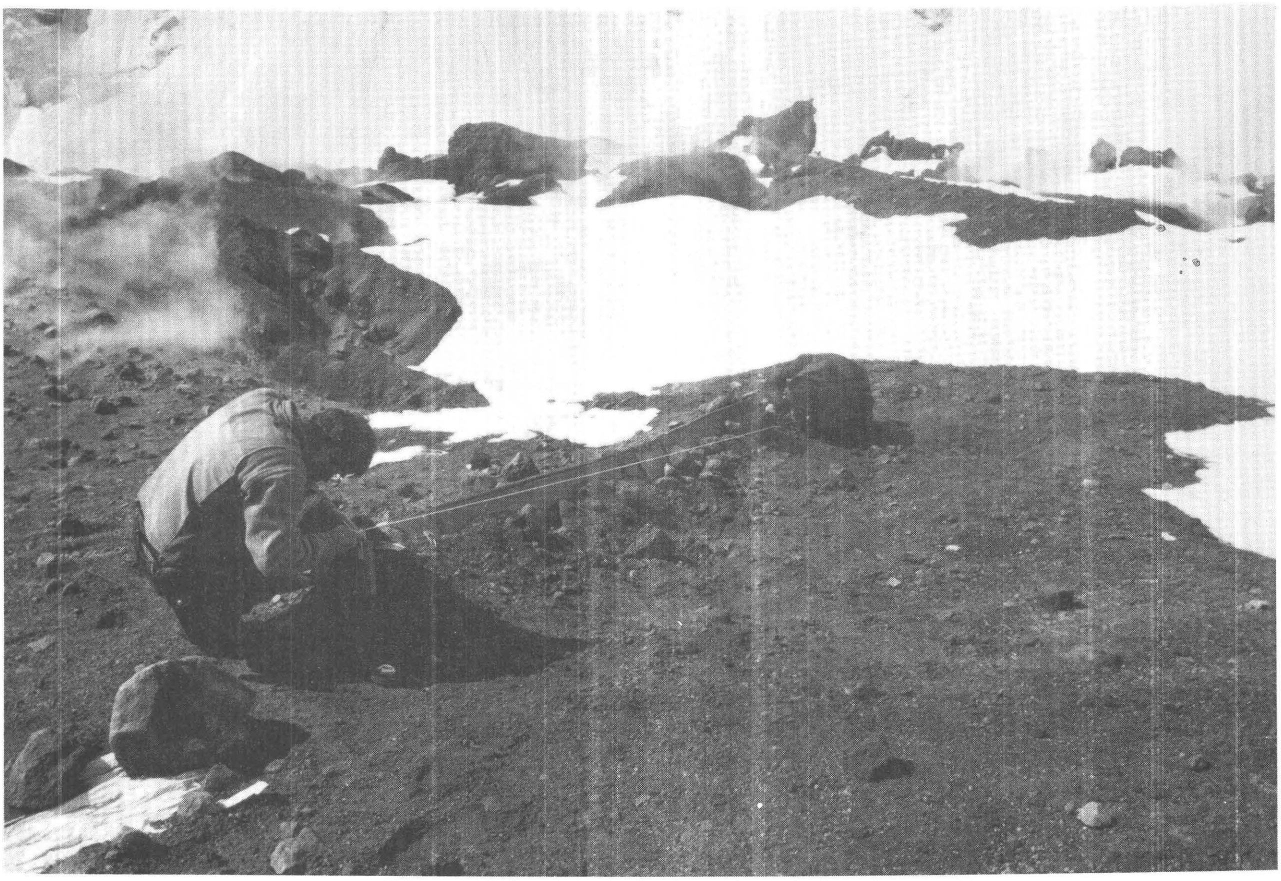


Figure 9.5. Scientist measuring South August crack with a steel tape in 1985. Steger displacement meter is in background. Note top of A-frame (behind tape) and dirt piled against it for lateral support.

from the wire. During winter, snow typically melts from the ground up because of the warm crack, thereby forming caverns under the snow that help improve air circulation around the wire. More holes are drilled in the area where the wire crosses the crack, because that is where the gases and steam are most concentrated. We do not drill large holes (>3 cm) over colder areas, because snow can drift into the holes, pin the wire to the ground, and cause erroneous data.

DATA

Prior to the May 1985 episode, South August crack station and station Steger were monitored simultaneously (fig. 9.2). From taped distances alone, the start of deformation for the South August crack would not have been known, but telemetered data show the start to be May 18–19. The first day a taped distance indicated movement was May 21, after the start of deformation. On May 23, taped measurements and telemetered data indicated 33 mm and 31 mm of extension, respectively. The total amounts of displacement between taped distances and telemetered data are similar, but the curve is better defined by the telemetered 10-minute data. The reversal in trend on May 25 could be attributed to movement of a bounding block, south of both stations, which may have pushed the meter and crack northward. This corresponds to the formation of a large graben during this episode (Swanson, 1985; CVO monthly report, May 1985). South August crack began to widen, as it was possibly falling into the graben, just prior to the loss of telemetry.

Periods of quiet are more often the norm for displacement meters. Figure 9.6 is a plot of a 14-day period for the two displacement meters on the dome in 1989. Ground temperatures are monitored approximately 0.5 m beneath the surface near each instrument pier and show how relatively warm the ground remains. Data in figure 9.6 show that the meters are not seriously affected by large temperature fluctuations.

Snow may drift through the holes in the protective wood box and frame and accumulate on the wire, causing erroneous data (fig. 9.7). On March 25, snow accumulated on station Sandi (located on the upper west part of the dome) and caused apparent extension. Such extension is relatively sudden and steplike, and differs from the volcanic-deformation signal observed at station Steger (fig. 9.2). As the snow slowly melted, the signal returned to within about 1 to 2 mm of its previous position.

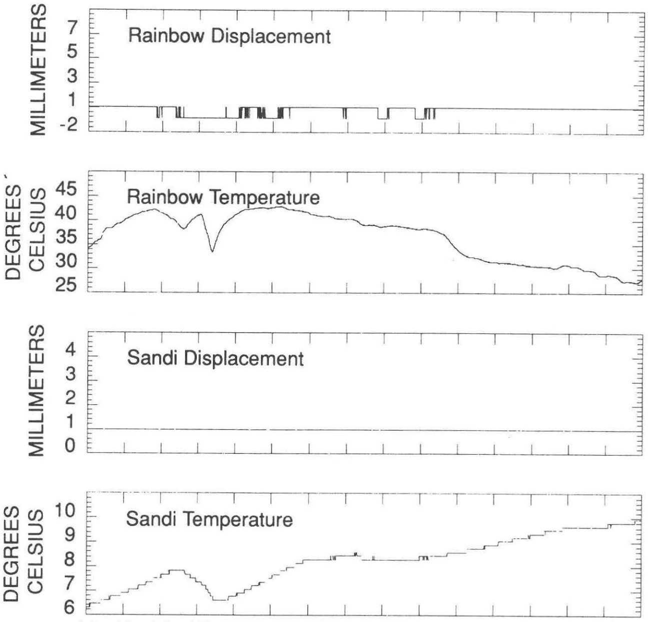


Figure 9.6. Plots displaying a 14-day period of quiet in 1989 at two displacement meters, Rainbow Warrior and Sandi. Straight line for Sandi indicates a stable instrument and electronics, while Rainbow Warrior (although quiet) displays 1 mm of background noise. Temperatures are monitored near instrument pier at a depth of 0.5 m. Temperature changes do not affect displacement-meter signals.

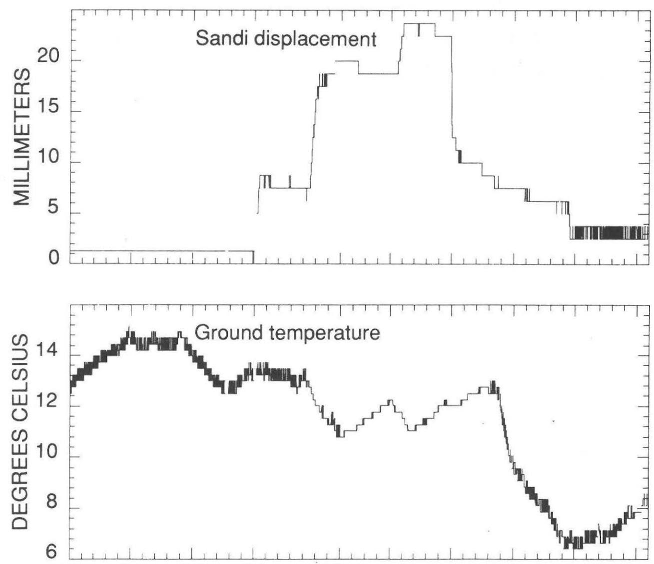


Figure 9.7. Effect of snow accumulating on wire of station Sandi during one heavy snowfall. These offsets normally occur quickly and are steplike as snow falls on framing, accumulates, then falls through holes and onto wire, causing appearance of crack widening. Signal returns to its pre-snowfall position (within 1 to 2 mm) after snow melts.

SUMMARY

The monitoring of cracks using displacement meters lends itself well to deformation studies of near-vent processes at Mount St. Helens. Structures likely to show displacement must be identified by field observation and carefully studied before installation of real-time monitoring equipment. The problems that arise with the installation of displacement meters have not been trivial, but the experience gained from earlier failures and successes is important. Continuous monitoring of crack movement at Mount St. Helens is especially critical prior to eruptive episodes. Deformation of an active crack corresponds to magma intrusion and can give information indicating the rate and amount of deformation taking place. During bad weather when crews cannot get into the field, displacement-meter data can be used with other telemetered data, such as tilt, gas, and seismic monitoring, to help decipher eruptive activity.

Having the foreknowledge that a particular crack widens or narrows during magma intrusion has helped in the design of individual stations. Each environment will have a special set of problems and answers. At Mount St. Helens, each failure has led to a better end product. Housing the meter and electronics in environmentally sealed cases, protecting the wire from snow and ballistics, and solving the problems of corroding wires are a few improvements that have helped us to design a longer lasting displacement meter.

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10. Trilateration and Distance-Measuring Techniques Used at Cascades and Other Volcanoes

By Eugene Y. Iwatsubo *and* Donald A. Swanson

ABSTRACT

From 1980 to 1989, scientists of the U.S. Geological Survey's Cascades Volcano Observatory established trilateration and distance-measuring networks on Mount Baker, Mount Rainier, and Mount St. Helens in Washington; Mount Hood, South Sister, Newberry, and Crater Lake in Oregon; Medicine Lake, Mount Shasta, Lassen Peak, and Mammoth Lakes in California; and Augustine Island in Alaska. The networks were installed to provide baseline information on potentially active and dangerous volcanoes. The experience gained in monitoring Mount St. Helens has helped in designing guidelines for establishing these networks. One improved method of measuring air temperatures (for atmospheric corrections to the distance) at each bench mark has led to considerable savings in helicopter time by not requiring continuous temperature measurements along the path of the infrared signal. Bench-mark stability is critical and must be carefully evaluated both during installation and later if movement is measured. The equipment and methods currently in use are sufficient to meet the precision (±2-3 ppm about any given distance) that is required for baseline data.

INTRODUCTION

Trilateration and distance-measuring networks have been established on 12 potentially active volcanoes in the Pacific Coast States beginning in 1980. These networks, once the baseline information has been collected, can detect surface deformation that may reflect magma movement up the conduit. The rates of deformation increase as magma approaches the surface, and these measurements can therefore help determine where and when an eruption may occur (Lipman and others, 1981). Before 1980, electronic distance meters (EDM's) had been used primarily to monitor horizontal deformation during inflation and deflation of shield volcanoes (Kinoshita and others, 1974). Little horizontal deformation monitoring had been attempted on stratovolcanoes with the exception of Usu volcano, Japan, where up to 160 m of movement was observed using trilateration techniques to monitor cryptodomes forming in the summit area in 1977–78 (Yokoyama and others, 1981). Several distances at Mount St. Helens and Mount Hood were measured in 1972 but were not remeasured prior to the reawakening of Mount St. Helens in 1980. Several distances were measured twice at Mount Hood in the summer of 1980, owing to an earthquake swarm, but no complete network was established and no significant changes were observed.

In mid-April 1980, measurements of distances and angles were initiated at Mount St. Helens, primarily to monitor the rate of deformation of the bulge on the north side of the volcano. Displacements of 1.4–1.6 m/day were measured on the bulge prior to May 18, but there was little or no significant change outside the bulge area (Lipman and others, 1981). A complete EDM network was established at Mount St. Helens shortly after the catastrophic eruption on May 18, 1980 (Swanson and others, 1981; Iwatsubo, Topinka, and Swanson, chapter 8).

Monitoring networks were established at other volcanoes in the Pacific Coast States, including Augustine Island, Alaska, between 1981 and 1989 (fig. 10.1; table 10.1). All networks, except the Medicine Lake and partially completed Mammoth Lake networks (both installed 1989), have been reoccupied at least once. Periodic reoccupation of these networks is planned as part of an overall long-term monitoring program. Reoccupation serves as a check on previous data, solidifies the baseline information, and provides an assessment of the state of the volcano.

Techniques and equipment developed in the 1980's have helped to reduce costs for monitoring volcanoes without compromising the precision of the data. We explain in this report the techniques and procedures used by Cascades Volcano Observatory (CVO) scientists to measure distances at volcanoes. For

Table 10.1. List of years when each volcano has been measured
[Not included is Mount St. Helens, which has been monitored continuously since 1980. No networks were occupied in 1987]

Volcano	1981	1982	1983	1984	1985	1986	1988	1989
Augustine							X	X
Mount Baker	X		X					
Mount Rainier		X	X				X	X
Mount Hood			X	X				
Crater Lake	X	X	X	X			X	
South Sister					X	X		
Newberry					X	X		
Medicine Lake								X
Mount Shasta	X	X		X				
Lassen Peak	X	X		X				
Mammoth Mountain								X

further information on general trilateration and distance-measuring techniques, see Brinker and Minnick (1987) and Davis and others (1981).

EQUIPMENT

Most of the equipment used for surveying can be purchased commercially (see appendix). The methods we use to install bench marks and to measure distances, angles, barometric pressure, humidity, and air temperature are described below. These methods, in use in 1990, have been evolving since 1981 and should continue to improve in the future.

Bench-mark Installation

All bench marks installed are 10-cm-diameter brass bench marks with 7-cm stems that are cemented into bedrock or large boulders (Chadwick and others, 1985). Holes approximately 2.5 cm in diameter are bored into the rock, mainly by hand, using a masonry star drill. The bench marks are stamped with the station name and year of installation. A fast-curing cement (15 minutes curing time) is used to cement bench marks in place, because they are commonly installed at high elevations where the possibility exists of freezing, which destroys regular cement (24-hour curing time). Immediately after initial installation, we shade the bench mark and cement from direct sunlight to prevent cracking of the hardening cement. EDM bench marks can be used immediately after installation, but it is better to wait at least 24 hours to allow complete hardening of the cement. See Doukas and Ewert (chapter 11) for further discussion of bench-mark installations.

Surveying Equipment

We have used two EDM's that can measure distances up to 10 km, which is the longest distance measured in our monitoring program. The typical measured distance is 3 to 5 km. The majority of horizontal deformation work in the Cascades and other volcanoes is completed by helicopter and short excursions by foot, so the EDM must be portable. From 1981 to 1988, we used a Hewlett-Packard (HP) model 3808A (no longer manufactured); in 1989, we purchased a Geotronics model Geodimeter 114, which is much

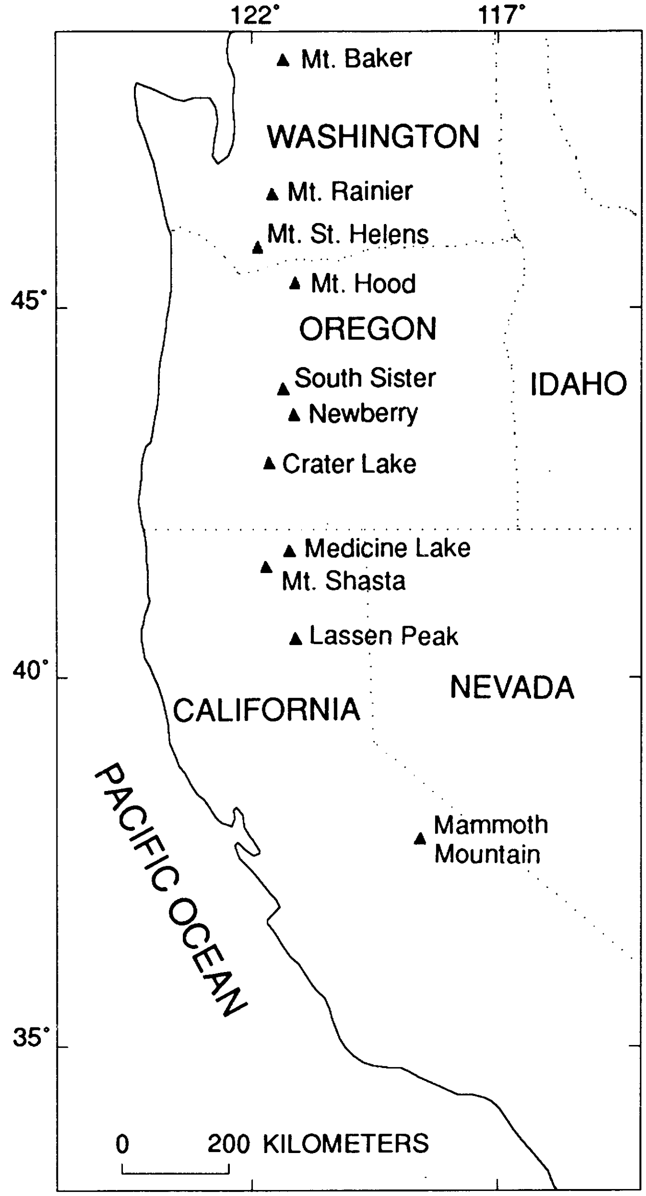


Figure 10.1. Volcanoes at which personnel of Cascades Volcano Observatory have installed horizontal-deformation monitoring networks. Not included is Augustine Island, Alaska.

Table 10.2. Specifications for HP3808A and Geodimeter 114

[Weight includes battery. Distances shown are those quoted by manufacturer for number of prisms on clear day (light haze or moderate sunlight) with light heat shimmer]

		HP3808A	Geodimeter 114
Prisms			
	1	3 km	6.5 km
	3	6 km	8.0 km
	Multiple	10 km (6)	9.0 km (7)
Weight		10 kg	2.7 kg
Size		345×318×283 mm	220×190×87 mm
Accuracy		±(5 mm + 1 ppm)	±(5 mm + 1 ppm)
Mount		Yoke	Yoke or Theodolite

smaller and lighter (table 10.2). Although the manufacturer's specifications for the Geodimeter 114 are better than those for the HP3808A, in practice our HP3808A is able to measure longer distances to the same number of prisms than the HP specifications state and farther than is possible with the Geodimeter 114.

The dimensions of an EDM are critical when used in moderate to high winds. The bulky HP3808A can catch wind and vibrate constantly, making it difficult to complete measurements. Each HP3808A measurement takes as long as 1 minute, depending on the length of the shot, even on calm days. When wind causes instrument vibration, measurement can take up to several minutes to complete and may even fail. The Geodimeter 114 takes 14–25 seconds for the first measurement, then repeats the measurement every 4.5 seconds. Often, the Geodimeter 114 can read 10 measurements before the HP3808A can measure one. This is a big advantage in marginal conditions.

The lightweight Geodimeter 114 is preferable for backpacking. A backpack frame is available for the HP3808A and is essential for most field applications; the carrying case for the Geodimeter 114 comes with straps that can be used as a backpack. Both EDM's use a 12-volt battery as the main power source. The HP3808A battery fits into the bottom of the instrument, whereas the Geodimeter 114 battery is connected to the EDM by an external cable. We advise purchasing an additional battery cable that can be used with a separate 12-volt sealed or automobile battery. This battery should be carried in the field as a backup power supply. If trips are planned to remote areas for extended periods and the recharging of batteries is impossible, several batteries must be carried.

The HP3808A has an internal telescope for sighting and is mounted on the tripod using its built-in yoke. The Geodimeter 114 does not have an internal telescope but can be used in two ways. The Geodimeter 114 is designed to fit on the telescope of the theodolite, which is used for sighting on the target. A yoke with a telescope (4–7× magnification) mounted on it can also be used, and we recommend purchasing the most powerful telescope (30× magnification minimum) available. Because of budget limitations we did not purchase the powerful telescope, and the 4–7× magnification telescope on the yoke is not powerful enough for our applications. Therefore we always mount the Geodimeter 114 on the theodolite.

When the EDM is yoke-mounted, the optical center or vertical axis of the EDM always remains the same, regardless of the tilt of the EDM. In other words, the EDM pivots over the center of the bench mark. However, when the EDM is mounted on a theodolite telescope, the optical center of the telescope pivots over the center of the bench mark, but the optical center of the EDM does not. The difference between the optical centers of the theodolite and of the EDM when tilted is the eccentricity error. To correct for this error, either a zenith or vertical angle must be measured and incorporated into the slope distance reduction. The formula to correct the slope distance (SD) for the eccentricity error (corr) is:

$$\text{corr} = e \cdot \cos(Z)$$
$$\text{corrected SD} = \text{raw SD} - \text{corr, where } Z < 90^\circ$$
$$\text{corrected SD} = \text{raw SD} + \text{corr, where } Z > 90^\circ$$

where e is the distance between the optical center of the theodolite and the EDM, and Z is the zenith angle (Bevin and Dip, 1983).

To measure zenith angles for the eccentricity error and to calculate station elevations, we use a Wild T2 (new style) theodolite. The Wild T2 is manually read to the nearest 1 second; any good-quality 1-second theodolite is recommended for measuring angles. The advent of microprocessors has revolutionized most surveying equipment, including the theodolite. Wild manufactures the T2000 theodolite, that is accurate to 0.5 second and digitally reads out to 0.1 second (Ewert, chapter 15). Its drawback for our purposes is its weight, 9.8 kg versus 6.3 kg for the T2.

Instruments and reflectors are typically mounted on Kern tripods with centering rods, but standard tripods with optical tribrachs can also be used. For more detailed discussion of tripods, see Iwatsubo and Swanson (chapter 6).

For reflectors, we use standard (accuracy within ±2 arc seconds), 7.3-cm diameter, glass corner-cube prisms in a triple nontilting mount assembly (a triad). When using the HP3808A, we carry two triads in each reflector backpack. For almost all of the measurements, two triads are sufficient. With the Geodimeter 114, four triads are carried in each reflector backpack, with 2–3 triads normally being set up for the average 3–5 km line. Recently, tilting mounts with smaller diameter (5.9 cm) prisms became available. Tilting mounts are superior to nontilting mounts when steep lines are measured, because they can be aimed directly at the EDM increasing the return signal strength. Steep lines can be measured with nontilting mounts but may require more reflectors.

Atmospheric System

Absolute barometric pressure, humidity, and air temperature are needed to correct the raw slope distance to an actual slope distance. The distance displayed by an EDM is based on some assumed standard atmosphere established by the manufacturer. Any deviation from the standard atmosphere must be corrected for. A correction of 1 part per million (ppm) is produced by

a 1 °C change in air temperature,
a 3.4 mbar change in barometric pressure, or
a 22.66 mbar change in water vapor pressure (Bevin and Dip, 1983).

Humidity has a very small effect on the measurements but nonetheless is included in all data reduction.

A complete atmospheric package, including pressure, humidity, and temperature sensors, is carried in all reflector and instrument packs. A barometric-pressure sensor we initially used to record barometric pressure performed well but was bulky, consumed considerable power, and needed frequent maintenance. A hand-held digital barometer/altimeter, model AIR-HB-1A, was purchased to replace the barometric-pressure sensor. The AIR-HB-1A is commercially available and has upgraded our barometric pressure measurements. It has a pressure range of 364 to 775 mm Hg with a resolution of 0.1 mm Hg; other specifications are listed in the Appendix. The size, capabilities, and ease of use of this unit make it ideal to be part of the atmospheric package. Another commercial barometer package is the Ultimeter model 12, which has a resolution of 1 mm Hg and a range of 330 to 787 mm Hg. Other pressure indicators, such as the Thommens altimeter/barometer, can be used but should be checked daily, before and after use, against a more accurate instrument (such as the AIR-HB-1A). Each of our reflector packs carries a Thommens altimeter as a backup for the AIR-HB-1A.

Humidity measurements above 0 °C are made using a sling psychrometer, which measures a dry- and wet-bulb temperature. When temperatures are below freezing, some other method must be found to measure humidity.

Air temperature is the most important atmospheric parameter measured. This is another area where we have improved our data collecting methods. Endpoint temperatures can be affected by ground radiation, but W.H. Prescott (unpub. USGS report, 1971) showed that measurement of temperatures 7 m or more above ground level can minimize this problem. We now use a telescoping, 7.6-m-long fiberglass rod as a pole for the temperature sensor. By using the 7.6-m rod in place of the previous 6-m poles (Iwatsubo and others, 1988), we have minimized the ground radiation effects. This longer rod is sufficiently sturdy to stand up in moderate winds and short enough (1.78 m collapsed) to be used in helicopter operations. The 6-m fiberglass poles are shorter (1.06 m collapsed) and lighter, and are still used when considerable hiking is required and there is enough wind to allow good air mixing, thereby helping to minimize ground radiation effects.

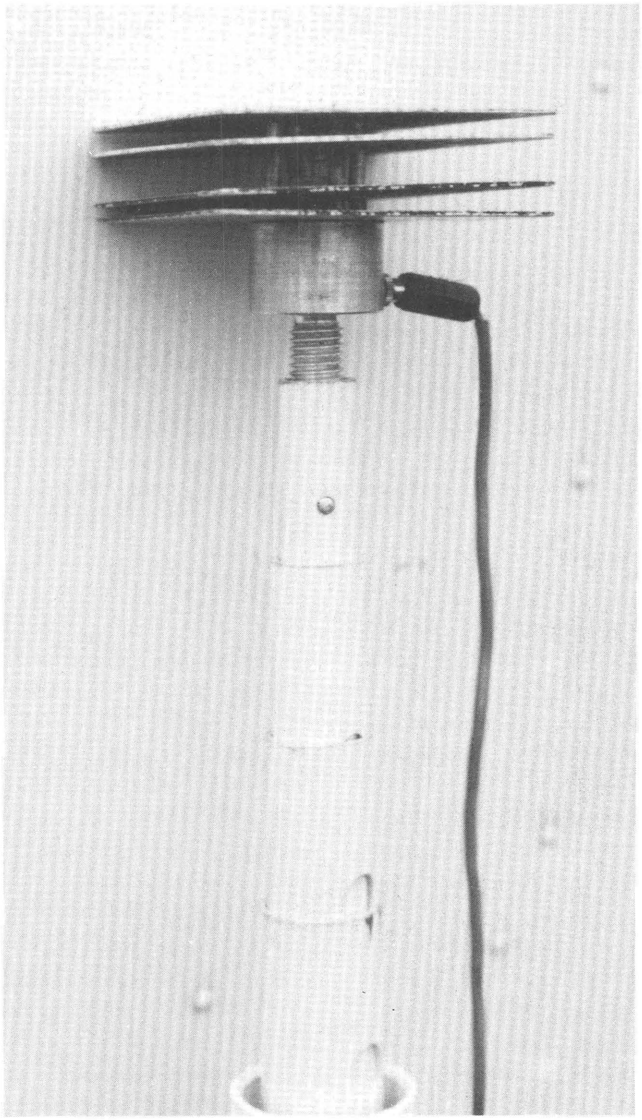


Figure 10.2. Temperature shield mounted on telescoping leveling rod. Sensor is mounted between two sets of parallel plates with wires connecting it to a plug on bottom of shield. Separate wire is then connected to box containing temperature-output display (fig. 10.3).

To avoid direct sunlight on the temperature sensor, a naturally aspirated shield is used to house the sensor. The shield consists of four thin aluminum plates 10 cm square, two above the sensor and two below (fig. 10.2). The pairs of plates are 5–7 mm apart, and the temperature sensor is mounted between the two pairs of plates, which are separated 1 cm apart. The shield is attached to the top of the leveling rod by threaded aluminum stock. The sides of each plate facing away from the sensor are painted white to reflect light, and the sides facing the sensor are painted black to absorb light.

Figure 10.3. Pelican case containing barometer/altimeter (left side), battery and 5-volt regulator (middle), and digital multimeter for temperature display (right side). Wire from temperature shield plugs into front of this box, just below handle.

This shield is lightweight and allows adequate air circulation.

A wire for power and signal output connects the temperature sensor to a separate box that contains the power supply, barometer, and a digital display for the temperature sensor. A foam resin case (47×39×17 cm; manufactured by Pelican Products, Inc.) that is airtight (with a pressure-release valve), corrosion free, and durable, houses this equipment (fig. 10.3). A central foam section that is easily cut to tightly fit any instrument protects the equipment inside the case. After years of use, no damage has occurred to any of our cases.

We use a National Semiconductor LM335 precision temperature sensor powered by a 5-volt voltage reference; an LM78L05 reference is currently being used (fig. 10.4), but we will update to an REF-02 for better stability. A 12-volt sealed rechargeable battery (6.5 Ah), which allows long periods of use without recharging, powers the 5-volt reference. For short periods, a 9-volt transistor battery can replace the larger 12-volt battery. This is sometimes necessary, when it is not possible to carry both the larger battery and the case because of weight or bulk. The signal output of the temperature sensor is displayed by a digital 4½-digit Fluke multimeter. The LM355 sensor-output signal is a voltage that corresponds to the air temperature and is displayed to the nearest 0.1° K. A flow chart (fig. 10.5) shows the path taken to record air temperatures.

The temperature sensors are calibrated at least once a year against a more accurate quartz thermometer. An environmental chamber, quartz-thermometer unit (HP2804A with a fast-responding probe), data-acquisition unit (HP3421A), and a personal computer are used for calibrating sensors. The range of

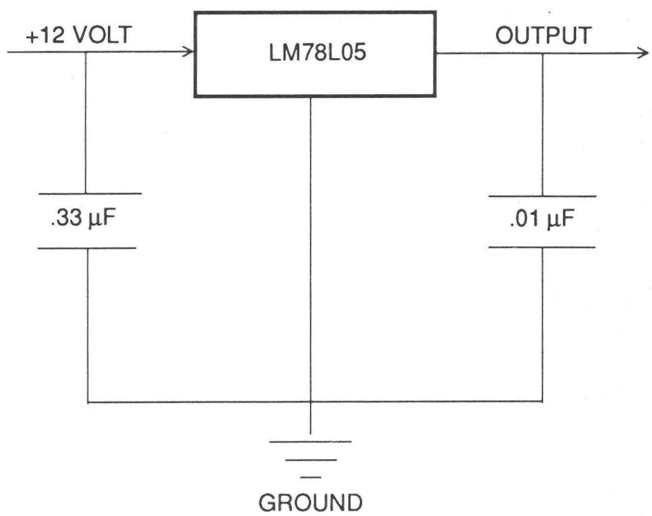


Figure 10.4. Circuit diagram of LM78L05 used to regulate voltage for temperature sensor. We will be swithching to a REF-02 for a more stable reference.

calibration is from -20 to 50 °C in 1 °C intervals (Iwatsubo and others, 1988).

All of the above equipment, except for the temperature rod and tripod, are packed inside a typical external-frame backpack. The tripod can be strapped to the backpack if desired. The pack is easy to carry and fits into a helicopter. These factors are important when setting up a system that must be portable.

NETWORK SETUP AND MEASURING PROCEDURE

Setting up a network starts with the best topographic map available, preferably one with vegetated areas marked on it. About six instrument stations are selected at the base of the mountain, approximately 60 radial degrees apart relative to the summit. Ideally each instrument station should be visible from the next station so that measurements can be made between them, but this is not critical and is commonly difficult to achieve. Next, we select reflector sites at medium to high elevations on the volcano that can be seen from at least two instrument stations. Reflector sites visible from three instrument stations are optimal. If only one instrument station can be seen and the line is considered important, then we install it. We try to form triangles when establishing stations and to connect the whole network together when possible. This ideal can sometimes be accomplished on a map but is rarely met when attempted in the field. Topography, vegetation, snow and ice cover,

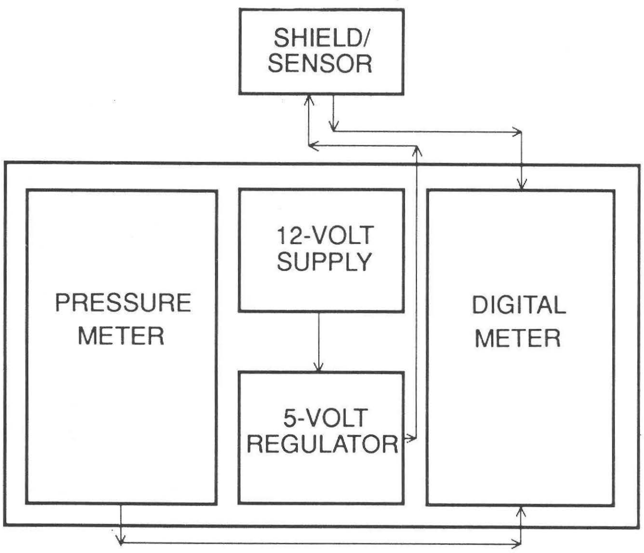


Figure 10.5 Flow chart representing atmospheric system. The 12-volt battery powers 5-volt reference, which in turn powers temperature sensor with its signal-output (temperature in kelvins) displayed by a digital voltmeter.

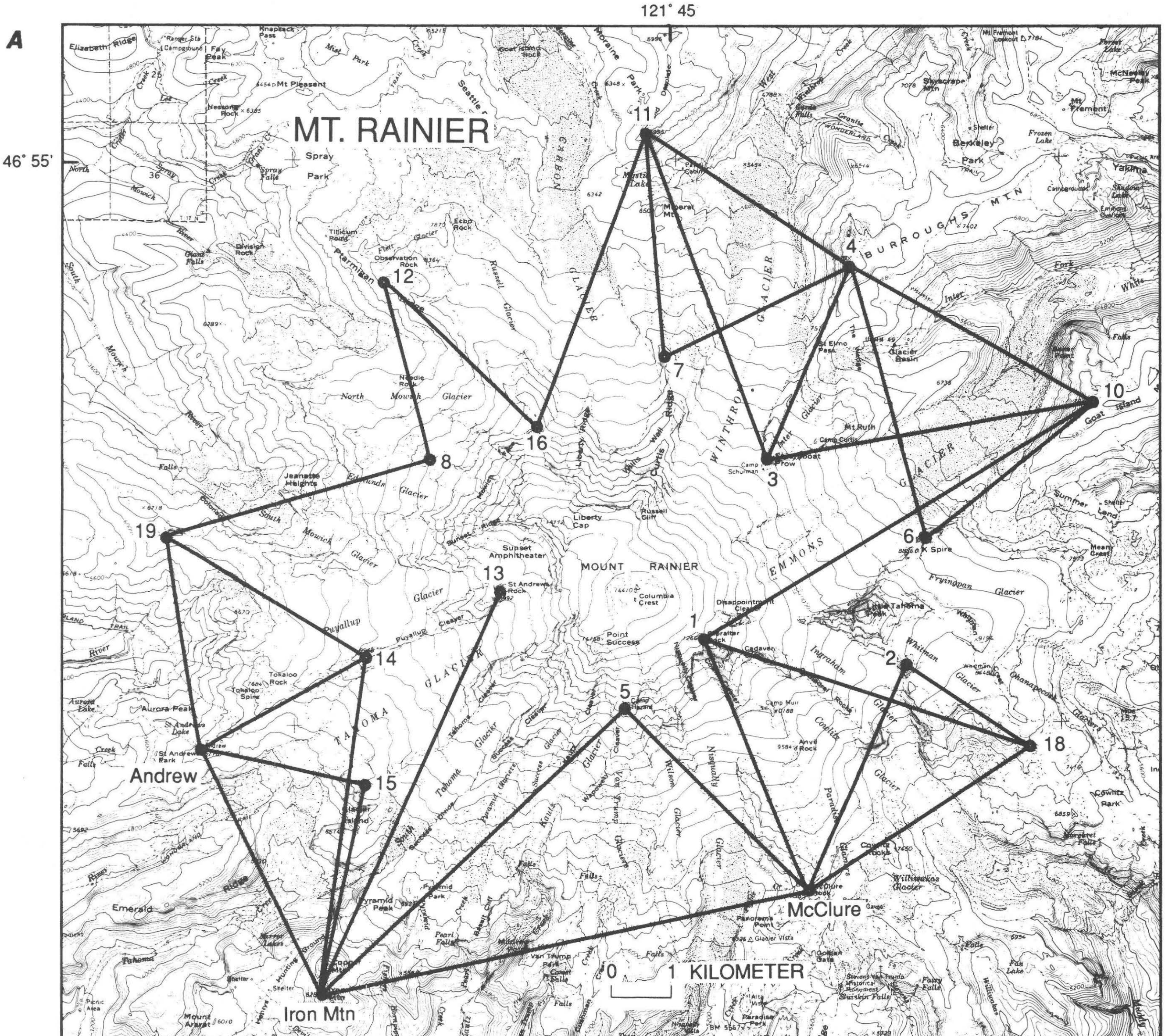
and bedrock outcrops ultimately dictate what can be established at any volcano. Examples of three monitoring networks are shown in figure 10.6 to demonstrate their diversity.

During installation of a network, one person occupies a potential instrument site, and one is located at each respective reflector site. If a solid rock outcrop or large boulder firmly set in the ground is present and visibility is good, the bench marks are installed. People move around the volcano until the network is completed. It is imperative that visual confirmation be made before the bench marks are set. There have been times when an instrument site had to be moved several hundred meters to complete a triangle or to be seen from more than one reflector station.

Bench-mark location descriptions should be written at the time of installation and should be improved when the station is reoccupied during the measurement of the lines. Writing clear bench-mark descriptions in the field is important, so that in the future someone who has never been to the bench mark can locate it. We try to be as complete as possible. Descriptions should include anything that can help locate the station, taking into account any seasonal effects such as snow covering the bench mark, fallen leaves in autumn, and possibly future human intervention. We have had problems with vandalism at some sites where bench marks have been removed or damaged. If we anticipate vandalism, we now bury the bench marks several tens of centimeters below ground and write a careful description of where one needs to dig. Photographs of the bench mark and surrounding rocks are very helpful.

We typically use four people to measure a network, two at the instrument end and two separate reflector people. All parties should have two-way radio communications for a number of reasons; among other things, this ensures that the atmospheric data are collected simultaneously. Most often, it is not possible to locate the reflector from the instrument station without the aid of a signal mirror. Both instrument and reflector people flash toward each other, enabling the instrument person to aim the EDM and the reflector person to aim the prisms. Sometimes a flash from the EDM end of the line can be reflected by the prisms at the reflector end, and there is no need for the reflector person to flash. On cloudy days, bright clothing, flags, or flares are useful. Once the reflector is sighted, the slope distance and zenith angle are measured. Two lines can measured before someone moves. Measuring the network follows the same procedure as setting it up; people move from site to site in a leap-frog manner until all the lines are completed.

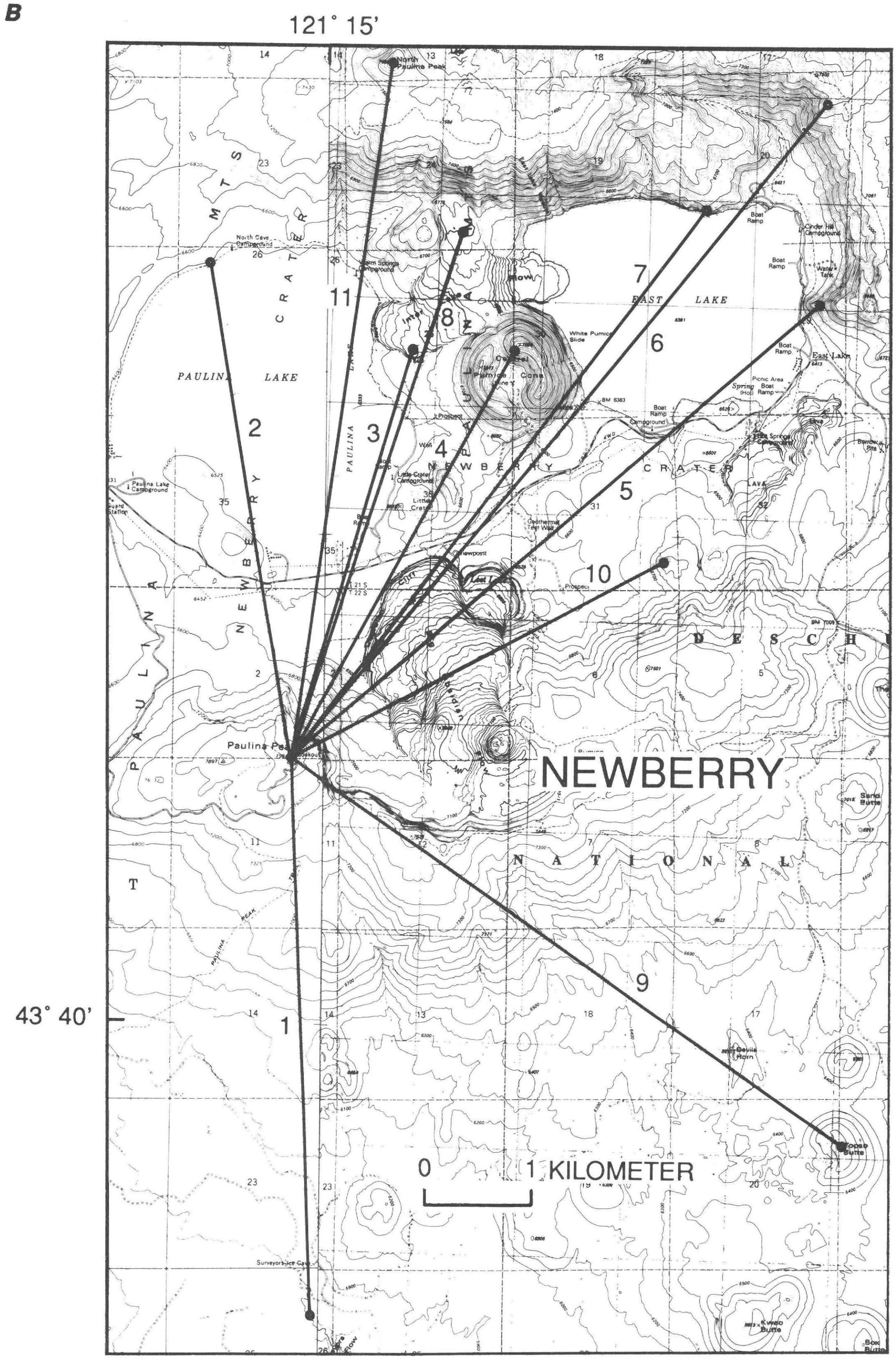
Complete recording at the instrument and reflector sites of all information necessary to reduce the data is critical but easily overlooked. A form that must be filled out completely before leaving the site is one way to minimize problems. We use a data sheet printed on "Rite-in-the-Rain" waterproof paper (fig. 10.7). Both the instrument and reflector people fill out appropriate parts of the same data sheet. Each backpack is assigned a number that corresponds to a specific calibrated temperature sensor and is referred to as the "BOX #" on the data sheet. Hence the same sensors, tripod, reflector set, and notebook are always together, thereby minimizing potential calibration problems. It is imperative that the height to the optical center of both the EDM and the reflector prisms be recorded in order to reduce the data (we reduce to mark-to-mark distances). The bottom lines on the data sheet are for recording angles. Miscellaneous notes can be recorded on the back of each sheet. Such notes might include the geometry of an unusual prism setup, sketches of landmarks, comments on weather conditions, or condition of the bench mark.



Base from U.S. Geological Survey, Mt. Rainier National Park, Wash., 1971, 1:50,000

Figure 10.6. Monitoring networks established at three Cascade volcanoes. Contours are in feet. *A*, Trilateration network at Mount Rainier, Washington. Numbers and names identify bench marks. Rainier network is a "typical" trilateration network. *B*, Distance-measuring network at Newberry, Oregon. Paulina Peak is on highest part of caldera rim, and all shots radiate down from it. This is an "atypical" network dictated by topography. Numbers identify each line. *C*, Another "atypical" network to monitor Crater Lake, Oregon. Line 1-3 was established as an independent measurement to check stability of 1-"Lodge" line.

B



Base from U.S. Geological Survey, Paulina Peak, Oreg., 1963, 1:24,000; and East Lake, Oreg., 1982, 1:24,000

Figure 10.6.—*Continued*

DISCUSSION

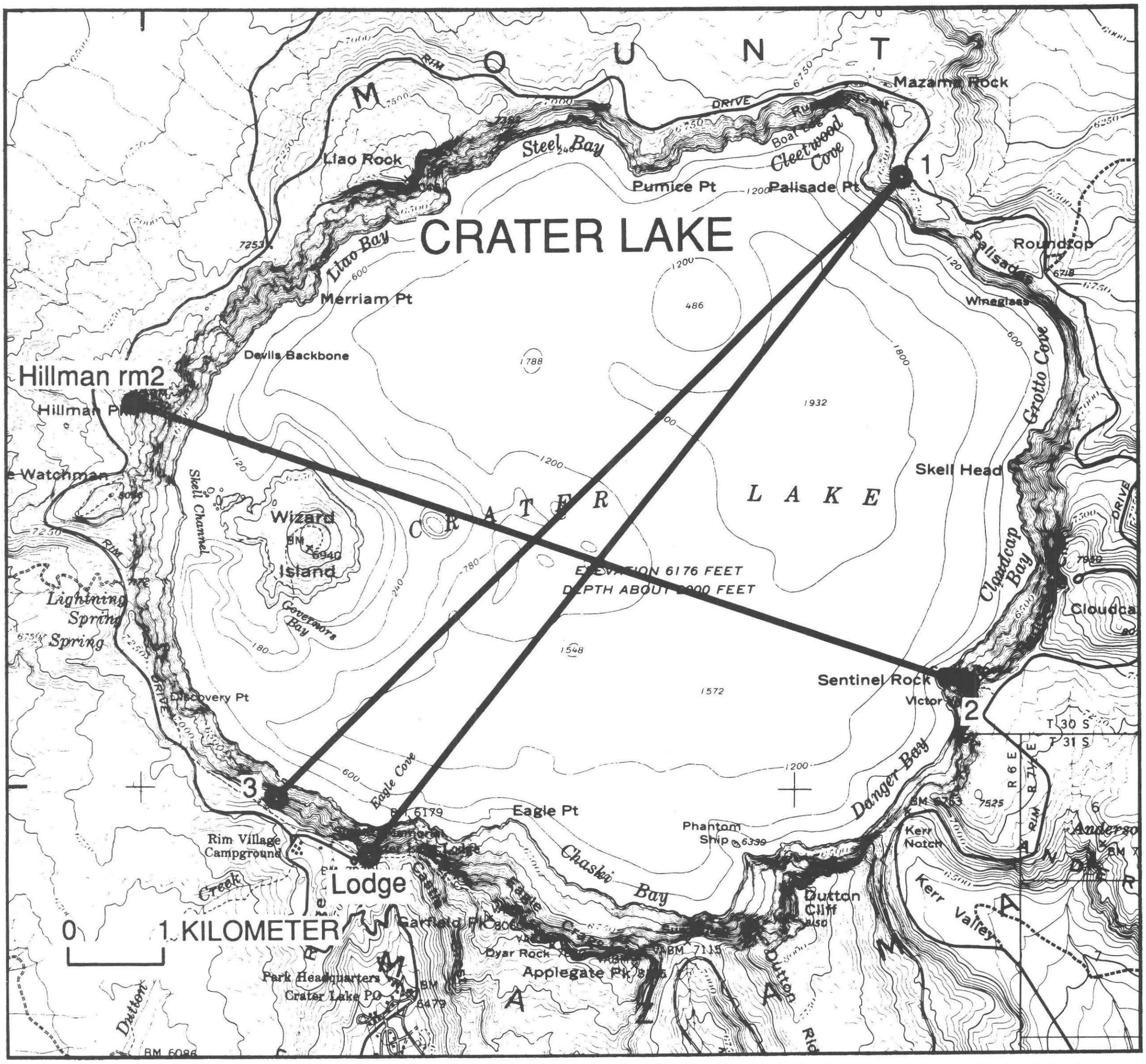
The type of equipment and methods used should be determined by the required precision of the data. If the project requires the highest quality data, expect large costs for specialized equipment and helicopter or airplane hours to fly temperature and humidity profiles along the lines. Precision of 3 mm and a proportional error of 0.2 ppm of line length can be attained using such methods with the greatest relative precision at longer distances (Savage and Prescott, 1973). However, we have found that owing to random errors, which include incorrect centering and inaccurate atmospheric conditions, systematic errors such as improper calibration and aiming errors (McDonnell, 1987), and bench-mark instability, our precision is ±(2.46 ±2.26 ppm) about any given distance. Such changes should be random and not define a pattern, but if a pattern is defined, the possibility of real deformation should be considered and an attempt should be made to reoccupy the network as soon as possible.

From 1981 through 1986, we used a helicopter to fly along each measured line and collect continuous temperature and humidity data. Barometric pressures were collected at each endpoint. An average index of refraction for the line path was calculated from this information and used in the data reduction. This is the standard procedure used for collecting high-precision strain data, when line lengths are typically 20–30 km and relatively flat, such as

C

122° 10'

42° 55'



Base from U.S. Geological Survey, Crater Lake National Park and vicinity, Oreg., 1956, 1:62,500

Figure 10.6.—*Continued*

those used in earthquake studies (Savage and Prescott, 1973). Lines measured on volcanoes are shorter and steeper and are very difficult to fly because they are in mountainous terrain where winds are typically strong and gusty. For these reasons, we compared distances calculated by using two-endpoint air temperature data obtained from the new 7.6-m rods with those utilizing the continuously recorded temperature and humidity data (table 10.3). There is little difference between the two sets of data; all of the differences are within expected error. Similar comparisons have been made for a number of networks with similar results. Consequently, we no longer fly the lines and have saved up to 50% on helicopter hours and time spent to complete a survey.

```
                 EDM RECORDING SHEET

INSTRUMENT?  RM/HP/LEITZ/GEOD 114/GEO 210

NETWORK______________  LINE NUMBER_____________

INST STA_____________  REFL STA________________

DATE ________________  TIME (LOCAL)____________


INST TEMP      ________ ________ ________  V/F/C

INST PRESS     ________ ________ ________  inHG/FT/MB

INST HEIGHT    ________  SH/HI   INST BOX # ________

GUN PERSON     _______________  W =______  D =______

REFL TEMP      ________ ________ ________  V/F/C

REFL PRESS     ________ ________ ________  inHG/FT/MB

REFL HEIGHT__________  SH/HI   REFL BOX # _____

REFL PERSON_______________  W =______  D =______

NUMBER OF TRIADS _______

DISTANCE:  M/FT

________  _______  _______  _______  _______
          _______  _______  _______  _______
          _______  _______  _______  _______
          _______  _______  _______  _______
          _______  _______  _______  _______


______ ______ ______        ______ ______ ______

______ ______ ______        ______ ______ ______
```

Figure 10.7. Data sheet used to record information during each measurement, printed on waterproof paper. The "W" and "D" spaces are the sling psychrometer wet- and dry-temperature readings.

Therefore, we have ultimately reduced the cost of each survey.

We have established networks on the following Cascade volcanoes: Mount Baker, Mount Rainier, Mount St. Helens, Mount Hood, Newberry, South Sister, Crater Lake, Medicine Lake, Mount Shasta, and Lassen Peak. Similar networks were installed at Augustine, Alaska, in 1988 and in late 1989 to help monitor Mammoth Mountain in eastern California. Repeat measurements of each network, except for those at Medicine Lake and Mammoth Mountain, both of which were first installed in 1989, have established baseline data (table 10.1).

Occasional reoccupation helps assess bench-mark instability, the major source of error in such networks. All the Cascade volcanoes have high snowfall, and bench marks are subject to severe freeze-thaw conditions. When establishing the networks, the best bench-mark location available at the time was chosen: in some cases this choice was dependent on the snowpack and led to incorrect assessment of bench-mark stability. Mount Rainier provides a good example of such a problem.

The network at Mount Rainier (fig. 10.6A) was established in 1982 and partially reoccupied in 1983. No major changes were seen during this interval. In 1988, a portion of the network was once again measured and larger than expected changes were seen on distances to several bench marks in an area where glacial-outburst flooding had periodically occurred since 1987 (T. Pierson, CVO, written commun., 1987). The distance to one reflector station high on the cone (station 13 in fig. 10.6A) had contracted 20 cm. Stations 14 and 15, both measured from Iron Mountain, had moved -0.036 and 0.057 m, respectively. We were uncertain if actual deformation was taking place, so the entire network was again measured in 1989. When the network was initially installed in 1982, the rock that contains bench mark 13 was mostly buried in snow and appeared to be solid. In 1989, after a winter with low snowfall, the person who installed the bench mark noted that the snow had melted away from the rock containing the bench mark, revealing that the rock was simply a loose slab lying on a rather steep slope and was clearly not stable. Data from the rest of the 1989 survey, stations 14 and 15 included, are within the expected error of the 1982 and 1983 surveys.

Potential bench-mark instability must be carefully watched. Instability can lead to large changes that may be interpreted as volcanic deformation. If there is no seismic activity and apparent deformation is seen, we look at the data very critically and do not accept them until the network has been reoccupied again and examined for bench-mark instability or atmospheric problems.

Table 10.3. Mark-to-mark slope distances (in meters) between lines where temperature and humidity were flown and lines where a temperature (elevated up to 7.6 m) and humidity were measured at each endpoint

[In both cases, barometric pressure was recorded at each endpoint. ppm, parts per million]

Line flown	Two endpoints	Difference	
		m	ppm
2612.3428	2612.3425	-.0003	-0.11
5142.2388	5142.2304	-.0084	-1.63
3787.7485	3787.7478	-.0007	-0.18
4567.9478	4567.9472	-.0006	-0.13
3229.0068	3229.0069	.0001	0.03
3155.4868	3155.4855	-.0013	-0.41
3944.7571	3944.7550	-.0021	-0.53
3134.0022	3134.0064	.0042	1.34
2073.8518	2073.8512	-.0006	-0.29
3559.6423	3559.6407	-.0016	-0.45
4558.1172	4558.1149	-.0023	-0.50
3241.0857	3241.0888	.0031	0.96
3243.4739	3243.4814	.0075	2.31
3823.2954	3823.2971	.0017	0.44
5079.7373	5079.7372	-.0001	-0.02
6681.5571	6681.5542	-.0029	-0.43
6101.5864	6101.5870	.0006	0.10
6391.9248	6391.9245	-.0003	-0.05
7573.0171	7573.0166	-.0005	-0.07
4461.7808	4461.7804	-.0004	-0.09
3502.0552	3502.0570	.0018	0.52
4507.9756	4507.9696	-.0006	-0.13
2814.4336	2814.4325	-.0011	-0.39
3014.4924	3014.4950	.0026	0.86
2717.0093	2717.0099	.0006	0.22

SUMMARY

Baseline horizontal-distance data have been collected on many potentially active volcanoes. We have saved considerable time and money by continually improving monitoring methods without compromising the data. We have seen that, despite care during installation, bench-mark instability remains a problem and could potentially be misinterpreted as real deformation.

The equipment and methods described in this paper are more than adequate to meet the precision for baseline data. Equipment and methods will no doubt continue to improve over the years, and as networks are reoccupied the baseline data on volcanoes in the Pacific Coast states will also continue to improve, statistically.

The intent of this paper was to describe the equipment and methods used at CVO to monitor volcanoes. We hope that this may serve as a guide for establishing equipment needs, methods, and procedures for similar projects elsewhere.

ACKNOWLEDGMENTS

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APPENDIX

Equipment list used at the Cascades Volcano Observatory to measure distances at volcanoes other than Mount St. Helens.

Site Installation

Bench marks -10-cm-diameter brass bench marks.
Star drill -3/4"–7/8" diameter.
Hammer-3-lb sledge.
Cement -Jet Set, fast-curing cement.

Surveying Equipment

EDM–HP3808A and Geodimeter 114.
Theodolite–Wild T2 (new style).
Tripods–Kern centering-rod style with adaptor plate. Any standard tripod with optical tribrach.
Prisms–One-piece corner-cube glass prism, accurate to within 2 arc seconds.

Atmospheric Equipment

Temperature

Unmarked leveling rod, 7.6 m length, Mound City.
Sensor, National Semiconductor LM355.
Aspirated shield, made in-house.
5-volt regulator, National Semiconductor LM78105 or Precision Monolith Corporation REF-02
12-volt sealed battery, 6.5 Ah.
Circuitry for 5-volt reference, in-house.
Digital multimeter, 4½ digits, Fluke 8060A.

Pressure

Model AIR-HB-1A Barometer, Atmospheric Instrumentation Research Inc.
Specifications:
Temperature range: -10 to 40 °C
Size: 3.0×9.11×14.5 cm
Weight: 280 g
Power: 9-volt transistor battery
Ultimeter model 12, Peet Bros. Company.
Thommen altimeter/barometer.

Humidity

Sling psychrometer.

Box

Pelican case, Pelican Products Inc.

Accessories

Spare 12-volt sealed battery and battery cable for EDM.
Spare 9-volt batteries for digital multimeter and AIR barometer.
Water for sling psychrometer.
Backpack for HP3808A and backpack straps for Geodimeter 114 case.
Signal mirror.
Notebook and pencil.

11. Installation of Bench Marks and Permanent Reflectors for Geodetic Deformation Networks

By Michael P. Doukas *and* John W. Ewert

ABSTRACT

To measure deformation over a large area at an active volcano, instruments and techniques are borrowed from surveying and geodesy. We discuss several methods employed at the Cascades Volcano Observatory for installing bench marks and reflector prisms used to measure deformation. We emphasize a versatile system designed for ease of portability, compatibility of components, and quick and easy installation on restless volcanoes.

Instrument bench marks and reflector prisms are installed into bedrock by drilling holes or into unconsolidated substrate by constructing concrete foundations.

Backsights, lines measured away from the volcano to areas presumed more stable, are used to test the stability of EDM bench marks and are included in deformation networks to provide a means of checking the relative stability of the bench marks. Careful site selection, building as much redundancy as is practical into deformation networks, and frequent measurements provide a check on reflector site stability.

INTRODUCTION

Monitoring surface deformation of a volcano helps scientists determine the possible course of an episode of volcanic unrest. Deformation may be monitored remotely at selected points with electronic sensors (tiltmeters, displacement meters, or strainmeters) that send the data via radio telemetry to a central recording site. To measure deformation over a larger area, however, instruments and techniques borrowed from surveying and geodesy must be employed. In this paper we discuss methodologies employed at the David A. Johnston Cascades Volcano Observatory (CVO) for installing bench marks necessary to measure deformation with surveying instruments such as electronic distance meters (EDMs), theodolites, and leveling instruments.

Floyd (1978) described procedures to install geodetic bench marks used in the United States vertical-control network in considerable detail. These procedures are generally suited only to truck-supported, roadside installation of monuments, but the information about site selection with respect to substrate type and climate is complete and pertinent to the installation of bench marks on and around active volcanoes. We describe here a versatile system for installing bench marks and reflector prisms on volcanoes. This system was developed by personnel of the U.S. Geological Survey's Volcano Crisis Assistance Team (VCAT). The systems and methods are designed for ease of portability, compatibility of the components, and quick and easy installation of reference points. The methods described here are those we have found effective, but availability of materials and local field conditions may require modification. All permanent bench marks should be corrosion resistant.

BENCH-MARK PLACEMENT

Most geodetic methods used to monitor volcanoes are capable of detecting crustal movement of a few parts per million, although on some active volcanoes displacements can be several orders of magnitude greater. It is important to assure that any changes measured truly reflect volcanic behavior, not local ground dislocations caused by site instability or other nonvolcanic effects, such as ground creep and slumps or thermal, diurnal, or seasonal changes (Banks and others, 1989). Thus the two most important factors in bench-mark installation are site selection and proper installation.

Site Selection

General guidelines during site selection include the following: (1) establish EDM lines that are as short as permitted by logistical constraints and safety considerations in order to maximize precision; (2) take account of geologic structure, such as dikes and faults, when locating monitoring networks (for example, lines normal to dike trends are particularly useful); (3) locate level lines on competent ground and radial to the deformation source; (4) monitor as much of the circumference of the volcano as is possible; (5) locate instrument stations with clear lines of sight; and (6) choose site locations that have good access, to reduce the time required for reoccupation, and that are protected from inundation by volcanic products. Geodetic tilt and leveling measurements require arrays of bench marks set out in accordance with instrumental needs and topographic limitations (Dzurisin, chapter 12; Yamashita, chapter 14; Ewert, chapter 15). The location of a bench mark to be used as an instrument station in EDM networks depends on the range and precision of the instrument used, length of lines from reference point to prisms, number of prisms needed (fig. 11.1), and the degree to which the instrument stations are interconnected (Iwatsubo, Topinka, and Swanson, chapter 8; Iwatsubo and Swanson, chapter 10).

Caution should be exercised in choosing the location for a bench mark so that volcanic products, such as mudflows or ash falls, are not likely to bury the mark. Bench marks should be placed on the crests of ridges rather than on side slopes, for example. This also minimizes mark instability owing to surficial ground creep, frost action, and movements related to seasonal changes in ground-water hydrology.

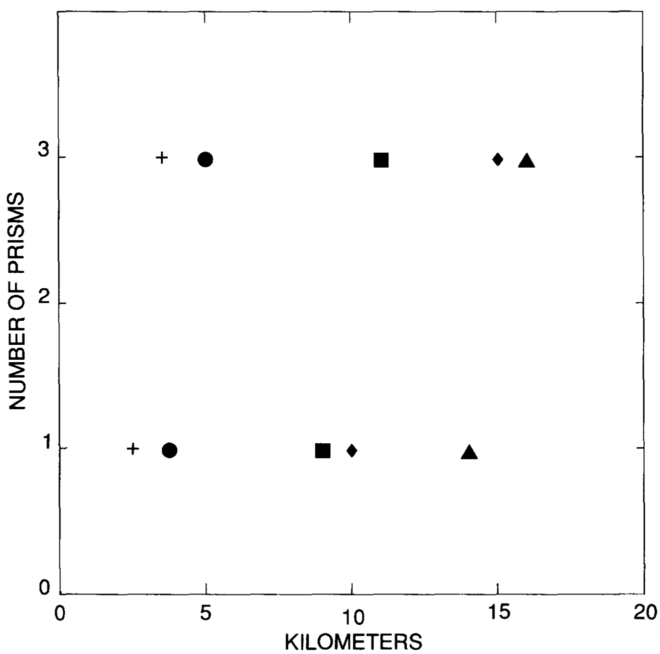


Figure 11.1. Average range and number of prisms required for five models of EDM. cross, Lietz model RED2A; dot, Wild model DI5; square, Wild model DI3000; diamond, Cubic Precision model Ranger Va; triangle, Geodimeter model 6000.

A bench mark set in bedrock is less susceptible to these effects than is a mark set in an unconsolidated substrate. An unconsolidated substrate requires more work, hardware, and concrete to support the bench mark and create a stable site. Bench marks used in single-setup leveling arrays should all be in similar substrate. Bedrock installations should not be mixed with unconsolidated substrate ones at any given single-setup leveling tilt site, because the thermal response of unlike substrates can be significantly different, resulting in spurious data (Sylvester, 1985).

Bench marks should not be located in areas that receive significant human traffic, to minimize the possibility of vandalism. If a mark must be placed at such a site, it is wise to bury the mark so it is not visible to the casual observer. Burial requires careful site description, so that the mark can be uncovered later. In general, a good description of the bench-mark location should be written with reference to landmarks not likely to be destroyed by an eruption.

Bench-mark Installation

Two general types of substrate characterize volcanic areas, competent rock (typically lava flow) outcrops and unconsolidated sediment (typically volcaniclastic material). Each type of substrate presents its own set of problems related to stable bench-mark installations.

Installation in Bedrock

A stainless steel anchor bolt is the quickest and easiest type of mark to install at a bedrock site. These bolts, key elements in our system, are used both as bench marks and as anchor points for reflector attachment. The bolt consists of a 100-mm shaft, threaded at the top (0.5 inch 13 National Course thread [1/2-13NC]), with a locking ring assembly at the base (fig. 11.2). The top of the bolt is center-punched to provide a unique reference point. Bolt-type bench marks can be used immediately after installation.

The tools required for installation of the bolt are listed in table 11.1. To install a stainless steel bolt, a hole is drilled the same size as the bolt but 88 mm deep using a star drill and hammer, or preferably a lightweight, hand-held, battery-operated hammer/drill with a carbide bit. The power tool can shorten the drilling time by a factor of 5–10, thereby decreasing exposure at potentially hazardous locations and increasing the number of stations installed per day. Rock fragments are blown from the hole using a plastic tube, and any plant or soil fragments are removed from around the hole. The anchor bolt is hammered into the hole until firmly seated (fig.

Table 11.1. Tools required for installation of anchor bolt or bench mark in rock

Field tools for installation of anchor bolts and bench marks
Hammer
Star Drill, 1/2 and 3/4 inch
or
Portable hammer/drill, battery operated
Batteries, with spares
Bit, 1/2 and 3/4 inch
Wrench, 3/4 inch
Plastic tubing, trowel, water, plastic sheet, mortor (1 part cement, 3 parts clean sand, 2 parts water)
Field tools and equipment for prism-mount assembly
Stainless steel anchor bolts, with nut and washer 4 inches long, 1/2-13NC thread
Bars, 1 1/2 inch × 8 inches long, four holes, 1/2 inch diameter equally spaced
Screws, hex drive, 1/4 inch × 2inch long, 1/2-13NC thread
Wrench, allen, 1/4 inch drive
Nuts, 1/2-13NC, washers

11.3). If the bolt is to be used as a leveling mark, its base should rest on the bottom of the hole. The bolt top is then peened with a hammer to create a rounded head on which a level rod can rest. If the bolt is to be used as an EDM mark, a cross is cut into the top of the bolt with a hacksaw. A nut is placed on the bolt and tightened, drawing the bolt slightly upward. This slides the locking ring on the bolt onto the conical wedge at the base of the bolt, expanding the ring to press against the hole walls and locking the bolt into place (fig. 11.3). In either case, the bolt cannot be removed without breaking the rock that holds it. A mortar patch is then placed around the nut and head of the bolt to protect the installation from infiltration of water and to strengthen the site. The last step when working with mortar is to cover the patch with a piece of plastic or other material to help the patch cure properly (fig. 11.4).

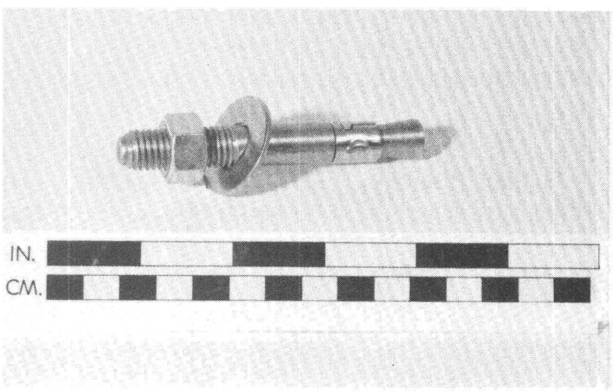


Figure 11.2. Stainless steel anchor bolt. Length is about 9 cm.

Formal bench marks in use at CVO are made of brass with a disk approximately 100 mm in diameter and a stem approximately 88 mm long (fig. 11.5). Identifying labels and numbers are generally stamped on the upper surface of the bench mark, a procedure not possible on a bolt-type installation. Bench marks used for EDM work have a flat disk with a cross in the center, whereas those used for precise leveling and single-site leveling have a nipple in the center that serves as a turning point. Two general types of stems have been used: a solid or hollow stem, round in cross section, and a solid, fluted and twisted stem. The fluted twisted shape gives the bench mark better grip in concrete than the round cross section, once the concrete has properly cured. The tools required for installation of a brass bench mark into bedrock are listed in table 11.1.

To install a brass bench mark in a bedrock site, a fairly level area on an outcrop that is not highly fractured or jointed is selected. A 100-mm-deep hole slightly larger than the stem is drilled. A plastic tube is used to blow the rock dust from the hole and immediate surroundings. Any soil or plant material is also removed from the area around the hole. The bench mark is placed

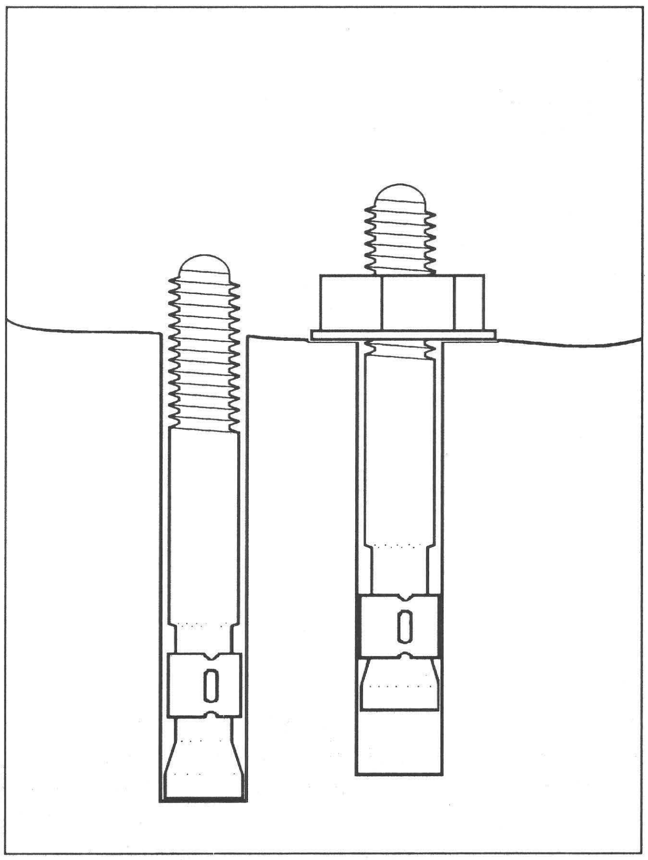


Figure 11.3. Anchor bolt in bedrock. For vertical stability during single-setup leveling, bolt is firmly seated (left); for horizontal stability during EDM monitoring, bolt is drawn up slightly (right).

in the hole to see that it fits properly and that the disk rests flush on the rock surface. The surface in and around the hole is wet slightly to improve the holding power of the mortar. Mortar is then mixed and placed in and around the hole. If a hollow-stem bench mark is being used, the stem and concave underside of the disk are filled with mortar. The bench mark is placed in the hole and seated firmly in the mortar. Mortar may be added around the rim of the mark to slightly cover the top edges. The last step, when working with mortar, is to cover it with a piece of plastic or cloth to help it cure slowly and properly. The bench mark can be used immediately as an EDM reference point, but the concrete must be allowed to cure for 12 to 24 hours before using the bench mark for leveling (fig. 11.6).

Installation in Unconsolidated Substrate

If a bedrock outcrop is unavailable, a foundation for the bench mark must be constructed. In areas where the ground freezes, the foundation must reach below the local frost line to prevent frost heave.

The preferred method of installing a vertically stable bench mark installation in unconsolidated substrate is to attach the bench mark to a single length of rod that has been driven to as far as possible (to refusal) through the bottom of a shallow hole (fig. 11.7). This installation is not good for horizontal control work unless the mark can be prevented from sideways sway by backfilling around the mark. Two-meter-long stainless steel or copper-clad steel rods are driven with a gasoline-powered hammer/drill or sledge hammer. Total refusal is 25 to 30 seconds of operation of the hammer without movement. If total refusal is not met in the first 2 meters, a second rod is coupled to the first with a threaded and crimped coupling, and driving is resumed. This procedure is repeated until total refusal. If the supply of rods is exhausted or total refusal not achieved, the bench mark should be identified as potentially

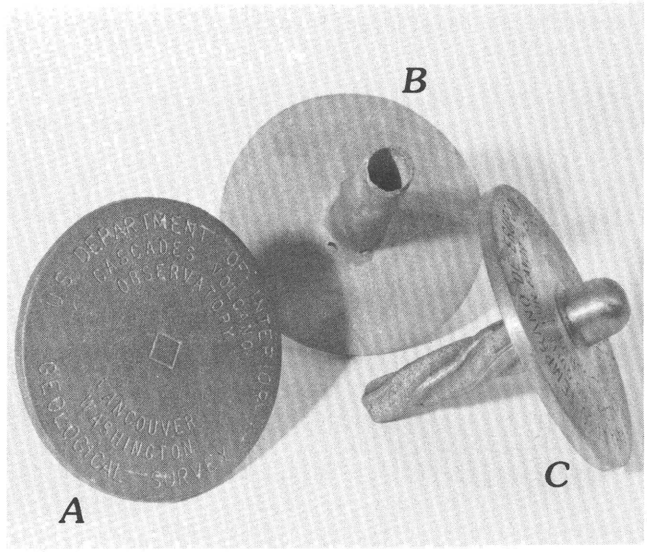


Figure 11.5. Types of bench marks. *A*, Bench mark for EDM monitoring with labeled, flat upper surface; *B*, hollow-stem bench mark; *C*, nippled bench mark with fluted stem for use in precise leveling networks.

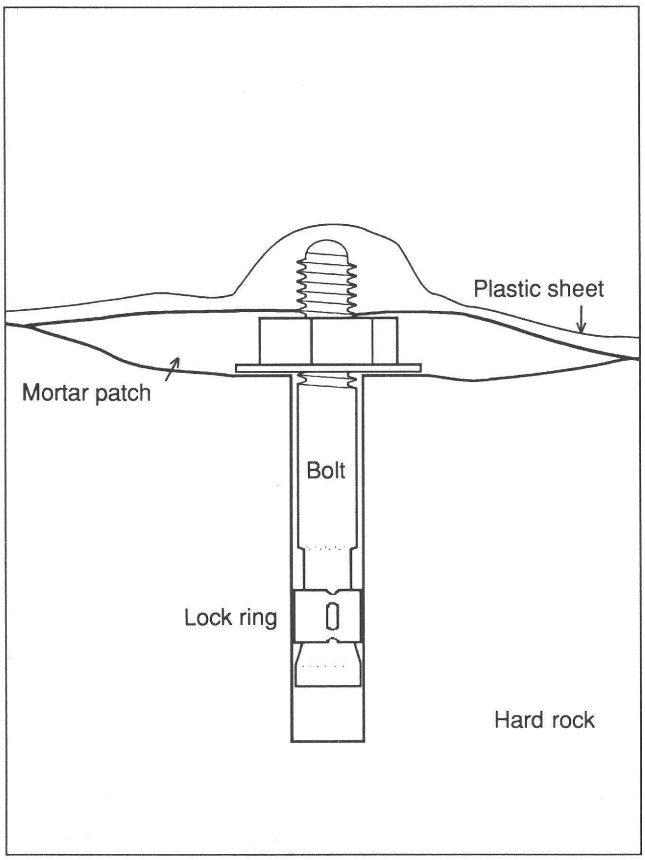


Figure 11.4 Anchor bolt in place with mortar patch and plastic sheet.

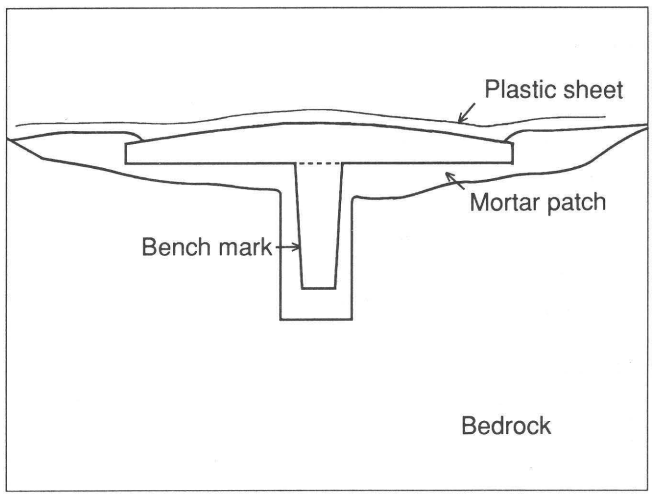


Figure 11.6. Bench mark installed in hard rock.

Table 11.2. Tools required for bench mark or rod assembly installation and cairn construction in unconsolidated substrate

Field tools for installation of bench mark with gasoline powered hammer
Gasoline powered hammer (24 kg) Hammer bit (3 kg) Threaded head Gasoline Hydraulic crimper Crimper jaws Adjustable wrench 1/2 to 1 inch diameter copper-clad, threaded, weld rod, 2 m long with threaded couplings
Field tools for installation of anchor bolts, bench marks, and construction of cairns
Three 2-m reinforcement rods, 9-13 mm diameter Shovel, trowel, water, mortar, gravel, and stones Plastic sheet, mortar (1 part cement, 3 parts clean sand, 2 parts water)
Field tools and equipment for prism-mount assembly
Sleeve, (cut, drilled, tapped) 3 inches long, 1" I.D. 1/2-13NC thread 2-m reinforcement rods, 15 mm diameter Bars, 1-1/2 inches wide, 8 inches long four holes drilled 1/2 inch diameter Screws, hex drive, lock, 1/4 inch 2 inches long, 1/2-13NC thread Wrench, allen, 1/4 inch drive Nuts, 1/2-13NC, washers

unstable. In areas with deep tephra, the total rod length may approach 15–20 m. Once at refusal, the exposed portion of the rod is trimmed to the desired length and a hollow-stemmed bench mark is attached with a hydraulic crimper. The weight and bulk of the tools needed make this sort of installation better suited to truck- or helicopter-supported operations. Table 11.2 lists the tools and materials necessary for this type of installation, and Floyd (1978) gives more detailed descriptions of the method.

A foundation must be constructed when it is impractical to use the method described above. This method is best suited to areas where deep freezing is not a problem. A hole is dug about 0.75 m in diameter and about 1 m deep. Three lengths of 9- to 13-mm diameter (3/8 to 1/2 inch) steel reinforcement rod (rebar), approximately 2 m long, are driven through the bottom of the hole. If refusal is met before all the rod is in the hole, the end of the rod is cut and then bent over back into the hole. The hole is then filled to ground level with layers of rocks, mortared together around the rebar. Wetting the rocks will improve the holding power of the mortar. A pad of mortar is created on top of the stonework and the bench mark is then set into the wet mortar. More mortar may be added around the rim of the bench mark to slightly cover its top edge (fig. 11.8). The last step is to cover the pad with a piece of plastic to help the mortar cure properly. The tools required are listed in table 11.2.

If no brass bench marks are available, a stainless steel anchor bolt can be set in the mortar on top of the stone work. In this case, the nut and washer are threaded onto the bolt and the bolt is placed in the mortar upside down to maximize its holding strength (fig. 11.9).

PRISM ATTACHMENT SYSTEM

Dependable EDM monitoring of active volcanoes requires a horizontally stable reflector installation.

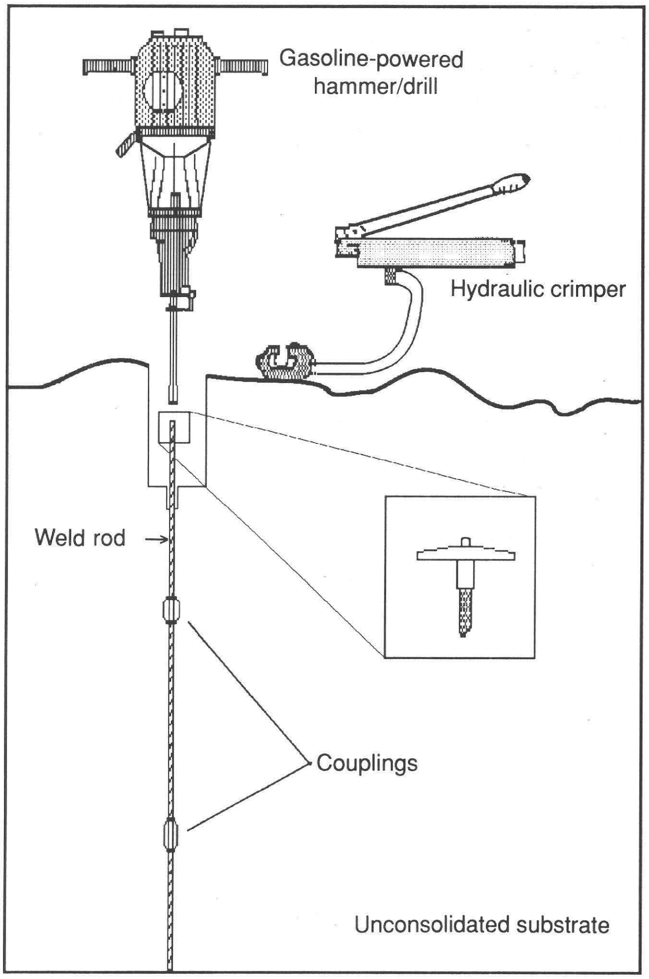


Figure 11.7. Use of gasoline-powered hammer/drill for driving steel rod into soft ground for installation of a bench mark. A hollow-stem bench mark is crimped onto rod after refusal has been reached.

Depending upon considerations of time, funding, safety, and accessibility, it may be more advantageous to place a permanent reflector on the volcano than to send a reflector crew onto the volcano's flank for each measurement.

At Mount St. Helens, permanent EDM reflectors are mounted on 3-m-high steel towers on the outer flanks of the volcano, so that they stand above winter snow. Similar towers, located off the flanks of the volcano, serve as instrument stations on which the EDM is mounted (Swanson and others, 1981).

These towers weigh more than 200 kg each and were placed by helicopter. This system works well for long-term studies (Iwatsubo, Topinka, and Swanson, chapter 8), but the amount of funding, fabrication time, and logistical support necessary to create such a network of stations precludes its use in rapid or short-term responses. On other Cascade volcanoes a mobile reflector system has been used (Chadwick and others, 1985; Iwatsubo and others, 1988, Iwatsubo and Swanson, chapter 10). The mobile reflector system is set up over an established bench mark at the reflector site and consists of a tripod, tribrach with optical plummet or a centering stem, prism holder, and prism(s) (fig. 11.10). This system works well on volcanoes that are monitored on an infrequent basis with helicopter support (Iwatsubo and Swanson, chapter 10). A distinct advantage in using a mobile system is that temperature and pressure data can be obtained at the reflector site by the reflector crew and the EDM data can then be better corrected for environmental conditions. However, use of the mobile system is time-consuming and requires more personnel to set up and measure.

During periods of volcanic unrest, the use of a mobile reflector system can place personnel at higher risk than may be appropriate. For such cases a lightweight, easy-to-install reflector kit was developed by VCAT members at CVO (see also Iwatsubo and Swanson, chapter 6). This kit consists of equipment for attaching the reflector directly to the ground, mounting hardware for attaching the reflector to the anchor, and a suitable reflector (tables 11.1 and 11.2). The kit's hardware is standardized to minimize the number of tools required during installation and to increase the versatility of any one component. The anchor bolts (1/2-13NC) are the same as those described in the bench-mark section of this paper. The permanent reflector generally requires one visit for installation and can be set up by one person. Some stations require extra time because of the need to

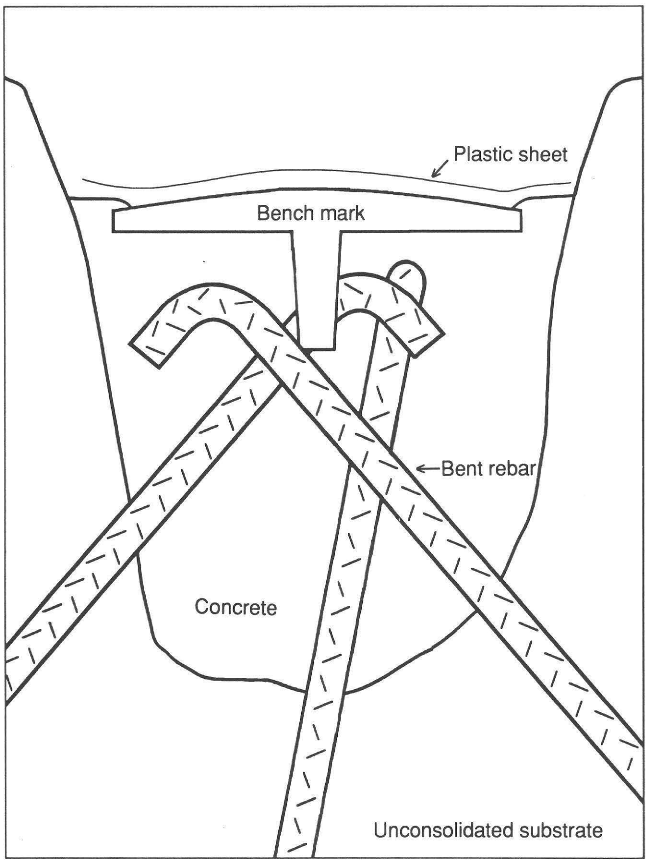


Figure 11.8. Bench mark installed in unconsolidated substrate, showing bent rebar and mortared stonework.

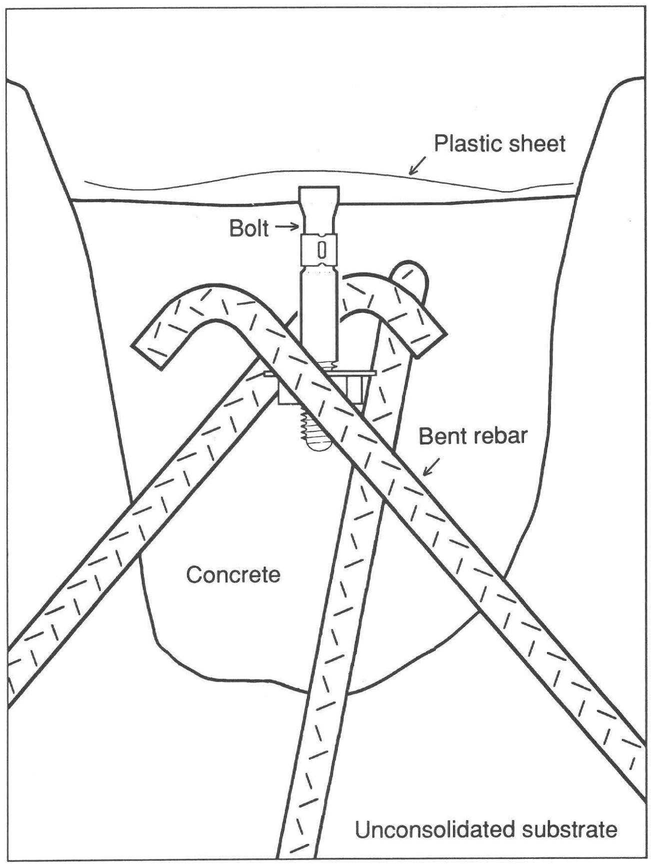


Figure 11.9. Installation of anchor bolt in mortared foundation. Anchor bolt is installed upside down for added stability.

protect against vandalism or volcanic activity. Shop tools are needed to thread the prism stud and prepare hardware before going into the field (table 11.3), and field tools are needed to attach the prism at reflector sites (tables 11.1 and 11.2).

As with bench marks, the anchor system for the reflector must be adaptable to either bedrock or unconsolidated substrate. Cliff faces with rock outcrops offer the best locations for prism installation because installation is quick and the prisms tend to be protected from the accumulation of volcanic products. To install a prism on a cliff face, a hole is drilled parallel to the line of sight from the EDM location to the prism, the stainless steel anchor bolt is driven in and secured (fig. 11.11), and the prism or a multiple-prism mounting

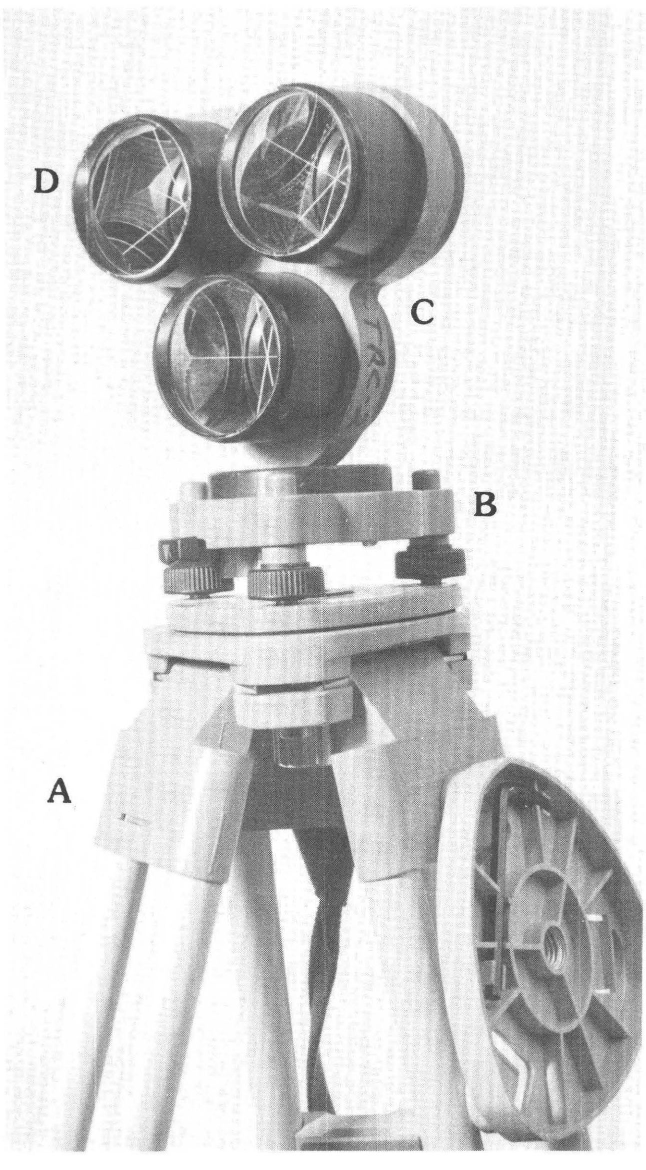


Figure 11.10. Typical mobile reflector system, including (A) tripod, (B) tribrach, (C) prism holder, and (D) prisms.

Table 11.3. Shop tools for preparing reflector prism and prism-mount assembly (sleeves and bars)

Tap set, handle
Tap, taper, 1/2-13NC, for sleeve modification
Tap, bottom, 1/2-13NC, for prism modification
27/64-inch bit, drill
Vise
Metal hacksaw
Electric drill, drill press

bracket is attached. The tools required for installation of an anchor bolt to bedrock are listed in table 11.1.

The general idea when working in unconsolidated substrate is to secure to the ground a length of rod to which a mounting sleeve and prism will be attached (fig. 11.12). For such an installation it is important to get the prism at least 50 cm above the ground level (preferably twice that or more) to minimize strong near-surface refraction effects. A stonework foundation, similar to that described for bench marks in unconsolidated substrate, may be necessary to support the rod. How much work goes into unconsolidated substrate installations will depend, to some extent, on how great the hazards are at a particular site and how long the monitoring activity is expected to continue. For example, at Mount St. Helens before the May 18, 1980, eruption, reflectors were merely affixed to steel fenceposts driven into tephra (Swanson and others, 1981). The tools required for installation of a reflector rod into unconsolidated substrate are listed in table 11.2.

The mounting system was designed to use the same basic, interchangeable hardware for any substrate encountered. The mounting hardware for EDM prisms consists of readily available, corrosion-resistant parts. The prisms we use are solid glass corner cubes in a plastic case. These have a hollow stud at the back that

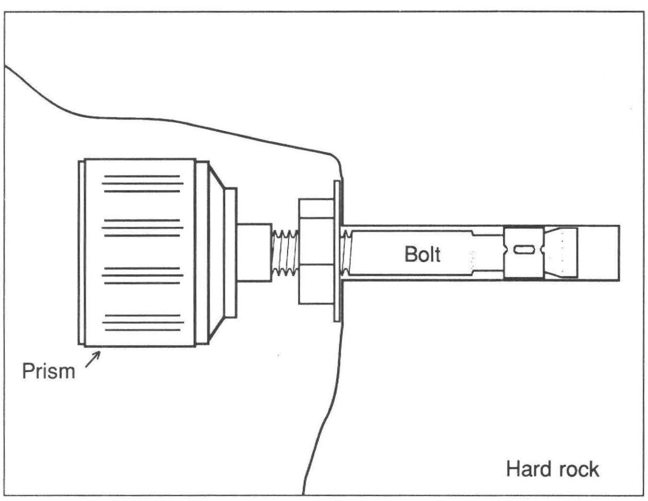


Figure 11.11. Anchor bolt installed in vertical cliff.

can be threaded to accept thread common to our system (1/2-13NC). Thus, a single prism can be attached directly to the threaded portion of the anchor bolt in a bedrock installation (fig. 11.13*A*). To install a multi-prism station a rectangular metal bar, long enough to hold two or three prisms is attached to the bolt, and prisms are attached to the bar (fig. 11.13*B*) using hex drive setscrews and nuts (table 11.1). The metal bar is 25 mm x 6 mm galvanized or painted steel with evenly spaced holes drilled to accommodate screws by which the prisms are attached. Another bar can be attached crosswise to accommodate more prisms.

A sleeve is placed over and attached to the anchor rod with a threaded setscrew (fig. 11.13*C*, table 11.2). The setscrew is secured with a nut. The sleeves are sections of steel pipe 35 mm outside dimension, 25 mm inside dimension (1.4 in. OD, 1 in. ID) cut into approximately 75 mm lengths. Holes are drilled and threaded to accept the screw size (1/2-13NC) common to the system. One prism or a rectangular metal bar of multiple prisms can then be attached to the setscrew (fig. 11.13*C*, 11.13*D*).

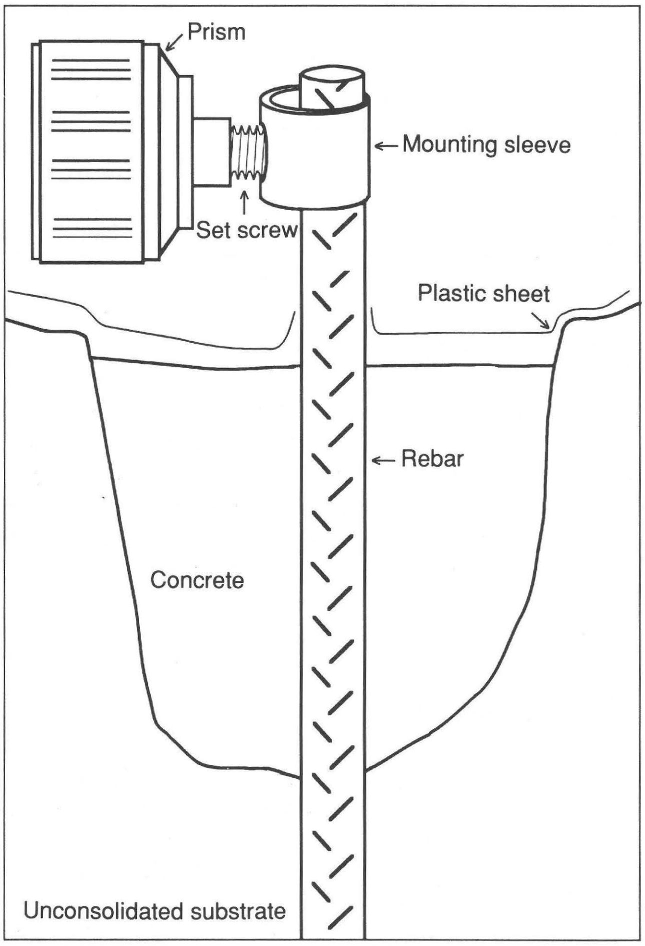
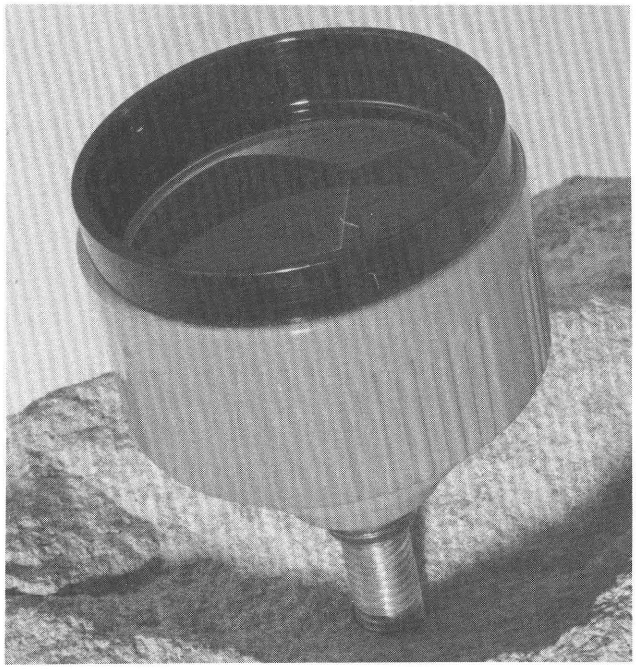
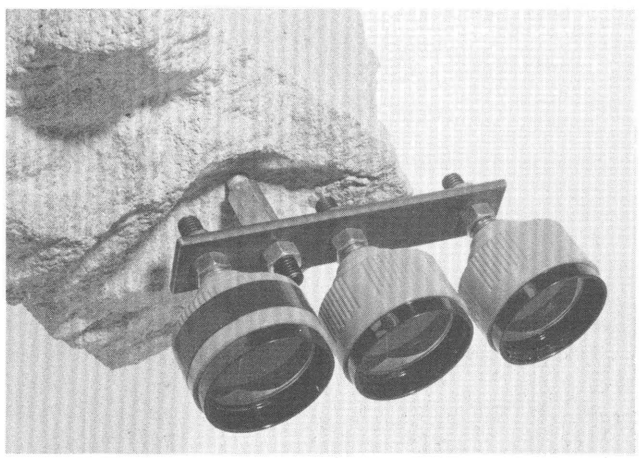


Figure 11.12. Mounting sleeve attached to anchor rod installed in unconsolidated ground.

Consideration should be given to protecting the monitoring station from volcanic activity, the weather, and vandalism no matter what type of anchor-mounting system is used. A projecting overhang might be found to protect the site at bedrock sites (fig. 11.11, 11.14). Artificial protection may be constructed, by drilling holes into the rock, placing rods into them, and using mortar or rock to construct a roof over the prism, or at locations of flat or sloping ground a protective cairn might be built out of concrete and rocks (fig. 11.14, table 11.2). This



A



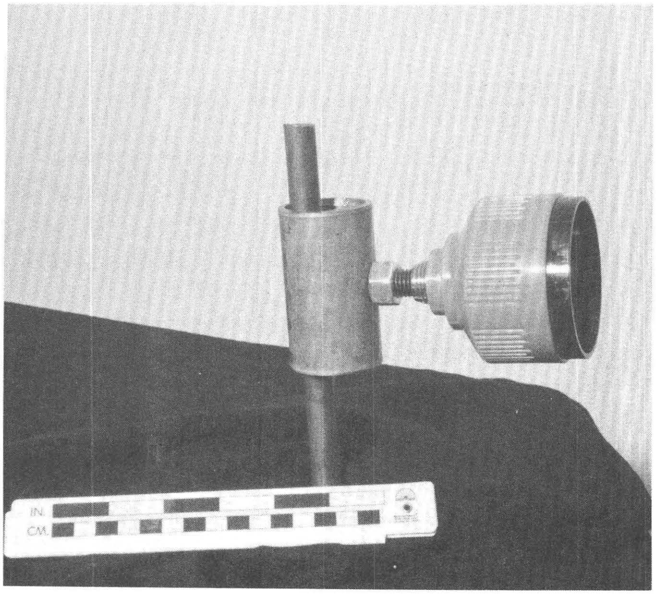
B

Figure 11.13. Single and multiprism assemblies. *A*, Single prism in rock site. *B*, Multiprism assembly in rock site. *C*, Single prism in unconsolidated ground site. *D*, Multiprism assembly in unconsolidated ground site.

cairn should be constructed around the rod or anchor surrounding the prism. Sometimes vandalism is difficult to avoid. One could remove the prisms during quiet periods or camouflage the station.

ASSESSING BENCH-MARK STABILITY

The stability of a bench mark should be continually evaluated after installation. Seasonal movement of the ground around the mark can give the false impression of deformation related to volcanism. Some method of checking bench-mark stability should be built into deformation networks. Backsights, lines measured away from the volcano to presumably more stable areas, can be used to test the stability of EDM bench marks (fig. 11.15). Single-setup-leveling and traverse-leveling arrays can have redundant bench marks to provide a means of checking the relative stability of the bench marks.



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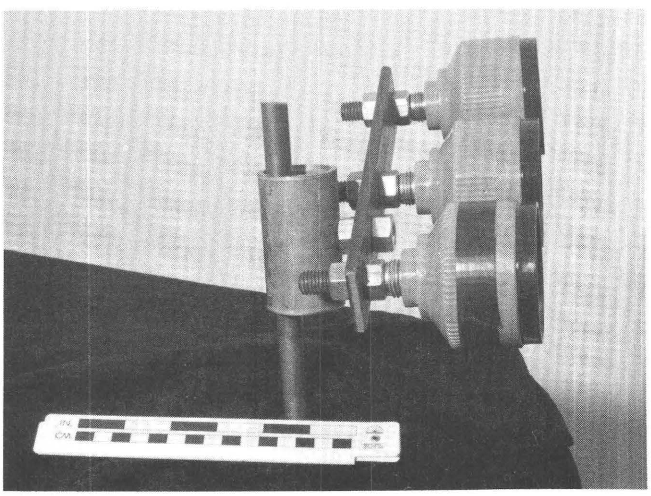

D

Figure 11.13. *Continued*

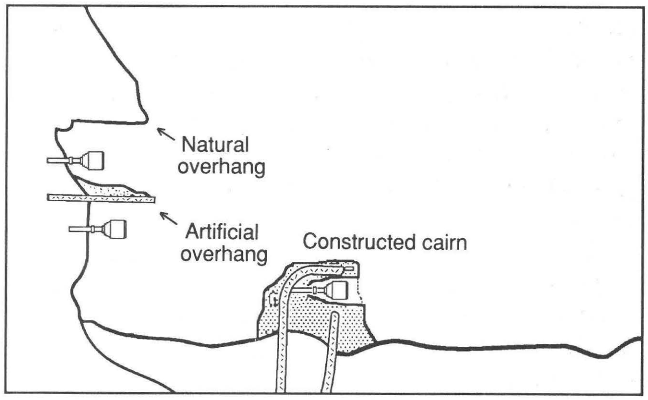

Figure 11.14. Three types of prism-protection schemes.

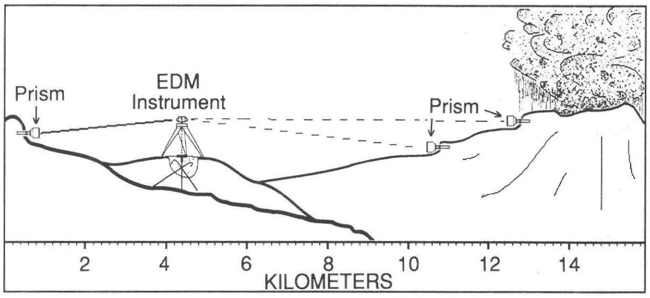

Figure 11.15. Relative position of EDM station with reflector at backsight station (left).

Reflector installations may also be subject to instability caused by environmental effects. We have found that careful site selection, building as much redundancy as is practical into deformation networks, and measuring the networks as often as possible are the best ways to eliminate uncertainty in what is being measured.

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12. Geodetic Leveling as a Tool for Studying Restless Volcanoes

By Daniel Dzurisin

Abstract

Although steep terrain, difficult access, hazardous conditions, and limited staff often discourage volcanologists from making geodetic leveling surveys at restless volcanoes, leveling has several advantages, including (1) greater precision for vertical displacements than virtually any other method over horizontal distances up to at least 100 km; (2) applications that range from single-setup leveling or short traverses designed to measure local ground tilt to long traverses that measure vertical displacements over broad areas; (3) sufficient redundancy based on field procedures and the large number of bench marks along a typical traverse to virtually eliminate measurement error and bench-mark instability as sources of uncertainty; (4) well-established procedures, relatively inexpensive equipment, and straightforward data processing; and (5) the utility of vertical displacement data as input for numerical models of the deformation source. Disadvantages include (1) substantial manpower requirements for long traverses; (2) logistical problems imposed by equipment that is difficult to transport to remote volcanoes and impractical to use in dense vegetation; and (3) the relatively slow pace of traverse leveling compared to other volcano monitoring techniques. An experienced first-order leveling crew of four to six people will traverse 3–6 km per day on mean slopes of 10 degrees or less, or 1–2 km per day on slopes of 10–30 degrees. Alternatively, a leveling crew can measure several short traverses or more than a dozen single-setup arrays in a day. The standard deviation of vertical displacements determined from successive first-order class II leveling surveys is 1 mm/km$^{1/2}$ × L$^{1/2}$, where L is distance along the leveling line (that is, ±3.2 mm/10 km or ±10.0 mm/100 km). At mafic volcanoes, on the lower flanks of stratovolcanoes, at large calderas, and in terrain between volcanoes along volcanic arcs, long leveling traverses can provide important information on large-scale ground deformation. In virtually any terrain and particularly during volcanic emergencies, short traverses are a useful tool to quickly determine short-term deformation rates.

INTRODUCTION

Scope

Geodetic leveling is a long-established technique used to measure elevation differences between successive bench marks and, by repeated surveys, to measure elevation changes (vertical displacements) as a function of time. Leveling has been used as a geodetic measurement system for more than a century (Vaníćek and others, 1980), and has proved its utility at several active volcanoes (for example, Wilson, 1935; Mogi, 1958). However, recent innovations in precise geodesy sometimes overshadow the considerable and enduring strengths of leveling as a volcano monitoring tool, to the extent that leveling is overlooked in situations where it could make a unique contribution.

The goals of this paper are to (1) discuss the advantages and disadvantages of leveling at restless volcanoes, (2) dispel some misconceptions concerning the feasibility of leveling in volcanic terrain, (3) illustrate the utility of leveling surveys through two examples, and (4) urge volcanologists to consider leveling a primary element in any modern volcano monitoring program. A companion paper by Yamashita and Kaiser (chapter 13) describes the procedures and equipment used for first-order class II leveling surveys. Detailed standards and specifications for leveling surveys of various orders and classes are described in manuals published by the National Geodetic Survey (Schomaker and Berry, 1981) and Federal Geodetic Control Committee (1974, 1975, 1984).

Terminology

During conventional geodetic leveling, a spirit level or other type of leveling instrument (most modern levels are self-leveling and do not include a spirit level) and a pair of graduated leveling rods (typically 3 m long, graduated every 0.5 or 1.0 cm) are used to measure the elevation difference between permanent bench marks by accumulating the elevation differences between a series of temporary turning points. The forward turning point (relative to the direction of the traverse) is called the foresight and the backward turning point is called the backsight. Typically, bench marks are spaced 1–3 km apart and turning points are 20–100 m apart (depending on steepness of the terrain). Adjacent turning points bound a setup and adjacent bench marks bound a section; measurement of a series of sections constitutes a survey.

Leveling surveys can be used to serve two different but often complementary purposes. Long traverses (typically 10 km and longer) measure near-absolute vertical displacements with respect to a distant bench mark or group of bench marks that is assumed to be stable. Short traverses (typically 1 km and less) measure relative vertical displacements among a small group of bench marks, usually for the purpose of determining local ground tilt. Single-setup leveling is a special case in which relative vertical displacements within a small array of bench marks are measured from a single instrument setup to determine local ground tilt (particularly useful when deformation rates are high or surveying time is very limited) (Yamashita, 1981; chapter 14). Each of these approaches has unique advantages and disadvantages that determine which one is most appropriate for a specific application, as discussed below. One effective strategy is to measure short segments of a long traverse periodically, then measure the entire traverse when significant changes are indicated.

ADVANTAGES OF GEODETIC LEVELING

Precision

Recent advances in satellite geodesy and other modern methods notwithstanding, conventional leveling is still the most accurate technique available for measuring vertical displacements over horizontal distances up to at least 100 km. Such dimensions are of particular interest in volcanology, because they apply to most of the processes that affect active volcanoes (except for plate tectonics and other regional tectonic processes). Therefore, unless there is a compelling reason to choose some other method (such as safety or logistics), leveling is the preferred technique for measuring vertical displacements at restless volcanoes.

Unlike emerging techniques for which measurement uncertainties are still being evaluated, the empirical accuracy of leveling surveys has been well established through decades of repeated surveys and comparisons with other methods. Leveling errors usually are categorized as blunders, systematic errors, and random errors. Blunders (gross reading errors, rod movement during a setup, recording errors) are easily detected, particularly by surveys that are double-run with dual-scale rods (Vaníček and others, 1980).

Systematic error accumulates in proportion to distance, elevation, or elevation gradient. Certain types of systematic error, such as those associated with imperfect collimation of the instrument, can be virtually eliminated through rigid adherence to prescribed field procedures. Other types, such as errors in rod length, can be tightly controlled through a combination of field and laboratory procedures, including frequent calibration against an invariant standard (calibrations available at the U.S. National Bureau of Standards). Two types of systematic error that have received considerable attention recently are refraction error (Strange, 1981; Stein, 1981; Holdahl, 1982) and magnetic error (Rumpf and Meurisch, 1981; Packard and MacNeil, 1983). Refraction error can be corrected using temperature-gradient data collected during the leveling survey or estimated from climate models. Magnetic error affects only self-leveling instruments, and it may vary from instrument to instrument or as a function of time with a single instrument. It can be eliminated by installing a magnetic shield (available as an option from the manufacturer).

Random error is introduced by inaccurate observations, nonsystematic imperfections in the equipment, and ever-present vagaries in atmospheric conditions. Random error generally can be diminished through redundancy, such as that achieved through double running and the use of double-scale rods (Vaníček and others, 1980).

The standard deviation of an observed elevation difference (OED) due to random error is given by

$$\sigma(h) = \sigma_0 L^{1/2}$$

where $\sigma(h)$ is one standard deviation in the OED between any two marks, σ_0 is a constant for each type (order and class) of leveling survey, and L is the distance along the leveling traverse. The contemporary value of σ_0 is 0.7 mm/km$^{1/2}$ for first-order class II surveys, 1.3 mm/km$^{1/2}$ for second-order class II surveys, and 2.0 mm/km$^{1/2}$ for third-order surveys (Vaníček and others, 1980).

For double-run segments, an estimate of σ_0 can be obtained from the discrepancies between forward and backward OED measurements using

$$\sigma_0^2 = \frac{1}{2m} \sum_{i=0}^{m} \frac{\delta h_i^2}{l_i}$$

where m is the number of double-run segments, h_i is the discrepancy between forward and backward OED measurements for section i, and l_i is the length of section i (Pelton and Smith, 1982). The empirical precision of any leveling survey can be estimated by double-running a representative number of sections and computing σ_0 from the equation above. If the computed value exceeds the desired standard, field procedures should be checked and the survey repeated. Experience of the U.S. Geological Survey and National Geodetic Survey shows that random errors associated with geodetic leveling (hence, the value of σ_0) are functions of the order, vintage, and character of the survey. For example, first-order leveling procedures in the United States currently are such that where L is given in kilometers, the estimated standard deviation in the OED between any two marks for class 1 and class 2 surveys is about 0.5 mm $\cdot L^{1/2}$ and 0.7 mm $\cdot L^{1/2}$ respectively. However, experience shows that the standard deviation for first-order leveling in general (class 1 and class 2) was about 2.5 mm $\cdot L^{1/2}$ prior to 1901, about 2.0 mm $\cdot L^{1/2}$ during the period 1901–1916, about 1.5 mm $\cdot L^{1/2}$ during the period 1917–1955, and about 1.0 mm $\cdot L^{1/2}$ during the period 1956–1974 (Vanícek and others, 1980). In practice, the standard deviation also depends on the character of the survey; that is, surveys in mountainous terrain generally have larger standard deviations than surveys in flatter terrain, partly because more setups are required to traverse the same distance in steep terrain and therefore random error accumulates faster. The best approach is to measure σ_0 empirically by double-running a representative number of sections and using the equation for σ_0 given above. For surveys that are entirely single-run, values of σ_0 such as those quoted above should be regarded as lower limits on the likely standard deviations in most cases.

The standard deviation of a vertical displacement (change in the OED between marks) measured between any two surveys, $\sigma(\delta h)$, is equal to the square root of the sum of the squares of the deviations for each survey. The standard deviation of the corresponding vertical velocity, $\sigma(V)$, is given by $\sigma(\delta h)$ divided by the time interval between the surveys (Pelton and Smith, 1982).

Figure 12.1 shows the random error in vertical displacements determined from contemporary leveling surveys of various orders and classes as a function of distance along the leveling route. The standard deviation of a vertical displacement between two bench marks separated by 1 km is 1.0 mm if determined from successive first-order class II surveys, 1.8 mm from second-order class II surveys, and 2.8 mm from third-order surveys. The corresponding values are 3.2 mm, 5.8 mm, and 8.9 mm for a separation of 10 km; and 10.0 mm, 18.4 mm, and 28.3 mm for a separation of 100 km. For successive first-order class II surveys, this corresponds to a precision of 1.0×10^{-6}, 3.2×10^{-7}, and 1.0×10^{-7} over distances of 1 km, 10 km, and 100 km, respectively. For comparison, the standard deviation of repeated GPS observations over distances up to 11 km is 4–6 $\times 10^{-7}$ (horizontal) and 1–2 $\times 10^{-6}$ (vertical). The standard deviation of GPS measurements increases only slowly with distance, such that at 225 km the precision increases to 3–5 $\times 10^{-8}$ (horizontal) and 2×10^{-7} (vertical) (Prescott and others, 1989).

Redundancy

Another advantage of leveling is built-in redundancy that serves to minimize two sources of uncertainty that plague other techniques. The first source is measurement blunders, which, as noted above, are easily detected and virtually eliminated by strict adherence to established procedures. When dual-scale rods are used, the elevation difference between foresight

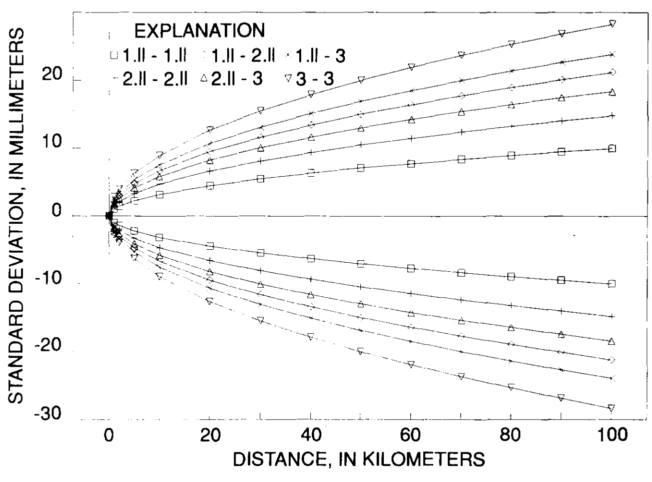

Figure 12.1. Standard deviation of vertical displacements measured by pairs of geodetic leveling surveys of various orders and classes as a function of distance. Explanation indicates types of surveys for each pair: 1.II-1.II refers to successive first-order class II surveys; 1.II-2.II refers to a first-order class II survey and a second-order class II survey, and so forth. Standards for various types of surveys are from table 1 of Vaníćek and others (1980).

and backsight is measured twice at each setup. The procedure for making the readings depends on the type of instrument used, but the concept is the same. The sequence of readings (backsight low-scale, foresight low-scale, foresight high-scale, backsight high-scale) includes a closure check on the stability of the turning points and the instrument (that is, the difference between low-scale and high-scale OED measurements at each setup must be less than a specified value: 0.30 mm for first-order class II surveys).

In our experience using this system over the past seven years, blunders rarely escape detection. The most common blunder is disturbance of the foresight rod, usually by wind, after the backsight rod and leveling instrument have been moved ahead to the next setup but before the disturbed rod has been measured as a backsight. When this occurs, the traverse must be repeated from the previous bench mark. A less obvious but equally serious error occurs if a setup is measured without first leveling the instrument. It is possible that such a setup would pass the low-scale/high-scale closure test (both OED measurements can be equally wrong). However, in most cases such an oversight would be obvious when viewing the rods through the eyepiece, or, if the instrument were significantly out of level in the direction perpendicular to the traverse, the setup would fail the low-scale/high-scale closure test. The only other error that has gone undetected is a bookkeeping error in which a failure of the low-scale/high-scale closure test goes unnoticed, and the survey proceeds to the next setup. This possibility has been practically eliminated by programming the recording device to output an audible tone and text message whenever the low-scale/high-scale closure criterion is not met (Yamashita, 1989).

A second source of uncertainty that is virtually eliminated by redundancy in geodetic leveling is bench-mark instability. Except for single-setup arrays, most leveling networks include a large number of bench marks with relatively close spacing, so anomalous movement of unstable marks generally can be recognized and discounted. This point is discussed below. In rare cases, movement of a single mark can indicate real ground movement (such as localized faulting), so it is important to consider the geologic context of each mark before discounting anomalous movements.

Even though unstable marks can usually be recognized, it is nonetheless important to install only the highest quality marks possible to ensure reliable results. This is particularly true for relatively short traverses with a small number of marks, and for any type of survey in steep or unstable terrain. The National Geodetic Survey classifies and provides specifications for various types of bench mark installations (Floyd, 1978; Federal Geodetic Control Committee, 1974, 1975, 1984). A thorough reading of these publications is absolutely required before marks are set by an inexperienced crew. The usual practice is to establish, at 1- to 3-km intervals, bench marks set in bedrock, stable manmade structures (preferably grounded on bedrock), and concrete posts, or secured to rods driven as deeply as possible (or to a stable stratum) with a jackhammer or sledgehammer. Large buried boulders and foundations not grounded on bedrock are sometimes used, but each traverse also should include an adequate number of high-quality bedrock or rod marks (preferably at least one every 5 km for long traverses, and one at each corner of short traverses and single-setup arrays).

Timeliness

A third advantage of leveling over more sophisticated techniques such as GPS is that leveling provides timely results that can be interpreted immediately in the field and factored into assessments of volcanic hazards. To maximize the accuracy of leveling observations, it is necessary to make a series of corrections that require access to a computer (Balazs and Young, 1982; Yamashita and Kaiser, chapter 13), but in most volcano-monitoring applications these corrections are small compared to the deformation signal. For example, the largest total correction along a 43-km leveling traverse across Yellowstone caldera that has been measured annually since 1983 is typically 2–3 mm, whereas the annual signal is 20–30 mm. In a more severe case along a 193-km leveling loop at Medicine Lake volcano, which included more than 600 m of elevation difference and atmospheric conditions that produced large refraction corrections, the largest total correction was 43 mm. This compared to a corrected closure error of 19 mm and a maximum subsidence of 389 ±43 mm from 1954 to 1989. Thus, except in very steep terrain or extreme climatic conditions, corrections to observed vertical displacements over distances of 1–100 km can be ignored in preliminary assessments of a volcanic hazard.

DISADVANTAGES OF LEVELING (REAL AND PERCEIVED)

Geodetic leveling, especially of long traverses, is not commonly used to study volcanic unrest worldwide (Newhall and Dzurisin, 1988). This may be due in part to a common misconception about the feasibility of leveling in volcanic terrain. Admittedly, long traverses require the efforts of several people for an extended period. A typical leveling crew of four to six persons (crew chief, two rod persons, a recorder, and up to two people to direct traffic) will average 1–6 km of first-order leveling per day, depending on the terrain. Only the crew chief need be experienced; other crew members require only a few hours of training to be effective. This is a substantial commitment, but it should be weighed against the precision and coverage afforded by long traverses. If staff support is limited or at times of rapid deformation or increased hazard, short traverses or single-setup arrays are a reasonable alternative to long traverses. This is especially true when deformation is so rapid that closure cannot be obtained on long traverses.

Another disadvantage of leveling is limited access to most of the world's active volcanoes: A road to the summit of a restless volcano is a rare luxury. However, leveling can be done along trails or across open country if the equipment can be transported to the vicinity of the volcano. In the absence of roads or trails, dense vegetation can be a serious obstacle, particularly at tropical or subtropical volcanoes. Helicopter support is a major advantage if the leveling rods can be safely transported. Even at remote sites with dense vegetation and no road access, short traverses or single-setup arrays usually offer viable alternatives to long traverses.

Time is another consideration that often weighs against long leveling traverses at restless volcanoes. Long traverses are marathons that require endurance, whereas short traverses and single-setup arrays are sprints that feature speed. It is true that a leveling crew can measure several short traverses or even 15–20 single-setup arrays in a day, but it is also true that the same crew can traverse completely around or over most volcanoes in one to two weeks!

As an example, two crews from the Cascades Volcano Observatory (CVO), each consisting of an experienced crew chief and four others (some with no prior experience), measured a 193-km leveling traverse at Medicine Lake volcano in northern California to first-order class II standards in nine crew-weeks during July–August 1989, at an average rate of 3.5 km/working-day/crew. Most of the route is over steep unpaved roads, with more than 600 m of elevation gain and loss. At Yellowstone caldera, where the topography is relatively flat, CVO crews average about 5 km/day/crew, so that a 43-km line across the caldera can be measured by one crew in fewer than 10 days. Even on the steep slopes of stratovolcanoes such as Pacaya and Fuego in Guatemala, a leveling crew can cover about 1 km/day (J. Marso and J.W. Ewert, written commun., 1989). When precision is a less stringent requirement than speed, second order surveys may be a wise choice. At Kilauea volcano in Hawaii, where large movements are associated with frequent eruptive activity, leveling crews from the Hawaiian Volcano Observatory average about 7 km/day for second-order class II surveys (K.M. Yamashita, written commun., 1989).

Other Considerations

Like any marathon, long leveling traverses can cause human fatigue that must be properly managed for the survey to be successful. Fatigue not only lowers morale but also increases the likelihood of blunders going undetected. Our experience at Medicine Lake, camping and working in a remote area, is that 2–3 weeks of uninterrupted leveling is an upper limit to ensure good morale and top performance. For longer surveys, crew members or entire crews should be rotated occasionally, or the work schedule should include adequate time for rest and relaxation.

The cost and availability of equipment is another issue to be considered. A first-order leveling instrument costs $4,000 to $6,000, a pair of Invar rods and stays (to hold the rods erect) costs about $5,000, and miscellaneous equipment including a recording system and temperature sensors costs an additional $1,000 to $2,000. The total cost of $10,000 to $13,000 is substantial but generally not prohibitive for volcano-monitoring projects with governmental support. Owing to its utility in engineering and general surveying applications, leveling equipment is available in most countries of the world.

Data processing requirements also must be considered, but they are no more severe for leveling than for most other surveying techniques (considerably less severe than for GPS surveys). Data recording in the field can be automated using a hand-held computer that is programmed to record rod and temperature readings, perform a low-scale/high-scale comparison at each setup, and calculate the backsight/foresight stadia imbalance, stadia distance, and observed elevation difference at each setup (Yamashita, 1989). Corrections for rod scale, temperature, refraction, and other effects (Balazs and Young, 1982; Yamashita and Kaiser, chapter 13) can be made at the conclusion of the survey, or even daily in the field using modern data recorders or computers.

RELATIVE ADVANTAGES OF LONG TRAVERSES, SHORT TRAVERSES, AND SINGLE-SETUP ARRAYS

Long traverses offer several distinct advantages over short traverses and single-setup arrays, but the latter type of measurement sometimes is feasible under conditions that preclude longer traverses. Perhaps the most important advantage of long traverses is the ability to determine near-absolute vertical displacements with respect to a reference outside the deforming area (also possible with vertical-angle or GPS measurements). The choice of a reference usually is arbitrary, but the resulting uncertainty can be minimized by extending the survey beyond the area of unrest as indicated by other observations (usually seismicity) and by considering the spatial pattern of vertical displacements. For most purposes, an adequate datum can be selected from among bench marks that (1) are located outside the identified area of unrest and (2) did not move with respect to each other during the period between leveling surveys.

A second advantage of long traverses is the redundancy inherent in a large number of bench marks. Short traverses are almost as good in this regard, but single-setup arrays are susceptible to large errors if redundant marks are not measured at each site. Consider the case of a single-setup array of two bench marks spaced 40 m apart. If one of the marks were to move vertically by 0.5 mm relative to the other owing to some extraneous process (thermal expansion or contraction, ground-water changes, cultural disturbance), the resulting tilt change would be given by 0.5 mm/(40×10^3 mm) = 12.5 microradians. On the other hand, if the same 0.5-mm displacement were to occur at one of the marks bounding a 1-km section of a leveling traverse, the indicated tilt change would be only 0.5 microradians. In addition, anomalous movements of several millimeters or more usually can be recognized and discounted if the unstable mark is one of several closely spaced marks. Three lessons from this example are that (1) long traverses are less affected by unstable marks than short traverses, (2) the more bench marks along a traverse, the greater the opportunity to recognize unstable marks, and (3) redundant marks always should be included in single-setup arrays.

The third advantage of long traverses over short traverses or single-setup arrays is the utility of spatially coherent data as input to numerical models of the deformation source. In theory, such models work equally well with measurements of vertical displacements or tilt changes as input. In practice, however, tilt measurements are more susceptible to extraneous small-scale effects than are vertical displacement measurements that span a much larger area.

The primary advantage of short traverses and single-setup arrays is speed. This is particularly important when surveying time is limited or deformation rates are high, as during volcanic emergencies. At such times, information from long traverses may not be timely enough, closure may not be possible, and it may be prudent to limit the exposure of field crews to volcanic hazards. Short traverses or single-setup arrays can be measured quickly with adequate precision for hazard assessment during the crisis; longer traverses can be measured later as appropriate.

EXAMPLES OF LEVELING SURVEYS IN VOLCANIC TERRAIN

The following two examples were chosen to illustrate the utility of leveling surveys in volcanic terrain as a tool for studying active magmatic and tectonic processes. Individual traverses range in length from 196 m at South Sister volcano to 193 km at Medicine Lake volcano. Measurement of the South Sister network of four short traverses requires one or two crew-days, while the Medicine Lake traverse requires about nine crew-weeks. Both networks were established as part of a CVO effort to obtain baseline geodetic measurements at each of the potentially active volcanoes of the Cascade Range.

South Sister Volcano: A Network of Short Traverses to Determine Tilt Changes

South Sister volcano is located along the Cascade volcanic chain in the Three Sisters Wilderness Area of west-central Oregon. The area has been the site of recurrent silicic volcanism during Pliocene and Quaternary time. Rhyodacite tephra, lava domes, and lava flows erupted during late Holocene time from more than 20 vents on the flanks of the volcano (Scott, 1987).

In 1985, CVO established a network of four linear leveling traverses ranging in length from 196 m to 317 m at South Sister (Yamashita and Doukas, 1987). The purpose of the network is to provide baseline geodetic information for comparison with future surveys, especially at times of volcanic unrest. Triangular or L-shaped arrays would have been preferable, but those configurations were precluded by the steep terrain. The flanks of the cone are sparsely vegetated, so the biggest obstacle to longer traverses was the steepness of the flanks. The traverses are located at elevations of 2,200 m to 2,500 m along radial ridges on the north, east, south, and west flanks of the volcano (fig. 12.2). In spite of numerous short (10 m and less) setups required by the terrain, the network can be double-run in one or two days with helicopter support.

The South Sister network was remeasured in 1986 to verify the initial observations and determine if measurable deformation had occurred since the network was established. Measured tilt changes ranged from 0.8 to 6.5 microradians. No pattern was apparent in the changes, which are attributed to measurement error. Better precision (1–2 microradians) could be obtained from longer traverses (about 1 km), but the time required for the measurements would increase accordingly. The existing network is thought to be a good compromise, adequate to detect precursory deformation in the event of renewed volcanic activity.

Medicine Lake Volcano: A Single Long Traverse to Determine Regional Deformation

Medicine Lake volcano is a Pleistocene and Holocene shield volcano located in northeastern California about 50 km east of Mount Shasta, near the western margin of the Basin and Range tectonic province. Lava Beds National Monument is located on the northern flank of Medicine Lake volcano and encompasses mostly basaltic and some andesitic lavas. Higher on the volcano, basaltic lava is mostly absent, andesite dominates, and rhyolite and small volumes of dacite are present, the latter mainly near the 7 × 12 km Medicine Lake caldera (Donnelly-Nolan, 1988).

A 20-km traverse across the summit area of Medicine Lake volcano was measured during August 1988. This first-order class II survey repeated a second-order survey made in 1954 by the National Geodetic Survey. After it was recognized that substantial subsidence had occurred between the two surveys and that the deformation field extended well beyond the 1988 traverse, a more ambitious leveling effort was conducted in summer of 1989. The 1989 survey crossed Medicine Lake volcano and the Stephens Pass area, where intense swarms of shallow earthquakes occurred in 1978 and 1981. Closure for the 1989 survey was 19 mm around the 193-km circuit, well within NGS requirements for first-order class II surveys[1] (5 mm $\cdot L^{1/2}$ = 69 mm; Vaníček and others, 1980). Approximately 80% of the 1954 bench marks along the route were recovered, and missing marks were replaced to maintain an average spacing of 1.5 km.

The most obvious feature of the vertical displacement data (figs. 12.3–12.5) is an area of

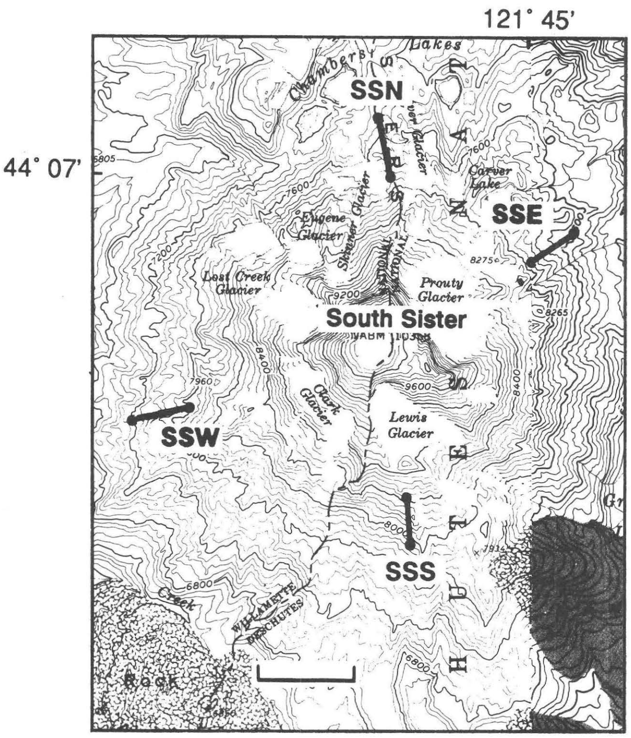

Figure 12.2. Locations of four short leveling traverses on flanks of South Sister Volcano in west-central Oregon, from Yamashita and Doukas (1987). Contours are in feet.

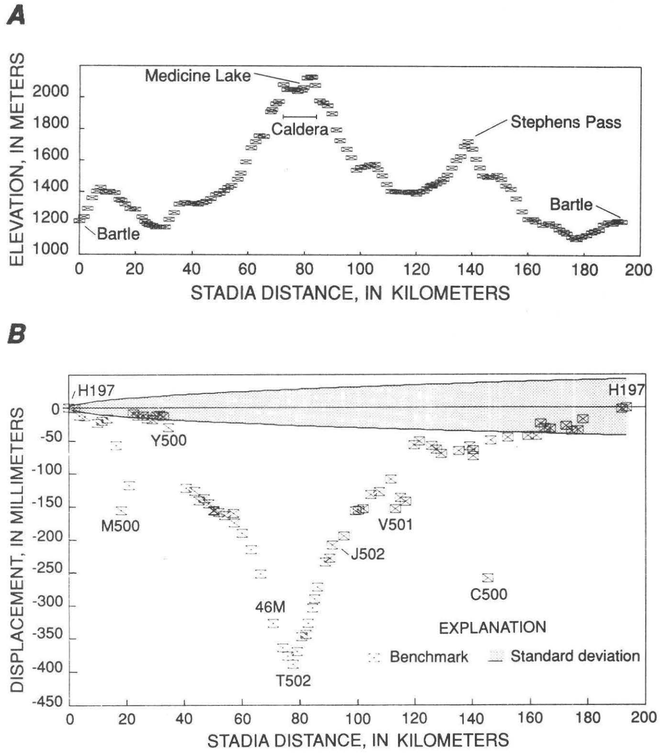

Figure 12.3. Topography (*A*) and vertical displacements (*B*) along a 193-km leveling loop across Medicine Lake volcano and Stephens Pass, California. Displacements were calculated by comparing results from a second-order survey in 1954 and a first-order class II survey in 1989. Bench mark H197 near Bartle was held fixed. Shaded area in *B* indicates ±1 standard deviation.

[1]A common source of confusion is the distinction between the standard deviation of an OED, $\sigma(h)$, the standard deviation of an OED change, $\sigma(\delta h)$, and the maximum allowable circuit closure, C, for surveys of a given order and class. For first-order class II surveys, $\sigma(h)$ = 0.7 mm $\cdot L^{1/2}$; $\sigma(\delta h)$ = 1.0 mm $\cdot L^{1/2}$; and C = 5.0 mm $\cdot L^{1/2}$ (Vaníček and others, 1980)

pronounced subsidence (maximum 389 ± 43 mm at T502, corresponding to an average rate of 11 mm/yr) in the summit area of Medicine Lake volcano, near the center of Medicine Lake caldera. Subsidence extends beyond the caldera rim and across the entire volcanic edifice. In addition, there is evidence in several places along the leveling route for localized faulting, presumably associated with historical crustal extension in the western Basin and Range tectonic province (for example, near M500, Y500, V501, and C500).

The apparent inverse correlation between topography and vertical displacements raises the possibility that the calculated displacements are contaminated by systematic error in one or both of the leveling surveys. For example, if the leveling rods used for the 1954 survey were poorly calibrated or the rod corrections were incorrectly applied, error would have accumulated as a function of elevation. As a result, the difference between the 1954 and 1989 surveys would indicate elevation-dependent displacements. This possibility is currently under investigation, but at present the calculated displacements are thought to be correct because (1) the magnitude of the rod-correction error that would be required to explain the displacements is implausibly large (389 ± 43 mm in 600 m elevation change is approximately 6×10^{-4}); (2) the correlation between topography and displacements breaks down in detail, particularly in the Stephens Pass area; and (3) a general correlation between topography and vertical displacements makes sense if the displacements are caused by isostatic loading, magmatic deflation, or some other volcanogenic process.

The area of localized subsidence near C500 (about 20 cm with respect to nearby marks) is within the epicentral area of the 1978 Stephens Pass earthquake swarm, which was accompanied by ground breakage (Cramer, 1978; Bennett and others, 1979). Although only one bench mark is involved, both its undisturbed appearance and proximity to the 1978 epicenters suggest that the displacement was caused by faulting rather than bench-mark instability or cultural disturbance. Unfortunately, several nearby marks were destroyed by road work during the period between the leveling surveys. The grabenlike feature near V501 probably is associated with a swarm of shallow earthquakes that occurred just north of Tennant during 1981. No historical seismicity has been recognized that might correlate with the area of localized faulting near M500 and Y500, but that area is cut by many young faults that bound the Whitehorse Mountains and horst-and-graben terrain to the west.

The cause of the 1954–1989 subsidence at Medicine Lake volcano is still under investigation, but almost surely there are both tectonic and volcanic aspects to the problem. Crustal thinning owing to Basin and Range extension, isostatic loading by the weight of the volcanic pile, and processes within a possible magma

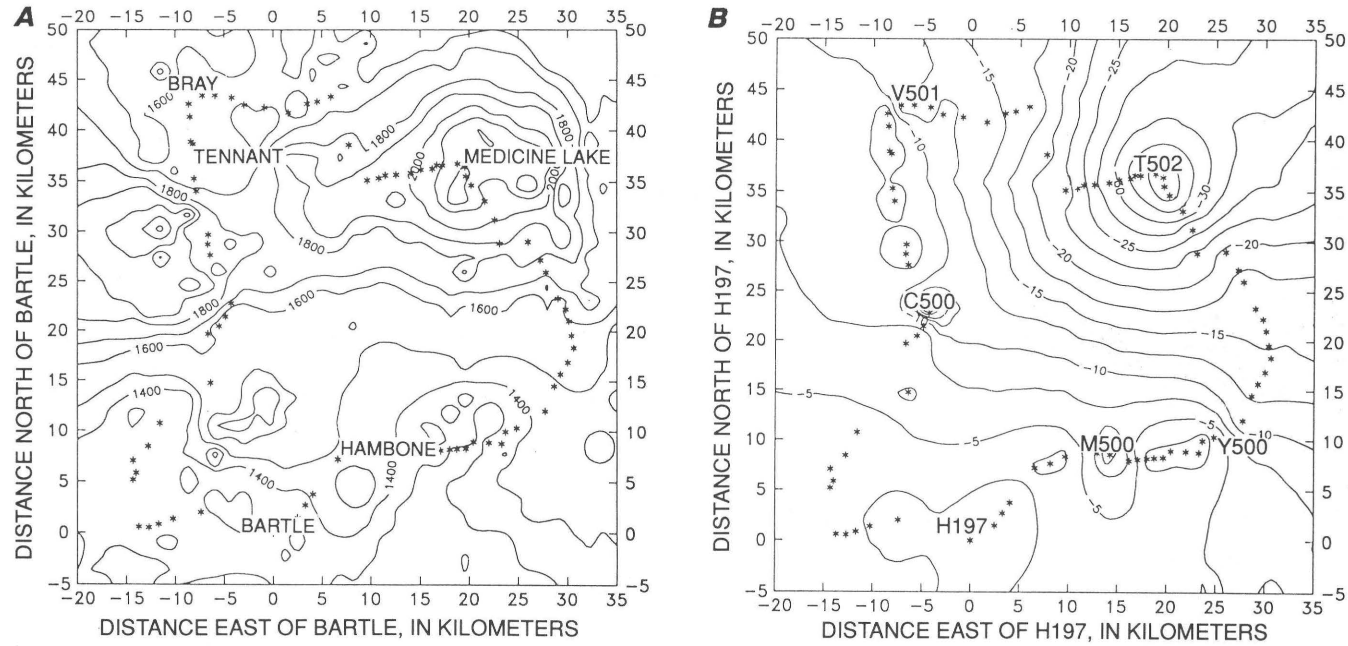

Figure 12.4. Smoothed topography (*A*) and vertical displacements for 1954–89 (*B*) in Medicine Lake region of northern California. Center of Medicine Lake caldera is near bench mark T502 (*B*, upper right). Contour intervals are 100 m in *A* and 2.5 cm in *B*. Displacements are relative to bench mark H197 near Bartle. Large negative displacements near bench marks M500, Y500, V501, and C500 may indicate local faulting, although spatial distribution of these movements is poorly determined.

chamber beneath the summit area (Evans and Zucca, 1988) may each play a role.

RECOMMENDATIONS

The following general recommendations are based primarily on personal experience from leveling surveys at Kilauea volcano in Hawaii, at several volcanoes in the Cascade Range, and at Yellowstone and Long Valley calderas. Specific applications at other volcanoes might require modifications to accommodate local conditions and constraints.

1. Consider leveling a "technique of first resort." Are there specific reasons why a long leveling traverse is inappropriate or not feasible? If so, is a short traverse or a network of single-setup arrays a viable alternative? What types of information might be gained by a long traverse that are otherwise unavailable? Weigh the increased effort and surveying time against the advantages of greater precision and areal coverage.

2. Be meticulous in following established procedures. Standard deviations calculated for a survey of a given order and class of leveling strictly apply only if the appropriate procedures and specifications are followed exactly. Cutting corners may save a small amount of time and seem harmless in the field, but keep in mind that the results eventually may be compared to surveys conducted many decades later by other researchers with other goals or requirements.

3. Err on the side of precision. Field procedures should be matched to the requirements of the individual survey to avoid unnecessary complication, but the additional time and effort to conform to first-order standards is an investment that might pay dividends in the future.

4. Double-run segments to check procedures. It is tempting to single-run twice as far, but double-run at least 10 percent of each traverse to verify that the desired precision is being obtained.

5. Never skimp on bench marks. No amount of measurement precision can overcome the effects of inadequate bench marks. Follow established procedures for installing all marks (Floyd, 1978). Design short traverses and single-setup arrays with enough redundancy to eliminate mark instability as a potential source of error.

6. Combine leveling surveys with other types of geodetic measurements. No single data set is likely to be definitive. The combination of vertical displacements from long leveling traverses, tilt changes from short traverses or single-setup arrays, and horizontal displacements from EDM or GPS measurements provides a particularly powerful constraint for models of the deformation source and assessments of related hazards.

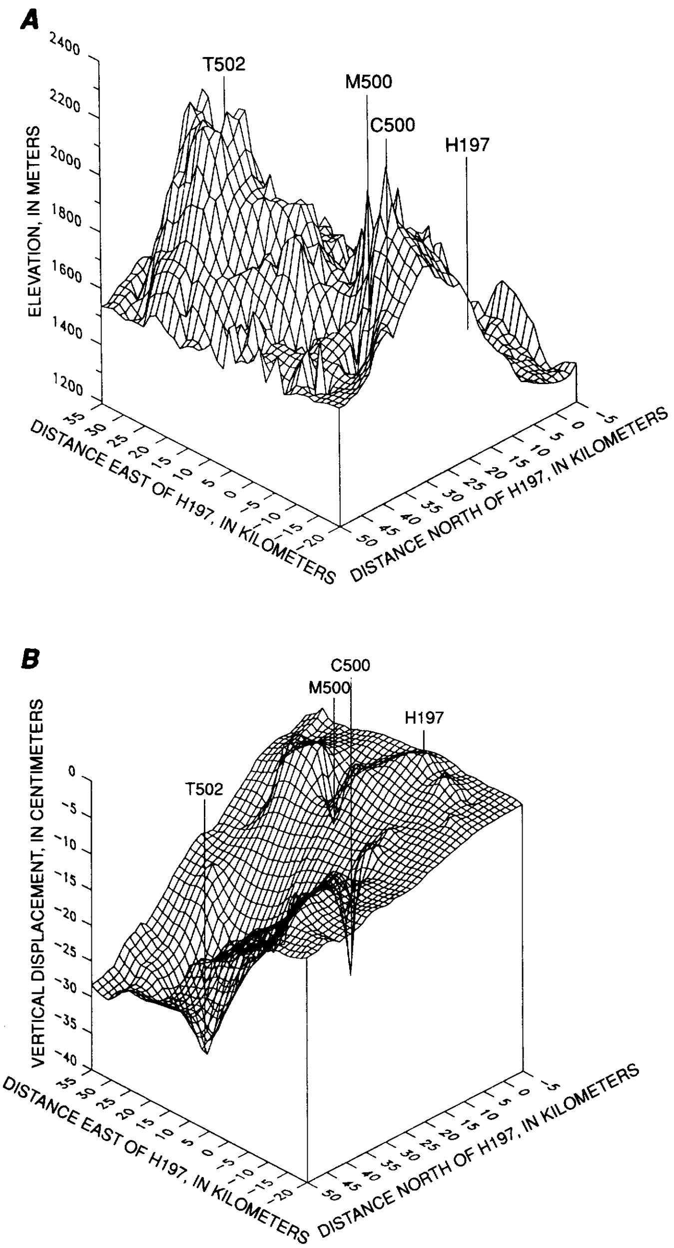

Figure 12.5. Three-dimensional representations of topography (*A*) and 1954–89 vertical displacements (*B*) in Medicine Lake region. Displacements are relative to bench mark H197 near Bartle. View is to southeast.

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The crew chief is the heart of every leveling crew, and CVO is particularly favored in this regard with the services of Ken Yamashita. On many occasions in the past 10 years, Ken has turned an inexperienced collection of students, teachers, bosses, and friends into a hardened

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13. Using First-Order Class II Geodetic Leveling Procedures to Monitor Vertical Displacement

By Kenneth M. Yamashita *and* William P. Kaiser

ABSTRACT

Levels have been used to monitor volcanoes since the early 1900's. Members of the Cascades Volcano Observatory use first-order class II geodetic leveling procedures as defined by the Federal Geodetic Control Committee to monitor vertical displacement at active or potentially active volcanoes. Equipment needs, bench-mark spacing and installation, data acquisition, and data reduction procedures are defined and described. Field procedures and technical specifications for equipment are summarized and consolidated to provide a guide for those interested in using geodetic levels as a method of monitoring vertical displacement.

BACKGROUND

The use of levels and other surveying instruments to monitor vertical displacement in volcanically active areas is not a new science. It has been in use in Hawaii since the early 1900's, when R.M. Wilson, comparing data from sea level to Kilauea volcano in 1926, determined that "this large circuit closure error may be in part due to ground movement" and stated that "The divergence of the 1926 line probably represents an actual subsidence of the ground surface" (Wilson, 1935). Since that survey, major improvements in both surveying instruments and methods have occurred.

In October 1983 members of the Cascades Volcano Observatory (CVO) in Vancouver, Washington, executed a first-order class II geodetic level survey to monitor vertical displacement at Yellowstone National Park, Wyoming (Dzurisin and Yamashita, 1986). Since that initial survey, geodetic leveling has been the principal method used at CVO to monitor vertical displacement for volcanic studies in the Western United States.

The objectives of this report are to (1) consolidate the many published reports on geodetic leveling, (2) provide a guide for those interested in utilizing leveling as a means of monitoring for vertical displacements, and (3) outline the procedures and techniques used by members of CVO.

FEDERAL GUIDELINES FOR GEODETIC LEVELING

Guidelines to coordinate national mapping, charting, and surveying activities were established in 1919 by the Federal Surveying and Mapping Agencies (FSMA). The FSMA was abolished in 1942 and its functions transferred to the Bureau of the Budget, which in turn transferred its authority to the Federal Geodetic Control Committee (FGCC) when it was chartered in 1968.

In 1975 and 1984 the FGCC updated its guidelines prescribing specific standards and accuracies for surveys included in the National Network of Geodetic Control, of which geodetic leveling is one technique used for vertical control. Under these guidelines, specific constraints are imposed as to procedure, accuracies, precautions, and equipment that can be used for a particular order and class of leveling (Federal Geodetic Control Committee, 1975).

FIRST-ORDER CLASS II LEVELS

First-order class II levels are used primarily for regional engineering and for measuring vertical displacement. One of the primary tasks of CVO is to monitor active or potentially active volcanoes, on which appreciable surface displacements may occur. Therefore, CVO crews typically run first-order class II surveys. This report outlines procedures and standards for such surveys.

Besides closure error, the criteria imposed to determine order and class of the level survey are governed by these guidelines: (1) equipment, (2) bench-mark spacing and installation, (3) data-acquisition procedures, and (4) data-reduction procedures.

Equipment

Level Instrument

For first-order leveling, an instrument with an optical micrometer capable of resolving 0.01 cm is the first criterion.

If a spirit level is used, the level vial of the instrument must be sufficiently sensitive and consistent to set the line of sight within 0.25 second of arc, and for compensator levels, the compensator should also be capable of setting the line of sight to within 0.25 second of arc. The instrument should have an objective lens diameter of approximately 50–70 mm, have a telescope magnification of about 40 power, and be equipped with a horizontal, V-shaped reticule.

Aside from these requirements, any instrument capable of producing results classified as first-order class II levels can be used.

CVO Instrumentation

The 1983 and 1984 Yellowstone surveys (Dzurisin and Yamashita, 1986; Dzurisin and others, 1986) used the Wild N3 precision level. All other surveys by CVO used the Wild NA2 compensator level.

The technical information supplied with the Wild NA2 indicates that the NA2 has an optional telescope magnification of 25, 32, or 40 power. The objective aperture is 45 mm, and it has a compensator setting accuracy of ±0.3 second of arc. The parallel micrometer plate is read to the nearest 0.1 mm and estimated to 0.01 mm.

Although the specification for the NA2 is just outside limits set by the FGCC, our data show that by following proper field procedures the NA2 is capable of producing first-order class II accuracy (Dzurisin and Yamashita, 1987).

The N3 spirit level has the option of using a 34, 45, or 46 power magnification and has an objective lens of 56 mm. The tubular level has a sensitivity of 10 seconds and a setting accuracy of the split bubble of ±0.25 second. The parallel micrometer is read to the nearest 0.1 mm and estimated to 0.01 mm. The N3 therefore meets all the requirements as set by the FGCC.

CVO purchased a Jena NI 002 A reversible compensator level in January 1989. It has a 40 or 50 power telescope magnification, an objective lens of 52 mm, and a pendulum setting accuracy of ±0.05 second. The micrometer scale is read to the nearest 0.1 mm and interpolated to 0.01 mm. The Jena NI 002 A therefore also meets all the requirements as set by the FGCC.

Level Rods

The level rods used should have rod scales composed of the metal Invar and have 1.0 cm or 0.5 cm graduations. Each rod should have two parallel scales, but the scales should differ in value by some constant. The level rod should have a circular level bubble accurate to 10 minutes of arc and be self-supporting, that is, capable of accepting stays or braces.

CVO uses Wild GPLE-3 Invar level rods and Kern Invar rods. Both have an Invar strip with 1-cm graduations, and both are capable of accepting braces to become free standing.

The rods are calibrated yearly by the National Bureau of Standards in Gaithersburg, Maryland, to an accuracy of 0.00005 m.

Temperature Probes

The temperature probes should be of the aspirated type, where the fans pull rather than push air past the temperature sensors. This prevents heat from the fan motor from biasing the true ambient temperature. The temperature sensors should be shielded from direct exposure to the sun and be accurate to 0.1 °C or 0.2 °F.

There should be two probes, one each located at 0.5 m and 2.5 m (Balazs and Young, 1982), or 0.3 m and 1.3 m (Schomaker and Berry, 1981), above the ground surface. The probes can be either hand-held or mounted on the tripod leg of the level instrument.

Bench-Mark Spacing and Installation

Bench marks along a first-order class II level route must not be spaced farther than 3.0 km apart or have an average spacing greater than 1.6 km apart. Bench marks are classified as class A, class B, or others (Floyd, 1978).

Most bench marks set by CVO are either on bedrock, and therefore classified as A, or set on rods without sleeves, and therefore classified as B marks, as per the classifications set by the National Oceanic and Atmospheric Administration (NOAA). See Floyd (1978) for complete details as to the classification and procedures for bench-mark installation.

Procedures to Follow During Data Collection

The accuracy of the field data depends on a number of factors, the most important of which are (1) adjustment of the level instrument, (2) adjustment of the level vials, and (3) field procedures.

Adjustment of Level Instrument

The instrument should be checked for collimation error daily, except for reversible compensator levels which are checked weekly (Federal Geodetic Control Committee, 1984).

Parallax Adjustment

Before the instrument is read, it should be checked for parallax by looking through the eye piece, focusing on a fixed object, then bobbing the head up and down. The horizontal wire should not appear to move with respect to the fixed object. If it does, then parallax exists, and must be removed.

To remove the parallax, focus the telescope on a plain background, then adjust the focus of the reticule, then adjust the focus of the telescope again. Continue to focus and refocus the reticule and the telescope. There should be minimal movement of the reticule when the parallax is removed.

Peg Test

Instrument collimation error can be detected and corrected by a procedure called a peg test. Tests conducted by the National Geodetic Survey (NGS) have found that performing a peg test during times of positive air—when the ground temperature is colder then the air temperature—can cause refraction errors that indicate that the instrument is out of adjustment when in reality it is not. It is now required that a peg test be conducted only during times of negative air temperature. The prescribed procedure is to perform a peg test no earlier than 2 1/2 hours after sunrise, and no later then 1/2 hour before sunset (Poetzschke, 1983).

Proper procedure for performing a peg test can be found in Schomaker and Berry (1981, p. 3-31).

Adjustment of Level Vials

The bulls-eye level on compensator levels can be checked by first leveling the bubble and rotating the level instrument 180°. If the level bubble is within 0.2 mm of center, the level is considered to be in adjustment, otherwise it needs to be adjusted (Schomaker and Berry, 1981, p. 3-26).

To adjust the level vial, bring the level bubble back half-way into the level circle using the level foot screws. Finish leveling the level vial with the adjustment screws located under the level vial. Rotate the instrument 180° and repeat the procedure until the level bubble stays within 0.2 mm of center when rotated.

The level vial on the rods can be easily checked by holding a carpenter's level along the edge and front of the rod. The level on the rod cannot be checked, or adjusted, by rotating the rod, as it was done with the level instrument. The rod is leveled using the carpenter's level, not the bulls-eye level. If the level is out of adjustment the bubble is brought back into the circle the full amount using the adjustment screws, and the rod is not rotated at all.

The level vial should stay within 2 mm of center or 10 minutes of vertical when rotated (Schomaker and Berry, 1981, p. 3-42).

Field Procedures

Explicit instructions outlining field procedures are given by the Federal Geodetic Control Committee (1984) for the class of leveling that is being performed. For first-order class II level surveys, the following field procedures should be followed.

The level survey should generally start from an established permanent survey mark, and at least two consecutive "old" bench marks should be incorporated in the new survey (Federal Geodetic Control Committee, 1984).

Before the level survey actually begins, the note-taker should record the date, the type of level instrument that is being used, and the instrument serial number. The brand type of level rod, the serial number, the units that the temperatures will be recorded in (Celsius or Fahrenheit), the geographical area in which the survey is made, and the serial number of the rod that is on the bench mark should also be recorded.

A rod is leveled with brace poles over the highest part of the monument. The level instrument is then set at some convenient distance from the backsight rod, but at a point no farther then 60 m away, and in such a manner that the lowest rod scale reading on the rod is no lower then 0.5 m because refractions close to ground level can cause appreciable errors (Whalen, 1981). The distance can be approximated by pacing, and the elevation difference can be accurately estimated with a hand level.

The foresight rod is established at a distance that is equal to that of the backsight rod from the instrument. This can be done by pacing the distance from the backsight rod to the instrument, and pacing an equal distance beyond the level instrument for the foresight position. The imbalance between the two distances cannot exceed 5.0 m, nor can the lowest rod scale reading on the foresight rod be lower than 0.5 m (Federal Geodetic Control Committee, 1984).

The foresight turning point is established by driving either a wooden stake or a metal pin into the ground; on a hard surface, a trivet or "turtle" should be used. Again, pace to establish the distance and use a hand level for the elevation difference.

Generally the first reading taken is on the backsight rod, low scale, then the top stadia wire, then the bottom stadia wire. The level is rotated to the foresight rod, a reading is taken on the low scale, and then the stadia are read and computed. If the stadia imbalance is greater then 5.0 m, the level instrument or the foresight rod should be moved so the imbalance is less then 5.0 m.

If a reversible compensator level is used, the compensator position should now be changed. For nonreversible compensator levels, the level should be disleveled and releveled (this has not been done by CVO crews or the National Mapping group), then a reading taken on the foresight rod, high scale, then on the backsight rod, high scale. If the field crew is using a level instrument with a reversible compensator, such as the Jena NI 002, consult Poetzschke (1983), which contains valuable information unique to reversible compensator levels.

The elevation difference computed for the low scales and the high scales cannot exceed 0.10 cm for reversible compensator levels, or 0.03 cm for all other levels. If the difference is greater, the entire setup should be rejected and read again. If the stadia readings were acceptable, the stadia need not be repeated.

Informing the rod people of the true distance as determined by the stadia readings will help them to more accurately adjust their pacing.

If the readings are acceptable, the temperatures are read top probe first, then the bottom probe. The thermometers should be aspirated for at least one minute before taking a reading (Schomaker and Berry, 1981).

When all the readings and checks for the setup are acceptable, the backsight rod and the level are moved leapfrog fashion past the foresight rod; again balance the stadia distance, and do not use the lower 0.5 m of the level rod. While the move is taking place, the previous foresight rod person should rotate the rod 180°, taking extreme care not to disturb the turning point in any way. The previous foresight rod now becomes the backsight rod, and the previous backsight rod is now the new foresight rod.

The new foresight is established by pacing the distance from the backsight rod to the level instrument, and pacing an equal distance beyond the level instrument for the new foresight position.

The recorder should be keeping track of the running elevation difference between the foresights and backsights and also the cumulative stadia imbalance, and informing the rod people of these values so that they can adjust for any imbalance. An imbalance of 5.0 m per setup and 10.0 m between sections (typically 1 to 2 km between bench marks) is allowed (Federal Geodetic Control Committee, 1984).

This leapfrog sequence is followed until another bench mark is reached. Standards require that two rods be used and that the rods be alternately read as the foresight rod, then as the backsight rod.

After the reading on the foresight bench mark is made, the bench-mark ID is recorded together with a wind and cloud code.

The cloud codes are "0" if less than 25 percent of the readings are taken in sunny condition, "1" if 25 to 75 percent of the readings are taken in sunny conditions, and "2" if more than 75 percent of the readings are taken in sunny conditions. The wind codes are "1" if the wind speeds average less than 5 mph (10 kph), "2" if the wind speeds average 5-15 mph (10-25 kph), and "3" if the average is greater than 15 mph (25 kph) (Holdahl, 1985). The wind and sun codes are used to predict temperatures if these are not taken at the time of the survey.

Before continuing to another section, the data collected should be checked against previous data to ensure that there are no obvious errors. Closure error should be computed and verified for double-run or closed loops.

At CVO, all data are recorded on an HP-71B hand-held computer (Yamashita, 1989), where all the checks and balances are made. If a similar data collection system is utilized, the field data should be printed, or recorded on a digital recorder at this time. The HP-71B has enough memory to hold a day's worth of level data, but we have had a "memory lost" problem with this computer and feel safer by dumping the data at each mark.

CVO crews have been reversing the direction of the run after each bench mark. In other words, if the direction of the first run from bench mark to bench mark was from north to south, the next run would be in the opposite direction, from south to north. It is recommended that the direction of leveling be reversed from morning to afternoon or every other day (Federal Geodetic Control Committee, 1984). The reasoning is that by reversing the direction between runs (for single-run lines), cumulative errors due to pin settling (accumulation of small systematic errors from turning point movement) can be minimized by cancellation.

Sources of Error

Errors are normally characterized as being random or systematic. Random errors are normally attributed to unpredictable variations encountered during the survey. These errors can be caused by movement of the tripod or the turning points, or by the effects caused by imbalanced shot lengths. Systematic errors are those that are inaccurate but consistent, such as the effects of the Earth's magnetic field on certain kinds of compensator levels (Rumpf and Meurisch, 1981), or the errors that can be introduced by using instruments or level rods that are not in adjustment or poorly calibrated.

Some errors can be directly attributed to departure from accepted field practices, but these can be minimized or eliminated by adhering to procedures as set forth by the Federal Geodetic Control Committee (1984). However, there are other sources of error that are inherent and present no matter what precautions are taken. These errors can be accounted for, and corrections applied, only during data reduction.

Errors incorporated during the field survey can be detrimental to the integrity of the data set and can appreciably add time and expense to the survey, not to mention the frustration of rerunning sections. The following procedures can minimize these errors:

1. Check for parallax frequently by moving the head up and down while watching the reticule for bounce.

2. Perform a peg test daily (but only during times of negative temperatures), or whenever there is reason to suspect that the instrument has drifted, for example if the instrument was jarred during transportation, or if there are an inordinate number of "no checks" between low-scale and high-scale readings.

3. Check the level vial on the instrument frequently during the day. Glancing at the level bubble after the instrument is rotated between foresight and backsight is sufficient to see if the level bubble is out of adjustment. The level vial on the rod can be quickly and easily checked while the instrument is being set up for the peg test. Adjustments on the level vials should be done before doing the peg test.

4. The rod person should ensure that nothing is on the bottom of the level rod before setting it on either the bench mark or the turning point. This can be accomplished by wiping off the bottom of the rod before setting it on the mark, or by rotating the level rod slightly from left to right and listening for any grinding noise which would indicate dirt. The rod person should also use extreme care to ensure that the level rod is not only on the bench mark but on the highest part of the mark, and that no part of the rod is touching anything but the bench mark. It is critical that the turning points do not move during the transition from being a foresight rod to becoming a backsight rod. This is one of the few areas where there is no way to check for a blunder.

5. The instrument person can ensure that the tripod is stable and not subject to movement between reading, and that the reading sequence is as described earlier. This gives two independent elevation differences for the setup. If the instrument or tripod has not moved between the high-scale and low-scale readings the elevation difference should be the same to 0.03 cm. If the level line runs along an asphalt paved road, the instrument person should ensure that at least two of the three tripod legs are off the pavement because of the possibility of the tripod legs sinking into the asphalt.

6. The recorder is responsible for noting that all required information such as equipment serial number, wind and cloud codes, date, time, and bench-mark ID's are recorded correctly. The recorder needs to ensure that the checks between the low-scale and high-scale readings are within the tolerance prescribed for that particular order and class of survey, and that the elevation difference and stadia distance are current. It is important that the stadia distance be balanced and any imbalance corrected. Balancing the stadia distance will eliminate, or at least minimize, errors introduced by a maladjusted instrument and by the effects of curvature (where the line of sight is not parallel to the equipotential surface (Schomaker and Berry, 1981). If the data are recorded electronically, the recorder needs to ensure that they are properly stored on another electronic medium for transfer to a PC or other computer device.

Both the field chief of party and the recorder should calculate double-run, or loop-closure, errors. Single-run data should be compared to the previous survey, and any discrepancies should be resolved before leaving the site.

The field chief of party must be sure that the direction of runs is reversed twice daily, or every other day at a minimum.

Data Reduction

Data collected in the field give only a close approximation of what the true elevation differences between bench marks are; they must be corrected for several factors in order to maximize precision.

Corrections for rod-scale error, refraction of the light path, changes in length of the ivar strip of the level rod, effects of the Earth's magnetic field, closure errors for double-run or loop sections, and orthometric heights are some of the gremlins that can affect the data. These corrections must be applied. The following are equations to correct for these factors.

Computation of Collimation Error

$$C = [(\Delta h_1 - \Delta h_2) - 0.27]/ - \Delta s_2$$

where C = collimation error in mm/m,
Δh_1 = elevation difference in mm for first setup from middle,
Δh_2 = elevation difference in mm for second setup, and
Δs_2 = difference in stadia distance between rod and instrument.

The equation is derived from Schomaker and Berry (1981, p. 3-32). The values listed in the refraction and curvature table (Schomaker and Berry, 1981, p. 3-31) are not correct. The term (-0.27) in the above formula was taken from Zilkoski and Ward (1989, vol.1).

If the height difference is greater than ±10.0 seconds or ±0.05 mm/m (Federal Geodetic Control Committe, 1984), the instrument should be adjusted.

$$CF = \text{stadia2} \cdot (C/100) \cdot 4$$

where CF = correction factor to be added to the far rod reading,

stadia 2 = exact stadia distance from the instrument to the far rod,

C = collimation error derived previously, and

4 = constant factor for full-centimeter rods (8 for half-centimeter rods).

This equation is modified from Schomaker and Berry (1981, p. 3-33).

Refraction Correction

$$R = -10^{-5} \cdot 70(S/50)^2 \cdot \delta(D/2)$$

where R = refraction correction,

S = distance from rod to instrument, in meters,

δ = temperature difference in degrees Celsius between the two temperature probes, and

D = difference in elevation for the setup.

The correction is added to the observed elevation difference. This equation is modified from Balazs and Young (1982, p. 6).

Orthometric Correction

$$C_o = -2h\alpha \sin 2p \left[1 + (\alpha - 2\beta/\alpha)(\cos 2p)\right] \sin dp$$

where C_o = orthometric correction,

h = average height of the section,

α = 0.02644,

β = 0.000007,

p = average latitude of section, and

dp = latitude difference between the beginning and end points of the section. dp is positive when the ending point is north of the beginning point.

This equation is from Balazs and Young (1982, p. 4). The equation as originally published is incorrect in that the sine of dp, not dp alone, should appear at the end (Emery Balazs, written comm., 1989).

Rod Temperature Correction

$$C_t = (t_m - t_s)\, DCE$$

where C_t = rod temperature correction (same units as D),

t_m = mean observed temperature of the Invar strip,

t_s = 25 °C,

D = observed difference of elevation between bench marks, and

CE = 1×10^{-6} per degree Celsius.

This equation is from Balazs and Young (1982, p. 4).

Level Collimation Correction

$$C_c = -(e \cdot SDS)$$

where C_c = level collimation correction, in millimeters,

e = collimation error, in radians · 1000 or in mm/m, and

SDS = accumulated difference in sight lengths for the section, in meters.

This equation is from Balazs and Young (1982, p. 4).

Equation to Calculate Standard Error for Double-Run Segments

$$\sigma = \frac{1}{2n}\sqrt{\Sigma\left(\frac{d^2}{k}\right)}$$

where σ = error, in millimeters,

d = difference between the backward and forward measurements of a section,

k = distance in kilometers, and

n = total number of double-run sections.

This equation is from Whalen and Balazs (1977, p. 22).

Equation to Calculate Closure Error

When the level line is closed by running over the same route twice (double-run), the equation to calculate the closure error is

$$4mm\sqrt{k}$$

where k = total distance leveled in kilometers (twice the one-way distance).

When the level line is closed by a circuit or loop closure, the equation to calculate the closure error is

$$5mm\sqrt{k}$$

where k = distance in kilometers for the closure loop.

These equations are from NOAA (1980).

Magnetic Error

A linear correction is applied when using the Wild NA2 level:

$$0.1 \cdot L_{mn} \text{ mm}$$

where L_{mn} is the magnetic north component of the distance, in kilometers, along the leveling line (Rumpf and Meurisch, 1981). CVO has two NA2 compensator levels, and both instruments have been magnetically shielded by a dealer-installed shield.

C. T. Whalen (written commun.) reports that the DC error of 1 earth-field for the NI 002 level is 0.024 mm/km, and AC-induced errors are insignificant at 1–5 earth fields. This would indicate that the NI 002 is not very susceptible to magnetic problems, and on short lines a magnetic correction probably need not be applied.

The Wild N3 level does not have a compensator but instead is leveled very precisely by means of a long level vial and a split-image level. Since the magnetic problem only affects compensator levels, no magnetic correction need be applied.

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14. Single-Setup Leveling Used to Monitor Vertical Displacement (Tilt) on Cascades Volcanoes

By Kenneth M. Yamashita

ABSTRACT

Many different methods have been employed to detect tilt or other manifestations of ground deformation at Kilauea and other volcanoes throughout the world. This report (1) gives a generalized overview of the evolution of tilt monitoring, (2) outlines different approaches to single-setup tilt leveling, and (3) gives the pros and cons for the different methods used at the Casades Volcano Observatory to monitor volcanoes of the Cascades Range for vertical displacement.

HISTORY OF TILT MEASUREMENT

The first rudimentary tilt measurements at the Hawaiian Volcano Observatory (HVO) were made by noting the wanderings of the recording stylus of the two-component Bosh-Omori seismograph at Kilauea during the early 1900's. An improvement to this system was to suspend a plumb bob from a seismometer and to plot the departure of its point (The Volcano Letter, 1930).

Ground deformation associated with active volcanic processes was first recognized in Hawaii by Jaggar and Finch (1926), who noted that a horizontal pendulum seismometer installed in the Whitney vault near the summit of Kilauea volcano, Hawaii, effectively recorded long-term changes in ground tilt. In 1936 a "Clinoscope" was built at HVO. The Clinoscope consisted of a tripod shaped device with a heavy ring weight, in a cushion of oil, centered between the legs. When the ground tilted, the ring would move a pointer on a disk, marking the direction and distance from center (The Volcano Letter, 1936).

In 1958, J.P. Eaton and the HVO staff installed 10 water-tube tiltmeters around the summit of Kilauea (Eaton, 1959). The station installation consisted of sunken, triangular concrete piers to which a brass container (pot) was attached. The pots were connected by a water hose and an air hose. The water hose was used to fill the pots from pressurized tanks and to allow water from one container to flow freely into the other pot until an equilibrium was reached. The pressure was to flush the system of any air bubbles and was not meant to pressurize the system. The air hose assured equal pressure between the containers.

A micrometer within the container was used to measure the height of the water in the individual pots. When the water heights were read simultaneously, the elevation differences between the piers could be calculated.

These devices were simple to use but were limited to areas where the elevation difference between the piers was no greater then 1.5 cm (the effective length of the micrometer) in an equilateral triangle with sides 25–50 m long. In addition, the highest precision was obtainable only during heavy cloud cover or at night, owing to thermal expansion and contraction of the water in the system during the daylight hours. Because water was used as the medium to determine the elevation differences between the piers, the term "wet tilt" was adopted for this system.

SINGLE-SETUP LEVELING TECHNIQUE

To circumvent the difficulties of the wet tilt system, D. B. Jackson and T. L. Wright began development of a system of precise tilt leveling at HVO. This procedure involved precise leveling of a bench-mark array using a Zeiss NI-2 level and Invar rods. Because no fluids were involved, the term "dry tilt" (Yamashita, 1981) was soon adopted.

"Dry tilt" is not an accurate term and there has been controversy as to the use of this term, so it has been decided (by committee) that "single-setup leveling" (SSL) be the new name used to denote this technique of monitoring for vertical displacement.

Early tests showed that significant ground tilting could be detected by measuring bench-mark pairs

150–200 m apart. To shorten the base and still resolve meaningful tilt vectors, a Wild N-3 precision level and precise Invar level rods were acquired in 1969 (Kinoshita and others, 1974). Experience at HVO has shown that the accuracy of this technique when used with triangular arrays with 40-m sides is approximately 10 microradians (μrad).

Site Choice

The configuration of SSL tilt stations used by CVO is a nearly equilateral triangle with sides of 30–40 m (fig. 14.1). To establish the vertices of the triangle, a point is marked in the approximate middle of the site where the tilt station is to be installed. A transit is then plumbed over this point and a bearing is taken in a southerly direction; the exact bearing depends on the terrain and optimum geologic orientation for the triangle.

A distance of 23.1 m (for a 40-m equilateral triangle) is measured from the instrument along this bearing, and the resulting point is marked. The two remaining vertices are then located 23.1 m from the center point by turning successive 120° angles from the first marked point. After all the vertices are established, each leg of the resulting triangle is measured and recorded. Each leg should be roughly 40 m long. The elevations of the vertices are also measured to ensure that the elevation difference between the vertices is no greater than the length of the rods used. Ideally, only the upper 2.5 m of a 3-m rod should be used, because refraction close to ground level can cause appreciable errors (Whalen, 1981).

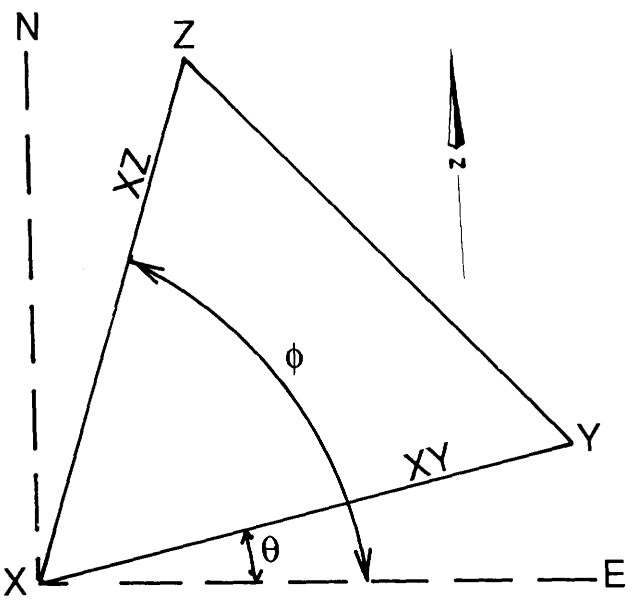

Figure 14.1. Single-setup leveling station layout.

An alternate method is to set the transit over one of the vertices, establish a direction for one leg of the triangle, measure a distance of 40 m along this axis, and mark the point. The transit is "zeroed" along this azimuth and a 60° angle turned from one end. A distance of 40 m is then measured along this line and the point marked. The distance along the tangent determined by turning the 60° angle should be measured to verify the accuracy of the angle. This distance should be 40 m. The instrument point is established by bisecting the 60° angle and measuring a distance of 23.1 m.

When the configuration is acceptable, a bench mark is installed at each vertex and the central instrument site is marked with a nail or bar. The vertices are labeled X, Y, and Z counterclockwise from the southernmost site.

A 40-m equilateral triangle is not a rigid requirement for a tilt configuration, and neither size nor shape is critical to the measurement of tilt. Linear, triangular, square, and hexagonal arrays have all been employed to advantage. Likewise, the station orientation and lettering scheme described above are standardized for the sake of convenience but can be modified as appropriate for specific installations.

Bench Marks

The type of bench mark currently used by CVO is die-cast red brass, with a 1.5 × 2.0 cm nipple in the center. The nipple assures that the rod is always on the highest part of the bench mark. This can be a problem with conventional flat bench marks especially if the bench mark is not set perfectly horizontal during installation. Bench marks set by CVO are either cemented in bedrock or fastened to the tops of rods driven into the ground until they can be driven no farther.

Guidelines for acceptable installation of bench marks can be found in Floyd (1978).

Instrumentation

Any instrumentation system capable of producing first-order level-survey results (Federal Geodetic Control Committee, 1980) can be used to determine tilt to the precision of ±10 μrad. Presently at the Cascades Volcano Observatory, the Wild N-3 and the Wild NA2 with a parallel micrometer plate are the instruments used. The Volcano Crisis Assistance Team (VCAT) uses the Wild T-2000 electronic theodolite with a DI-5 electronic distance meter.

Three-rod System

If three rods are available, they are labeled X, Y, and Z and leveled with self-supporting braces on the corresponding bench mark (fig. 14.2). The instrument is then leveled over the center mark of the triangle. The purpose of this scheme is to measure the elevation difference between each of three bench-mark pairs.

One approach to the reading sequence (table 14.1) is to take the initial reading on the Y rod, followed by two readings on the X rod, two readings on the Y rod, and a final reading on the X rod. If the maximum difference between the three sets of readings is no greater than 6×10^{-3} cm, the next set, X minus Z, can be taken. If the difference is greater then 6×10^{-3} cm, additional readings of Y minus X should be made until consistency is obtained. Under extremely windy conditions a difference of 6×10^{-3} cm or less may not be possible.

The last reading taken on the X rod is carried down as the first reading for the set X minus Z. Two readings are taken on the Z rod, then two readings on the X rod, and finally one reading on the Z rod. Again a maximum difference of 6×10^{-3} cm is allowed. As a measurement of the precision of the readings taken, the closure leg Z minus Y is read in a similar manner (table 14.2).

A closure error of about 6×10^{-3} cm is the accepted norm. If the closure error is greater than this, a determination as to which leg may be bad is made, and that leg is repeated until an acceptable closure is made. Atmospheric conditions may be a guiding force as to what is acceptable for that survey.

Table 14.1. Reading sequence and example data from a tilt triangle

Rod Reading	Difference	Rod Reading
Y rod	Y-X rod	X rod
*1 108.273	-130.650	238.923 *2
*4 108.277	-130.649	238.926 *3
*5 108.268	-130.648	238.916 *6
X rod	X-Z rod	Z rod
238.916	33.301	205.615 *1
*3 238.914	33.301	205.613 *2
*4 238.914	33.302	205.612 *5
Z rod	Z-Y rod	Y rod
205.612	97.350	108.262 *1
*3 205.614	97.351	108.263 *2
*4 205.616	97.352	108.264 *5

* Order in which readings are taken.

Data compiled over the last 10 years from 38 tilt stations on Cascade Range volcanoes indicate that 6×10^{-3} cm is the average closure with a standard deviation of 6×10^{-3} cm.

Two-rod System

If two rods are being used, they are labeled A and B. The A rod is set up on station Y and the B rod is set up on station X. Readings are similar to those of the three-rod system. After a consistent Y minus X reading is obtained, the rod on station Y is moved to station Z and the reading sequence repeated. If the readings are acceptable, the rod on station X is moved to station Y, and the set Z minus Y is read for the closure.

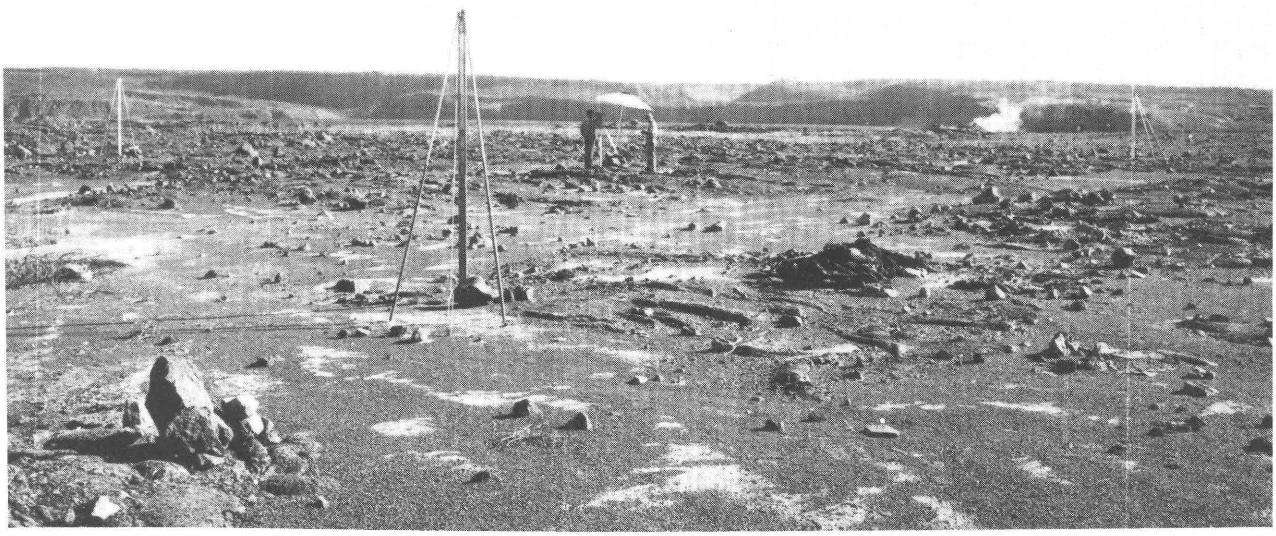

Figure 14.2. This typical single-setup leveling station uses three-rod system.

Table 14.2. Closure determination changes between surveys

[Closure is determined by algebraically summing the average readings of the Y minus X, X minus Z, and Z minus Y leg. Any closure error should be distributed equally among the three legs of the triangle]

Triangle leg	Average of rod difference (cm)	Adjusted reading	Change (cm)	Previous reading
		5/18/87		7/20/88
Y-X	-130.649	-130.650	-0.005	-130.645
X-Z	33.301	33.300	-0.010	33.310
Z-Y	97.348[1]	97.350	+0.015	97.335
Z-Y	97.351[2]			
	+0.003[3]			
Thus 0.001 cm is subtracted from each pair.				

[1] Calculated value for closing leg
[2] Observed value for closing leg
[3] Closure error, in centimeters

In the past we have sometimes double-run each station by reversing the rods on each side of the triangle and reading it twice. For example, the Y-X leg of the triangle is measured until satisfactory data are obtained, then both rods are interchanged and the leg remeasured. The intent was to eliminate any inaccuracies in the rod scales.

CVO rods are calibrated by the National Bureau of Standards in Gaithersburg, Maryland. The rod scale errors are found to be less than the precision of the individual readings, and because we have a calibration table, any inaccuracies of the rod scale can be corrected in the office. Therefore we no longer switch the rods.

Equation to Determine Tilt Vector

$$\tau(N) = \left[\left(\frac{-\cos\phi}{XY\sin(\phi-\theta)}\right)\cdot\Delta(Y\text{–}X) - \left(\frac{\cos\theta}{XZ\sin(\phi-\theta)}\right)\cdot\Delta(X\text{–}Z)\right]\cdot 10{,}000$$

$$\tau(E) = \left[\left(\frac{\sin\phi}{XY\sin(\phi-\theta)}\right)\cdot\Delta(Y\text{–}X) - \left(\frac{\sin\theta}{XZ\sin(\phi-\theta)}\right)\cdot\Delta(X\text{–}Z)\right]\cdot 10{,}000$$

In this equation, modified from Eaton (1959), τ is the elevation change in microradians in the north and the east component.

XY and XZ are the distances from the X-bench mark to the Y- and Z-bench marks, respectively, ϕ and θ are the angles measured counterclockwise from the east direction to the XY and XZ directions, respectively (fig.14.1), and Δ(Y-X) and Δ(X-Z) are the height changes from Y to X and from X to Z between two surveys (table 14.2).

Solution for Tilt Triangle

The magnitude of the tilt vector is computed by taking the square root of $(\tau N^2 + \tau E^2)$.

The azimuth of the tilt vector is computed by taking the arc tangent of $(\tau E / \tau N)$.

If the sign of τN is positive, the vector is to the north, down. If the sign of τN is negative, the vector is to the south, down. If the sign of τE is positive, the vector is to the east, down. If the sign of τE is negative, the vector is to the west, down.

When plotting the vector displacement, the length of the vector corresponds to the magnitude in microradians, and the azimuth is measured from the north if τN is positive, or from the south if τN is negative, and from the east if τE is positive, or from the west if τE is negative.

Example: If XY = 40.2 m, XZ = 40.08m, $\theta = 14.5^\circ$, $\phi = 74.5^\circ$, $\Delta(Y\text{-}X) = -0.005$, and $\Delta(X\text{-}Z) = -0.010$ then

$$\tau(N) = [-0.0077\,(-0.005) - 0.0279\,(-0.010)]\cdot 10{,}000 = +3.18\ \mu\text{rad}$$

$$\tau(E) = [\,0.0277\,(-0.005) + 0.0072\,(-0.010)]\cdot 10{,}000 = -2.11\ \mu\text{rad}$$

Thus the magnitude of the resultant tilt vector, $((3.18)^2 + (2.11)^2)^{1/2}$, is 3.8 µrad and the azimuth, $\tan^{-1}\left(\frac{2.11}{3.18}\right)$, is N 33.6° W.

Precision

The accuracy of an SSL tilt system as determined by the staff of the Hawaiian Volcano Observatory is about ±10 µrad (Kinoshita and others, 1974). Savage and others (1979) have also determined that the precision of a tilt network is about ±10 µrad.

There are too few data to determine what our precision is for SSL tilt sites on Cascade volcanoes, but data from linear arrays at South Sister, Oregon, and level lines at Newberry Crater and Crater Lake, Oregon (Yamashita and Doukas, 1987) suggest that the repeatability is approximately 1–6.5 µrad on lines less than 0.5 km long, about 2 µrad on lines at least 1 km long, and on the average less then 1 µrad on lines longer than 1 km.

CASCADES STATIONS

In 1975 W.T. Kinoshita and D.A. Swanson (Frank and others, 1977) installed three SSL stations on Mount Baker (fig. 14.3) in response to increased thermal activity in Sherman Crater on the summit of the volcano. Additional stations were installed on Mount Baker in 1981.

Since then, SSL stations have been installed at Mount St. Helens, on Mount Rainier (Dzurisin and others, 1983), on Mount Hood, and on Lassen Peak and Mount Shasta, (Dzurisin and others, 1982) (fig. 14.3).

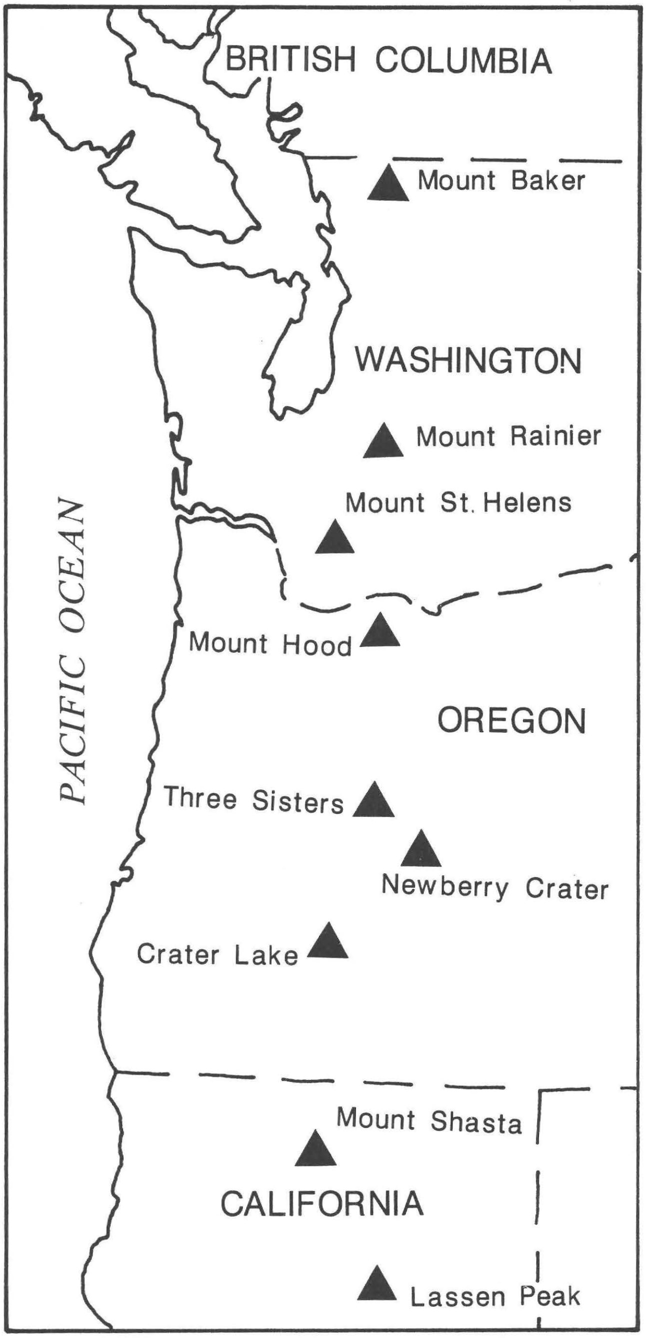

Figure 14.3. Locations of Cascade volcanoes with tilt stations.

Long-base tilt arrays (more than 400 m long) were installed at Crater Lake in 1983, linear arrays were installed at South Sister, in 1986, and leveling lines were established at Newberry Crater in 1986 (Yamashita and Doukas, 1987).

Survey Results

Two decades of data at the Hawaiian Volcano Observatory have shown single-setup leveling to be a reliable method of measuring ground deformation at Hawaiian shield volcanoes, but our experience on Cascade stratovolcanoes has not been as conclusive.

SSL stations at Lassen Peak, Mount Shasta, and Mount Rainier have shown randomly oriented tilt vectors; however, tilt vectors on Mount Hood (fig. 14.4) are more uniform. The random tilt patterns on some Cascade volcanoes cannot be readily explained. One explanation could be that as all of our tilt stations are at high elevations where freeze-thaw cycles often occur, these conditions may affect the stability of the bench marks and are enough to affect the precision that we require for meaningful results.

Because of the unsatisfactory results of SSL data on Cascade volcanoes, we have opted in favor of leveling lines (Dzurisin, chapter 12; Yamashita and Kaiser, chapter 13). These leveling lines are linear or L-shaped lines that range from a few hundred meters to as much as 190 km in length.

One advantage of a level line is that there are usually more than three bench marks in the network, and the loss or instability of any one mark is not critical to the integrity of the system. In the SSL system, if one mark is lost or disturbed the entire station is no longer usable. Also, an SSL site requires a large enough area to accommodate an SSL station and still be level enough that the maximum length of the level rod is not used. Terrain is not so critical for a linear array.

Another advantage of a longer base line is the ability of the system to tolerate slight bench-mark instability. On an SSL base of 40 m, a change of 0.05 cm would give a tilt change of 12.5 µrad while a change of 0.05 cm on a line 250 m long would be 2.0 µrad, and 0.5 µrad on a line 1 km long.

The disadvantage of a level line when compared to an SSL station is that it is more labor intensive. Two people can measure an SSL station in about 25 minutes, allowing a number of tilt stations to be measured in a day. A level line on the other hand requires a minimum of four people and about 1-1/2 hours per kilometer on level ground, longer on steep terrain. The areal coverage at this rate is substantially less than that covered by the SSL method, but the results are much more definitive and worth the extra time and effort in certain circumstances.

Another disadvantage of a linear array is that some assumptions about the plumbing system of the volcano have to be made. As it is not possible to compute a tilt component from a linear array, we assume that any deformation will occur at the center of the volcano, and therefore all of our linear arrays are installed radially from the summit. The fallacy of this assumption is that deformation can and does occur on the flanks, and depending on the location of the deformation relative to the linear arrays, this deformation could go undetected or be misinterpreted.

The best solution to this problem is to run a line perpendicular to the radial line, creating a cross-shaped or L-shaped array. Level arrays such as those at Crater Lake (Yamashita and Doukas, 1987) are probably the most efficient of the three different configurations.

SUMMARY

Data from Hawaii have proved conclusively that SSL is a reliable and effective method of monitoring for deformation on basaltic volcanoes lacking freeze-thaw problems; our experience with SSL on Cascade volcanoes so far has been inconclusive. We have no plans to abandon the existing tilt sites, and these stations will be reoccupied in future years, although our inclination is to install more linear or L-shaped arrays.

Ideally, a combination of tilt arrays and leveling lines such as those used at Kilauea has the advantage of using the tilt arrays as a quick monitoring tool to cover a large area in the shortest amount of time. Depending on the results of the tilt arrays, the level lines can be occupied for more quantitative results.

The advantages and disadvantages of both SSL and linear arrays have been discussed previously. The user should determine which system best suits the needs for each situation.

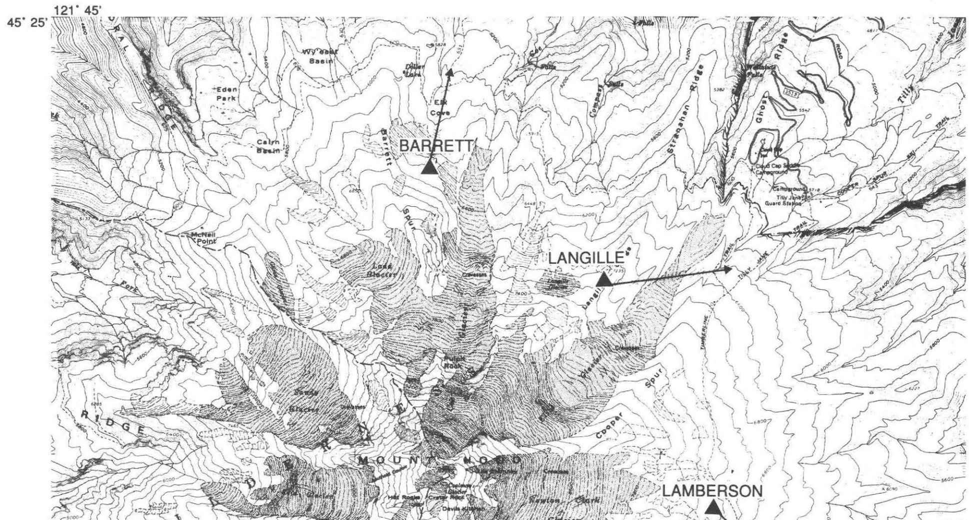

Figure 14.4. Vertical displacements at Mount Hood tilt stations, August 1983 to August 1984. Contours are in feet.

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15. A Single-Setup Trigonometric Leveling Method for Monitoring Ground-Tilt Changes

By John W. Ewert

ABSTRACT

Geodetic ground-tilt studies have been used to monitor volcanic activity since the 1960's. Development of more precise theodolites and high-quality, compact, lightweight electronic distance meters (EDM's) in the past 10 years has brought about a dramatic increase in the use of trigonometric leveling for high-order vertical control studies. A system for measuring ground tilt trigonometrically, employing a theodolite, EDM, and target/prism sets has been developed for use in volcanologic studies. This system enables the measurement of single-setup bench-mark arrays as much as 4 times larger than is possible with a level instrument at a single instrument setup site. The system is more compact and thus easier to transport in remote or rugged terrain than is the equipment for classical leveling. Data reduction is slightly more involved but is still simple if a programmable calculator or portable computer is used. A comparison of the two methods on the same triangle shows them to be approximately equivalent in their ability to measure ground deformation.

INTRODUCTION

Single-setup leveling (SSL) (also called dry tilt or tilt-leveling) has routinely been used at the Hawaiian Volcano Observatory (HVO) to measure and detect changes in ground tilt on Hawaiian volcanoes since the technique was developed in 1968 (Kinoshita and others, 1974). SSL has been used at Mount St. Helens (Lipman and others, 1981); at various volcanoes in the Cascade Range, including Mount Shasta and Lassen Peak (Dzurisin and others, 1983); at La Soufrière volcano, Guadeloupe (Fiske and Shepherd, 1990); on various active volcanoes within the Taupo volcanic zone, New Zealand (Otway and others, 1984); and at Karkar volcano, Papua New Guinea (McKee and others, 1981). The technique is also currently used in Costa Rica by Observatorio Volcanologia y Sismologia de Costa Rica (OVSICORI) on Arenal and Poas volcanoes and in Colombia by Instituto Geologico y Minas (INGEOMINAS) at Ruiz and Galeras volcanoes. A complete description of the original spirit-level tilt technique can be found in Kinoshita and others (1974). Yamashita (1981) also presented a detailed description, and a Spanish translation of this paper was published by Van der Laat (1982). The SSL method is also described in chapter 14 of this volume.

The SSL technique requires the use of two or three long Invar rods and rod stays, a level, and a micrometer plate. The bench-mark array is typically an equilateral triangle, 40 m on a side. When 3-m rods are used, sites on which a 40-m equilateral triangle can be placed are limited to relatively level areas with no more than 2.5 m elevation difference between monuments at the triangle apices (1.5 m if 2-m rods are used). Sites such as these tend to be rare on the flanks of steep-sided volcanoes. In addition to site limitations, 3-m Invar rods are difficult to transport on small vehicles, pack animals, and aircraft. These factors combine to make SSL of limited utility on many composite volcanoes and prompted me to find an alternate method that was both portable and suitable for use in steeply sloping terrain. A compact, precise method of single-setup trigonometric leveling (SSTL) was developed using a theodolite, electronic distance meter (EDM), and three target/prism pairs mounted on plumb poles.

SYSTEM REQUIREMENTS

To determine the instrumental requirements for the SSTL method of measuring ground tilt, the desired threshold of tilt detection must first be decided. Ground tilts of several tens to several hundreds of microradians (µrad) are common before volcanic eruptions (Newhall, 1984), and in this light a detection threshold of 7 µrad was decided as appropriate. This 7 µrad figure represents a two-sigma confidence level in measurements between pairs of marks and is comparable to, although slightly less sensitive than, the 2–3 µrad detection capabilities of the SSL technique reported by Kinoshita and others

(1974) and Sylvester (1978) for small-aperture (40 m) bench-mark arrays.

To meet this detection requirement, a theodolite capable of measuring zenith angles to 1 second of arc or better is required. Depending on the instrument and operator, a 1-second micrometer theodolite can measure angles accurately to ± 0.7 to ± 1.4 seconds of arc (Ruger and Brunner, 1982). More precise micrometer theodolites and some electronic theodolites can measure angles to ± 0.5 second (Whalen, 1984). EDM manufacturers report the accuracy of their instruments as plus-or-minus a constant number of millimeters (usually 1–5) plus a few parts per million (ppm). In short-range work, such as SSTL where measurements are typically over distances less than 100 m, the ppm figure is usually not of consequence. Therefore, an EDM with as small a constant error as possible is desirable and is actually the limiting factor in the accuracy of the method. Finally, the target/prism pair must be capable of being fixed at a height that can be reproduced to within a few tenths of a millimeter with each reoccupation of the station. Several theodolites, EDM's and target/prism mounting systems meet these specifications.

The working limits of the method were determined by analyzing random reading and pointing errors arising from angle measurements of differing precision, the constant error from EDM's, and a 0.2-mm uncertainty in establishing the target heights. Calculations were made following the methods outlined in Buckner (1983, p. 209) and Davis and others (1981, p. 124), treating as level loops the equilateral tilt triangles with the

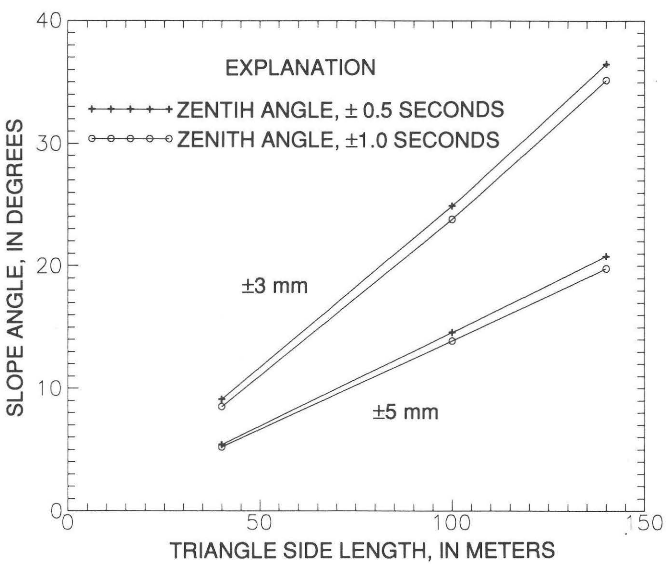

Figure 15.1. Maximum ground slope on which ground-tilt can be measured to approximately ± 7 μrad with EDM's of ± 3 mm and ± 5 mm accuracy and theodolites that can measure zenith angles to ± 0.5 and ± 1.0 second of arc.

instrument station in the middle, and distributing the accumulated error over the three legs. The ± 7 μrad limit was used to determine the approximate maximum ground slope over which ground tilt could be determined trigonometrically. Figure 15.1 demonstrates the topographic flexibility of this system.

SYSTEM DESCRIPTION

The trigonometric leveling system presently in use consists of a Wild T-2000 electronic theodolite, a Wild DI-5 EDM, and three target sets with tripods (figs. 15.2, 15.3). Instrument specifications reported by Wild and confirmed by Whalen (1984) indicate that the mean of

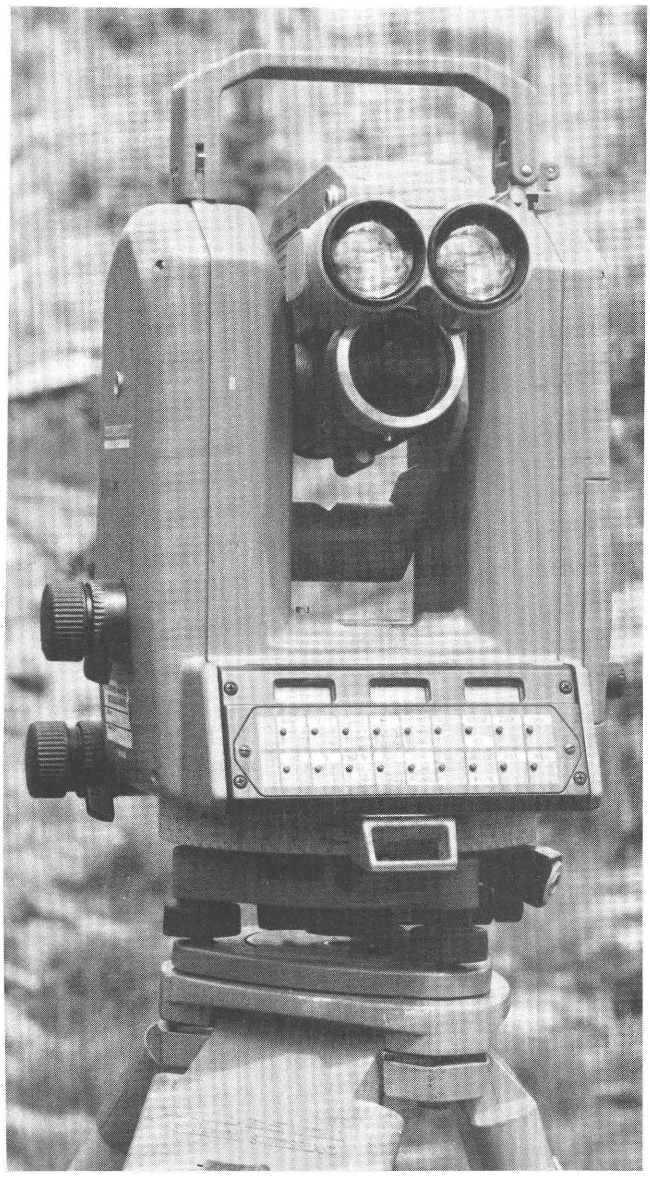

Figure 15.2. T-2000 electronic theodolite with DI-5 EDM mounted on theodolite telescope.

the direct and reverse zenith angles measured by the T-2000 is accurate to ± 0.5 seconds of arc (standard error). The DI-5 EDM measures distances reportedly accurate to ± 3 mm, and ± 2 ppm. The target sets for this system consist of tilting target/prism combinations, spaced apart the same vertical distance as the theodolite telescope and EDM to negate eccentricity. These target sets are mounted on aluminum plumb poles held upright by lightweight tripods. Each tripod-target set is labeled and placed in the same configuration on all the triangular bench-mark arrays.

SITE INSTALLATION

The ideal SSTL monument array is an equilateral triangle as large as practical to measure accurately. The exact orientation of the triangle is determined by the geological structure being studied. On steep-sided volcanoes, one side of the triangle is first laid out radial to the vent or summit area, and the third monument is positioned in the most favorable site. Although the exact configuration of the triangle is not important, the sighting distances should be approximately equal, and the ground slope should be nearly uniform between the instrument and targets to minimize refraction errors.

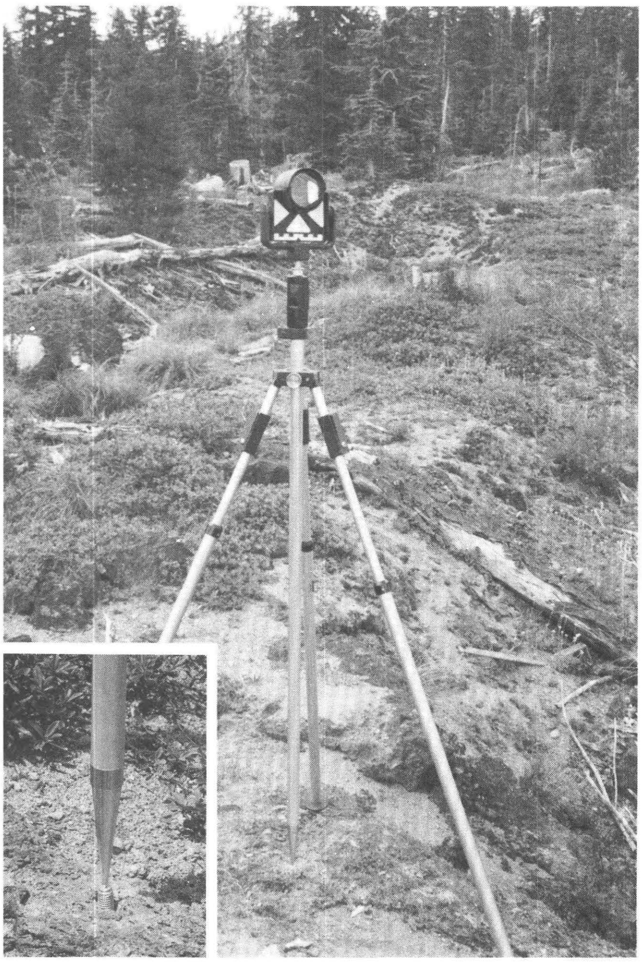

Figure 15.3. Complete target/reflector system, set up over an expansion bolt (inset) in a lava flow. Target-cross and prism are set apart vertically the same distance as theodolite telescope and EDM.

The southernmost vertex of the triangle is labeled X, and the other vertices are labeled Y and Z in counterclockwise order (fig. 15.4). To calculate the tilt vector, the slope distances from monument X to Y and Z must be measured (LY and LZ in figure 15.4). This can be done with a tape measure directly, if the triangle is not too large, or indirectly by measuring the slope distance and horizontal angle from the instrument site in the center of the triangle to each station with the EDM and theodolite and solving the triangle. Bearings from east must also be taken from X to Y and X to Z with a compass to orient the triangle (θ and ϕ in figure 15.4). The triangle parameters are assumed not to change and are used as constants in subsequent tilt calculations.

The formulas to determine the components of the tilt vector and magnitude with the SSTL system are:

$$\tau(N) = \left[\left(\frac{\cos\phi}{LY\sin(\phi-\theta)}\right)\cdot\Delta(Y-X) - \left(\frac{\cos\theta}{LZ\sin(\phi-\theta)}\right)\cdot\Delta(X-Z)\right]\cdot 10^6$$

$$\tau(E) = \left[\left(\frac{-\sin\phi}{LY\sin(\phi-\theta)}\right)\cdot\Delta(Y-X) + \left(\frac{\sin\theta}{LZ\sin(\phi-\theta)}\right)\cdot\Delta(X-Z)\right]\cdot 10^6$$

Where LY, LZ, $\Delta(Y\text{-}X)$ and $\Delta(X\text{-}Z)$ are in meters and $\tau(N)$ and $\tau(E)$ are in microradians (original equations

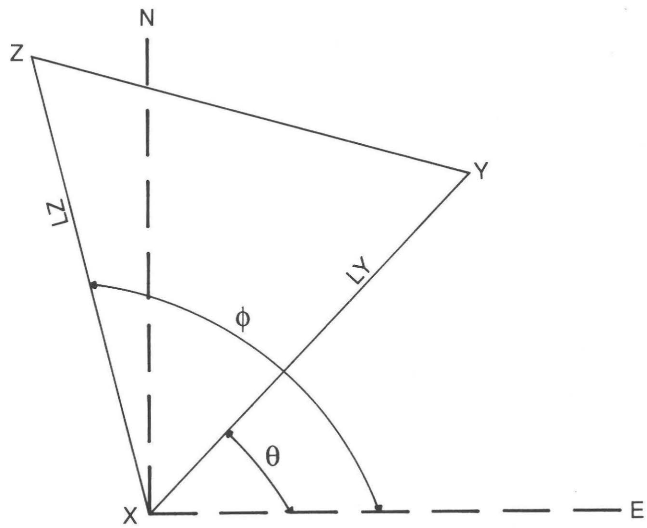

Figure 15.4. Physical layout of representative tilt station.

modified from Eaton, 1959). Compare these equations with those found in Yamashita (chapter 14) for use with the SSL method. The two methods of measuring the elevation differences lead to the sign change in the first terms of each equation.

Monuments

The monuments for a single-setup leveling array should be placed in similar substrates to minimize spurious noise effects caused by differential substrate response to diurnal thermal or seasonal hydrologic effects. Monuments placed in bedrock and those placed in soils should not be mixed in the same SSL or SSTL monument array. Bench-mark stability is critical when leveling or trig-leveling over short distances (Dzurisin, chapter 12). Therefore, redundant bench marks should be placed wherever possible to provide the means for checking the stability of individual bench marks in the array.

Several types of monuments can used as measurement points. Where bedrock is present (usually a lava flow), stainless steel anchor bolts or bench marks are placed in holes drilled in the rock (Doukas and Ewert, chapter 11). In our experience, bedrock is the most stable (and thus preferred) substrate for monument installation. Lacking bedrock, several methods of monument construction are possible. These include (1) driving a single rod straight down, coupling more rod as needed, until it will go no farther and affixing a bench mark to its top at or just below ground level, or (2) constructing a reinforced stonework cairn in which a mark can be placed (Floyd, 1978; Doukas and Ewert, chapter 11).

MEASUREMENT PROCEDURES

The target sets and plumb poles are numbered 1 to 3 and set up in the same configuration on every triangle; 1 on X, 2 on Y, and 3 on Z. The target tripods are leveled and centered over the monuments, and the theodolite/EDM pair is precisely leveled in the center of the triangle. The triangle is treated as a leveling loop beginning on the YX side, with the initial reading on the Y target followed by two readings on X, two readings on Y, and a final reading on X (table 15.1). Each reading consists of measuring direct and reverse zenith angles and the slope distance. The zenith angle is computed for each reading, and successive Y-X angular differences are computed. In our experience, if the spread of the differences of the three sets is less than 2 seconds, the XZ leg can be then be read. If the spread is larger than 2 seconds, additional readings should be made until consistency is obtained. The last reading on the X target is carried down as the first reading for the X and Z leg (table 15.1). Two readings are taken on the Z target, followed by two readings on the X target, and finally one reading on the Z target. Again, a maximum spread of 2 seconds is allowed. As a measure of the accuracy of the readings taken, the closure leg ZY is read in a similar manner.

When the three sides of the triangle have been read, the averages of the angular differences are summed to find the "field closure," which is not the closure of elevation differences but rather a measure of how consistently the angles were measured (table 15.1). Ideally, the differences should sum to zero. In practice, if the sum is less than or equal to 1.0 second the data are considered good. If the readings sum to a greater value, the triangle should be remeasured.

Our experience with the T-2000/DI-5 system has shown that sighting distances up to 130 m can be used with good results if there is no strong heat shimmer, but that sighting distances less than 100 m allow for the best repeatability of measurements in a wide range of viewing conditions.

Closure Determination of Error and Data Reduction

Recording and data reduction for the SSTL method of tilt surveying are slightly more involved than for the original SSL method. Position I and position II (direct and reverse) readings must be taken and the average angle computed. Temperature and pressure readings must be taken to correct the distance data. Because the sightings are generally taken parallel to the ground, temperatures are taken at instrument height. This is typically a very small correction, on the order of tenths of a millimeter, but could be significant in extreme conditions.

Elevation differences between the instrument and the targets are calculated by taking the cosine of the zenith angle and multiplying by the corrected slope distance (table 15.2). Once the elevation differences between the targets are obtained, the data reduction proceeds exactly like the original method outlined by Yamashita (chapter 14) and reproduced as an example below.

If a programmable calculator or laptop computer is available, a simple BASIC program can be written to calculate the exact closure and perform the rest of the data reduction while on site. To facilitate the computations by lessening the amount of data entry,

Table 15.1. Example of successive readings of the tilt triangle legs.
[Angles are the average of zenith direct and zenith reverse readings]

Individual target reading		Individual target reading		Angular difference between targets
Y target reading		**X target reading**		
Angle	Distance	Angle	Distance	
[1*]90° 37′ 10.7″	22.960 m	90° 39′ 42.9″	22.943 m[*2]	Y1-X2 = -2′ 32.4″
[4*]90° 37′ 09.7″	22.960 m	90° 39′ 42.7″	22.943 m[*3]	Y4-X3 = -2′ 33.0″
[5*]90° 37′ 10.4″	22.960 m	90° 39′ 42.5″	22.943 m[*6]	Y5-X6 = -2′ 32.1″
Y - average = 90° 37′ 10.3″		X - average = 90° 39′ 42.7″		Average Y - X = -2′ 32.4″ Spread = 1.2″
X target reading		**Z target reading**		
Angle	Distance	Angle	Distance	
90° 39′ 42.5″	22.943 m	90° 25′ 50.9″	23.043 m[*1]	X6 - Z1 = 13′ 51.6″
[3*]90° 39′ 42.3″	22.943 m	90° 25′ 51.9″	23.043 m[*2]	X3 - Z2 = 13′ 50.4″
[4*]90° 39′ 42.2″	22.943 m	90° 25′ 50.9″	23.043 m[*5]	X4 - Z5 = 13′ 51.3″
X - average = 90° 39′ 42.3″		Z - average = 90° 25′ 51.2″		Average X - Z = 13′ 51.1″ Spread = 1.2″
Z target readiing		**Y target reading**		
Angle	Distance	Angle	Distance	
90° 25′ 50.9″	23.043 m	90° 37′ 10.2″	22.960 m[*1]	Z5 - Y1 = -11′ 19.3″
[3*]90° 25′ 51.3″	23.043 m	90° 37′ 09.2″	22.960 m[*2]	Z3 - Y2 = -11′ 17.9″
[4*]90° 25′ 51.5″	23.043 m	90° 37′ 09.2″	22.960 m[*5]	Z4 - Y5 = -11′ 17.7″
Z - average = 90° 25′ 51.5″		Y - average = 90° 37′ 09.5″		Average Z - Y = -11′ 18.3″ Spread = 1.6″

Field closure = (Y - X) + (X - Z) + (Z - Y) = +0.4″ Note that 0.4″ at a shot length of 23 m is approximately equal to 0.000045 m

* Order in which readings are taken.

the average zenith-angle reading to each target on each leg of the triangle is calculated (table 15.1) and the elevation difference found using the averages (table 15.2). The result is the same as if the elevation difference for each set were calculated and then averaged.

If no programmable calculator or computer is available, the results of the survey can be calculated in the field with a simple calculator, albeit laboriously.

Example Calculation

In the following example LY = 40.97 m, LZ = 40.36 m, θ= 46.0°, and ϕ = 102°.

Triangle Side Differences (meters)

Y-X	0.01676 m
X-Z	-0.09169 m
Z-Y	0.07493 m (calculated)
Z-Y	0.07487 m (observed)
	-0.00005 m closure error

This closure is then distributed equally among the three legs of the triangle. In this case 0.00002 m would be added to each leg.

Adjusted Reading				Previous Reading	
6-July-88		Change (m)		30-June-88	
Y-X	0.01678	ΔY-X	-0.00009	Y-X	0.01687
X-Z	-0.09167	ΔX-Z	0.00014	X-Z	-0.09181
Z-Y	0.07489	ΔZ-Y	-0.00001	Z-Y	-0.07488

Reduced version of tilt equations using above values:

$$\tau(N) = (-0.0061(\Delta Y\text{-}X) - 0.0208(\Delta X\text{-}Z)) \cdot 10^6$$
$$\tau(E) = (-0.0288(\Delta Y\text{-}X) + 0.0215(\Delta X\text{-}Z)) \cdot 10^6$$
$$\tau(N) = (-0.0061(-0.00009) - 0.0208(0.00014)) \cdot 10^6 = -2.4$$
$$\tau(E) = (-0.0288(-0.00009) + 0.0215(0.00014)) \cdot 10^6 = +5.6$$

Magnitude in microradians = $\sqrt{N^2 + E^2}$ $= \sqrt{-2.4^2 + 5.6^2} = 5.8$

Bearing in degrees = $\tan^{-1}\left(\frac{E}{N}\right) = \tan^{-1}\left(\frac{5.6}{2.4}\right) = 66.8$

If τN is positive, vector is in the north half, down. If τN is negative, vector is in the south half, down. If τE is positive, vector is in the east half, down. If τE IS negative, vector is in the west half, down

The bearing is measured from the abscissa into the indicated quadrant.

Thus the magnitude is 5.8 µrad in a S. 66.8° E. direction.

Precision

As of this writing, the T-2000 based SSTL system has been in use for about a year and a half. Figure 15.5 shows a comparison of tilt vector components from the same triangle, derived from measurements made with the SSTL system and an SSL system. The tilt triangle was set up in the parking lot of the Cascades Volcano Observatory to allow frequent measurement for comparative purposes. The two methods agree quite well in terms of sense and magnitude of the apparent deformation.

The precision of this theodolite-based system is somewhat less than that of a level-based system, but as was pointed out by Savage and others (1979) and Sylvester (1978), factors such as bench-mark instability and topographic effects make the measurement of ground tilt with small-aperture bench-mark arrays accurate to only about ± 10 µrad regardless of the measuring precision.

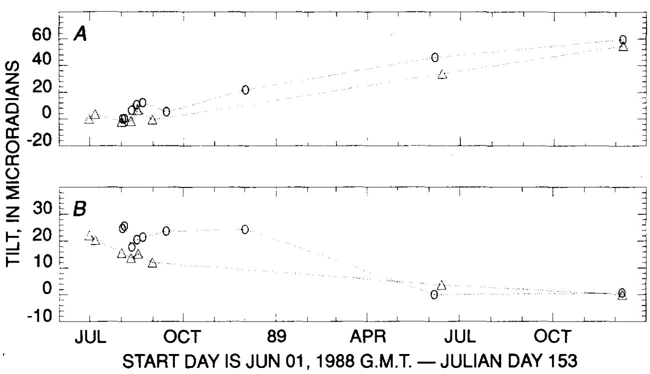

Figure 15.5. Comparison of tilt vector components from same triangle, measured with the level and trigonometric methods. *A*, North component. *B*, East component. Triangles represent SSTL method, circles represent SSL method.

Table 15.2. Elevation differences between instrument and targets calculated by multiplying cosine of zenith angle by the corrected slope distance.
[Zenith angles and distances from table 15.1]

Elevation differences
Y-X leg
Y-target
(22.960 m) · cos(90°37′10.3″) = -0.24826 m
X-target
(22.943 m) · cos(90°39′42.7″) = -0.26502 m
Y-X = 0.01676 m
X-Z leg
X-target
(22.943 m) · cos(90°39′42.3″) = -0.26498 m
Z-target
(23.043 m) · cos(90°25′51.2″) = -0.17329 m
X-Z = -0.09169 m
Z-Y LEG
Z-target
(23.043 m) · cos(90°25′51.2″) = -0.17329 m
Y-target
(22.960 m) · cos(90°37′09.5″) = -0.24817 m
Z-Y = 0.07487 m

Field testing thus far indicates that, on a triangle with sides of about 100 m, results can be reproduced to ± 5 µrad on each of the tilt components over a period of months. The system has yet to be tested on a volcano through the course of an eruption, but the indicated precision lies well within the magnitude of ground tilt often measured on active volcanoes. Therefore, although slightly less precise than the instrumentation typically used for geodetic leveling, the trigonometric system is suitable for measuring ground tilt on volcanoes.

SUMMARY

The single-setup trigonometric leveling system is a compact alternative method of measuring ground-tilt changes on volcanoes. This leveling system permits volcanologists to obtain tilt data at locations previously unfeasible and greatly facilitates work on remote volcanoes where access is often by jeep or foot, and transportation of bulky equipment is difficult. Triangular SSTL benchmark arrays can be up to four times larger than the SSL arrays, thereby allowing a longer baseline to be measured, and ideally creating a more precise measure of vertical deformation. The relative advantages

Table 15.3. Relative advantages and disadvantages of trigonometric system and the level system

Trigonometric system	Level-based system
Advantgages	
Easily portable	Simple and easy to learn
Same equipment can be used for EDM networks and triangulation	Equipment is widely available
Better topographic siting flexibility	Equipment is less expensive
Larger single-setup bench mark arrays lessen the effects of minor bench-mark instability	The same equipment can be used for conventional geodetic leveling of long traverses
Disadvantages	
Slightly less precise	Larger aperature arrays require much more time to measure in steep terrain
More expensive by a factor of 2 to 3	Long levelling rods are difficult to transport
More difficult to directly compare data from previous surveys while in the field	Topographically acceptable sites are difficult to find on steep-sided volcanoes and may not be best for monitoring purposes
Data reduction slightly more involced	Small aperature single-setup arrays are more susceptible to minor bench-mark instability

and disadvantages of the trigonometric system and the level-based system are listed in table 15.3.

The system described here can also be used to measure level lines and small trilateration networks (the DI-5 EDM can measure 2.5 km to a single prism). If a more powerful EDM, capable of measuring distances of 10 km or more, is used with the precise theodolite, the result would be an instrument system capable of performing all geodetic volcano monitoring tasks. The biggest drawback of the currently used T-2000 based system, or any trigonometric leveling system, is cost. Precise theodolites are expensive, and a complete system, such as that described herein, cost approximately $28,000 in 1986, whereas an SSL system such as that described by Yamashita (chapter 14) would have cost approximately $10,000 in 1986. The higher cost is partly offset by the versatility of the trigonometric system and by the fact that separate instruments need not be purchased to measure vertical and horizontal deformation.

ACKNOWLEDGMENTS

The development of the single-setup trigonometric leveling method has benefited through thoughtful comments and hard questions posed by Dan Dzurisin (USGS/CVO) and Arnold Okamura (USGS/Hawaiian Volcano Observatory).

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16. Lake-Level Monitoring as a Tool for Studies of Crustal Deformation

By Jack W. Kleinman *and* Peter M. Otway[1]

Abstract

A lake can be used as a large natural tiltmeter by measuring changes in water-surface elevation relative to nearby stable bench marks at two or more sites around it. Differential gaging systems can be either permanently installed or portable. The precision of either type of system is directly proportional to the size of the lake; tilt resolution increases with lake size. Permanent systems can accurately measure water level to within 0.5–1 mm, the equivalent of 0.5 to 1.0 microradian on a small (1-km wide) lake. Although portable systems can attain a similar precision on larger lakes, their precision on a small lake is estimated to be 1–3 microradians, depending on environmental conditions at the time. Factors such as wind conditions, seiche, instrument precision, temperature and barometric effects, and bench-mark stability need to be taken into consideration when gathering lake-level data.

INTRODUCTION

Monitoring regional crustal deformation can be useful in gaging volcanic restlessness. A lake located within an area of crustal deformation presents a unique monitoring opportunity. This paper presents the principles behind monitoring lake levels to detect crustal deformation, describes several different types of systems, and explains common sources of error associated with this technique. It is intended as an overview for someone interested in initiating a lake-level monitoring program. It should be stressed, however, that all lakes are unique; monitoring techniques will need to be adapted to each situation.

[1]New Zealand Geological Survey, Department of Scientific and Industrial Research, Private Bag, Taupo, New Zealand

PRINCIPLES

The operative principle in monitoring the level of a lake to study ground deformation is that its surface will remain level (horizontal) no matter how the surrounding crust is deformed. Therefore, relative changes in vertical displacement between fixed points and the surface of the lake can be used to determine the relative vertical changes between the points. In effect, the lake is used as a large tiltmeter.

The elevation of the water surface is determined relative to two fixed points (fig. 16.1*A*). They can be either above or below water level, depending on the type of instrument and monitoring system used. Water-surface elevations at both stations are then remeasured at a later time (fig. 16.1*B*, *C*). The differences in relative water-surface elevation are computed for both stations. One station is considered fixed; any water-level change at that station is interpreted as a universal change. Tilt is computed as the change in height between stations (4 cm in fig. 16.1*C*) divided by the distance between stations (1 mm/km = 1 μrad).

Note that displacement at any one station can be measured only relative to another station on the lake. Thus lake-level monitoring cannot detect vertical deformation that affects the whole lake equally. In a large lake with many instrument stations, localized areas of uplift or subsidence may be recognized.

LOCATING LAKE-LEVEL MEASUREMENT SITES

The size and shape of the lake, the required measurement precision, and the extent of expected deformation determine the optimum network configuration. The most important consideration is the spacing between stations. The accuracy of lake-level measurement is limited largely by the precision to which the mean water-surface level can be measured. A large component of the error in determining relative lake level is approximately the same at all measurement sites; thus higher resolution of ground tilt is attained with greater spacing between stations. For this reason, large lakes are generally better suited for monitoring than small ones.

Crustal deformation is easiest to detect if the line between stations is oriented radially from the suspected deformation source. For this reason, a long, narrow lake oriented tangentially with respect to a volcano or other deformation source would not be favorable for detecting tilt, even if the spacing between measurement sites were very large. For example, if two points subside or uplift equally, this tilt would go undetected unless other stations were measured. Stations should therefore be located at different distances from the suspected deformation source.

The number of stations on a lake should be increased in accordance with the extent of deformation. If uniaxial tilting is occurring, two to three widely spaced measurement sites may be sufficient. If deformation occurs on a scale smaller than the lake or is particularly complex, additional measurement stations enable the detection of localized areas of deformation.

Yellowstone Lake in Wyoming, the site of a lake-level monitoring program since 1987, provides a good example of network configuration. Five stations are used to monitor this lake (fig. 16.2). The margin of Yellowstone caldera crosses through the south part of

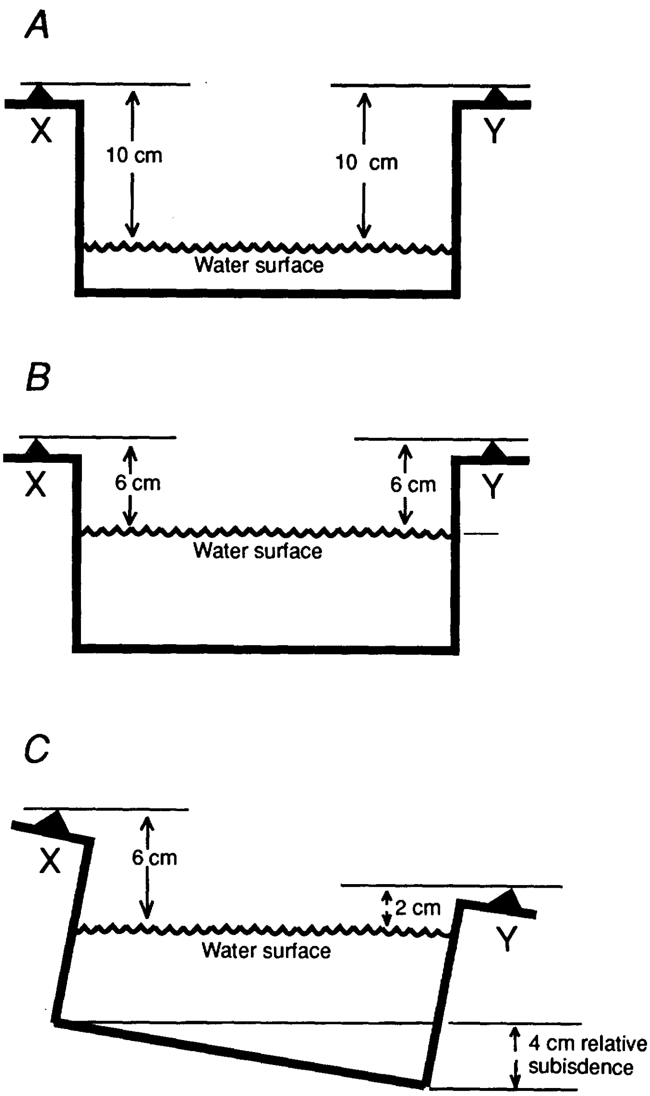

Figure 16.1. Idealized diagram demonstrating principles of lake leveling. Lake bottom is rectangular in profile. Triangles X and Y represent two fixed reference points on shore. *A*, Initial measurement of elevation difference between points X and Y and water surface. In this example, both are equal to 10 cm. *B*, Remeasurement at later time reveals elevation difference between points X and Y and water surface is now 6 cm, indicating a universal rise in water level of 4 cm. No detectable tilting occurred between points X and Y. *C*, Remeasurement at a later time reveals 6 cm of elevation difference at point X and 2 cm at point Y. Compared to initial measurement and using site X as fixed reference point, there has been 4 cm universal rise in lake level. At site Y, there is 8 cm elevation difference of which 4 cm is due to universal change in water level and 4 cm is due to subsidence of Y relative to X.

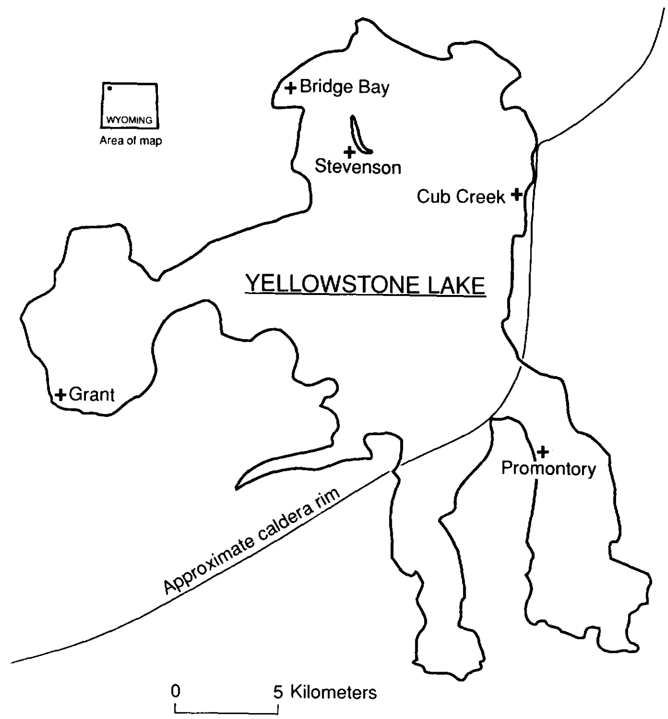

Figure 16.2. Outline of Yellowstone Lake, Wyoming, showing location of each lake-level monitoring station. Promontory station lies outside caldera and is used as a reference for elevation changes at other stations.

Yellowstone Lake. One of the gaging stations was established outside the caldera. Any deformation within the caldera can be detected by comparison with the station outside the caldera.

A long, narrow lake might require only two gaging stations for the computation of simple tilt, one near each end. As an example, San Andreas Lake in California (the site of a lake-level monitoring program since 1979) is such a lake and accordingly uses only two stations (Mueller and others, 1989). Additional stations between the end points could be established to help distinguish between regional and local tilts.

A third example is Lake Taupo in New Zealand, the site of ongoing lake-level monitoring since 1979 (Otway, 1986a, 1986b, and 1989). In that study, 22 different stations are now monitored 4-8 times per year (fig. 16.3). The crustal deformation occurring in the region is extensive and can be contoured given the relatively large number of measurement sites (fig. 16.4).

Both the San Andreas Lake and Lake Taupo studies are being carried out primarily to determine crustal deformation associated with active fault zones, although deep magmatic influences are also suspected at Taupo. The monitoring techniques are equally

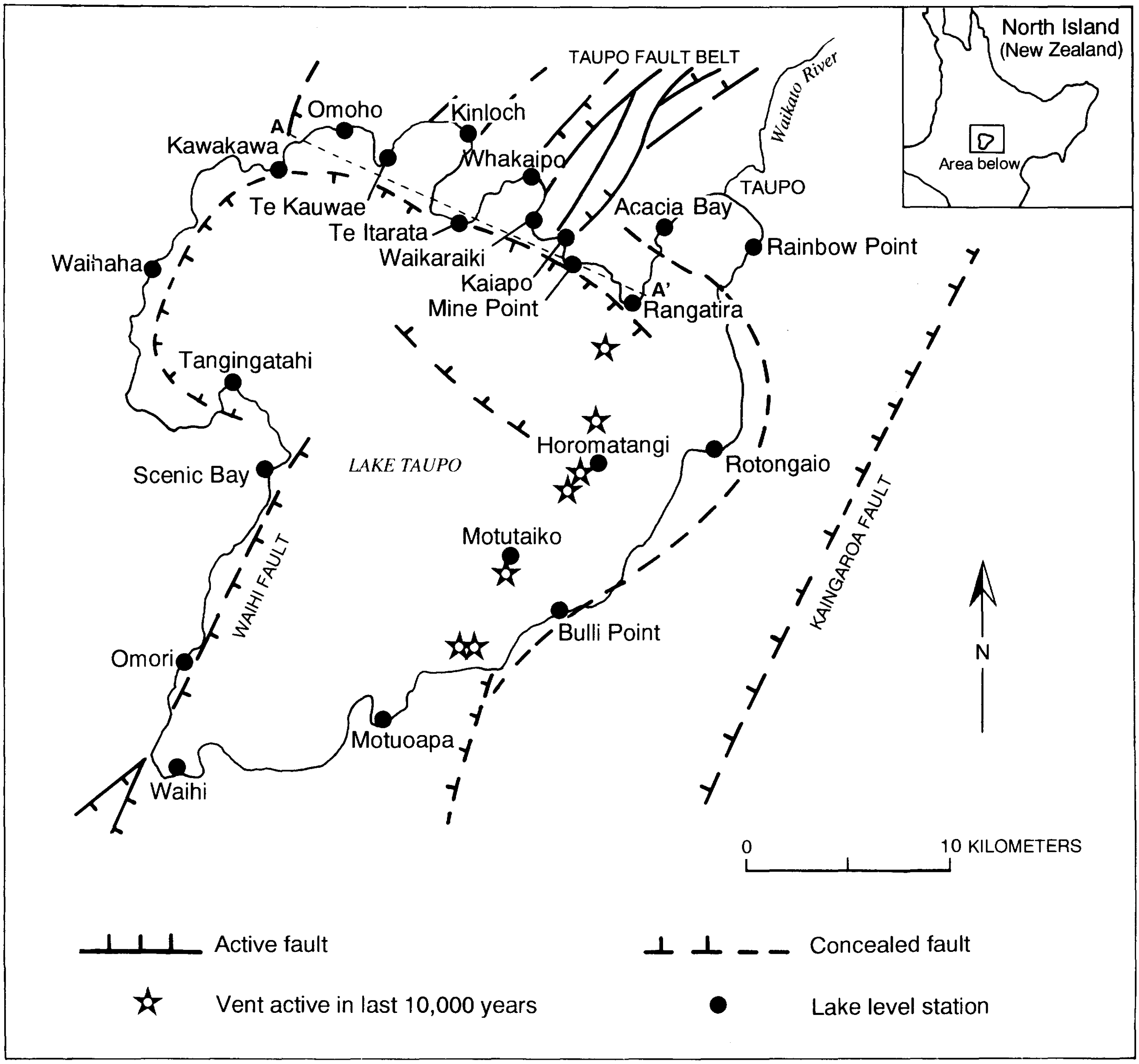

Figure 16.3. Lake Taupo, New Zealand, showing location of lake-level monitoring stations as well as Taupo Fault Belt and other local faults. Hachures on downthrown block.

applicable to lakes located in areas where volcanic deformation is the primary concern.

TYPES OF LAKE GAGING SYSTEMS

Two general types of systems can measure height of water in lake-level monitoring: permanent and portable. Common to both types is a gage that enables accurate measurement of water level. In a permanent system, the gage is mounted in the lake and the water level is recorded at regular time intervals. In a portable system, the gage is set up at a station, data are recorded, and the gage is then moved to the next site.

Permanent Systems

Instrumentation

A commonly used instrument to measure water level is a pressure transducer which measures the pressure due to the weight of the water column above it.

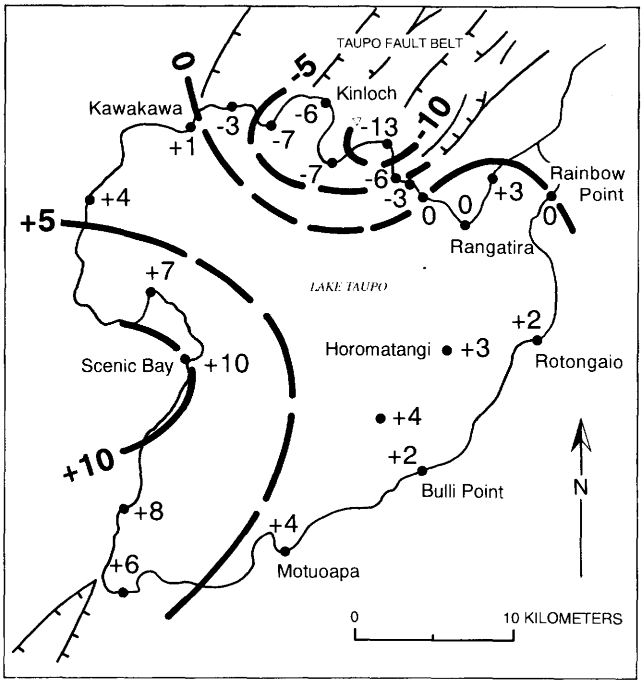

Figure 16.4. Vertical deformation (in millimeters) around Lake Taupo, November 7, 1987, to November 9, 1988. "Typical" annual deformation pattern at Lake Taupo indicates that center of Taupo Fault Belt is subsiding without associated seismicity at an average relative rate of nearly 10 mm/yr since a major earthquake swarm and deformation event in 1983 (fig. 16.11). Southern half of lake bed has undergone frequent episodes of short-lived deformation since then, often associated with minor seismicity. Hachures on downthrown block.

It is subject to errors caused by nonlinearity, temperature variations, and long-term drift. A transducer must be carefully selected on the basis of manufacturer specifications and then tested under conditions appropriate for field use. Another instrument is an ultrasonic sensor, which is placed in a stilling well to record the vertical distance between the sensor head and the water surface.

The monitoring at San Andreas Lake and Yellowstone Lake is done with permanent systems. The San Andreas Lake study uses Model 8020 Paroscientific Digiquartz pressure transducers chosen for their long-term stability and accuracy (Mueller and others, 1989). Each transducer has a 20-m dynamic range of water level, which is needed because San Andreas Lake is an artificial reservoir and can have large fluctuations in volume. The Yellowstone study presently uses Validyne Model P307 submersible pressure transducers with a 3-m dynamic range and an estimated ±0.5% accuracy. Workers from the Cascades Volcano Observatory (CVO) plan to enhance the current Yellowstone program by installing Paroscientific transducers with a ±0.01% accuracy and ±0.005% repeatability (the equivalent of 1 mm error when measuring 10 m of water), similar to those used in the San Andreas Lake study. Pressure transducers for monitoring lake levels need to be of sufficient quality to make repeatable, stable measurements to an accuracy of a few millimeters. Several significantly less expensive transducers with a lower accuracy (±2.0% linearity and ±0.15% repeatability, the equivalent of 200 mm error in a 10-m measurement) have also been used but were found to be unsuitable for lake-level monitoring, even after stringent calibration.

Testing and calibration

The transducers should be tested before installation. After placing a transducer in water and reading the output signal, the depth should be altered so that the resulting difference in output signal corresponds with the change in depth of water. If possible, differential tests should be done throughout the depth range of the transducer and over a range of water temperature appropriate for the field application. If more than one transducer is used, all should be run through these tests simultaneously. If the output curves are widely different, one or more of the transducers is malfunctioning. Minor variations between the curves can, however, be calibrated and corrected. Most high-quality transducers are calibrated in the factory, but this procedure is strongly recommended to confirm that they are functioning properly.

Installation

Once the sites for the permanent stations have been selected, the first step in establishing a permanent-installation lake-level monitoring program is to install the pressure transducers. The transducers will most likely be left at the site for long periods and hence will be subjected to seasonal lake-level fluctuations. The water level of Yellowstone Lake, for example, fluctuates by approximately 1–2 m annually. The pressure transducer should be mounted (1) so that it remains below water level throughout the low water period, (2) below wave base so that it is not damaged by breaking waves, and (3) below the common winter freezing depth so that it is not moved or damaged by ice. Transducers at Yellowstone Lake are installed about 1 m below the low-water level.

The method used for attaching the sensors to the bottom depends on the slope and material properties of the shoreline. The methods described here do not require the use of hydraulic drills or other heavy machinery, which is commonly prohibited by cost or environmental concerns. The transducers must be both immobile and below water-surface effects. Transducers are most stable if they can be attached to bedrock at a sufficient depth at the intended site. A perfect scenario would be a vertical bedrock cliff at the shoreline where holes could be drilled under water and the transducer attached using anchor bolts. If holes cannot be drilled under water, the transducer could be affixed to one end of a length of angle iron, and the other end (projecting out of the water) could be affixed to the bedrock. Another method is to attach the transducer to the bedrock using cement. A quick-setting cement works best when pouring under water. Cracks or other irregularities in the rock help cement adhere to the rock. Common sense and ingenuity need to be used, as every site is different. Lakes located in volcanic areas may be highly acidic; the anchoring and instrument housing materials used should be appropriate for the chemical conditions known to exist in the lake.

Lake bottoms are most commonly covered with sediment, as at both Yellowstone and San Andreas Lakes. At several sites on Yellowstone Lake, a single fencepost was driven almost 2 m into the sediment and the transducer strapped to it using hose clamps. This method is adequate for short-term studies but leaves some doubt as to the long-term stability of the mounting. The data from one of the transducers on Yellowstone Lake show an abrupt offset believed to have been caused by movement of the transducer on the fencepost or, more likely, movement of the whole fencepost.

A preferred method is to use anchor rods driven as far as possible, rather than to arbitrary depth. At San Andreas Lake, three rods were hammered into the lake bottom as far as they would go (typically more than 4 m) at each transducer site. A plate connecting the three rods was cemented in place for additional stability, and the transducer was then affixed to this baseplate. The rods commonly used are either 1.5-m lengths of copper-clad grounding rods with threaded ends or any convenient diameter of galvanized pipe. Copper grounding rods have the advantage of being of fairly small diameter (1.25 cm) and therefore easier to drive. One rod can be joined end to end with another rod using a threaded couple sleeve (see also Doukas and Ewert, chapter 11).

The battery power and data recorder or telemetry for the transducer are located on shore, connected by a power cable and a data cable to the transducer (fig. 16.5). All cables should be buried in a conduit to protect them from damage by waves, debris, wildlife, and vandals. Some types of transducers use atmospheric pressure as a reference and may also require a "dry" conduit hose connecting the transducer to the atmosphere.

Data collection

Data from permanent lake-level gaging systems can be collected using an on-site data logger or can be telemetered to a central recording station. Telemetry systems can use GOES satellite telemetry (as is currently used at San Andreas Lake) or a dial-up receiver (as is currently used at Yellowstone Lake). A more detailed description of applicable telemetry systems can be found in other chapters of this volume.

Portable Systems

Two types of portable gages for monitoring lake levels, one used by CVO scientists and one used at Lake Taupo, New Zealand, are presented as two different approaches to portable monitoring. The CVO system is experimental and uses an electronic linear-position sensor to measure lake levels. The Taupo system relies more heavily on manual readings.

CVO System

Instrumentation

The CVO portable system employs a linear-displacement transducer instead of the pressure transducer used in permanent systems. The Temposonics linear-displacement transducer claims a linearity of 0.05%, a repeatability of 0.001%, and no instrument drift. This device precisely measures the time interval between an interrogating electromagnetic pulse transmitted through an attached rod (the transducer waveguide) and a return electromagnetic pulse generated by a floating external permanent magnet (fig. 16.6). This time interval directly correlates with the position of the external magnet along the transducer waveguide. The dynamic range of the instrument depends upon the length of the transducer waveguide, 60 cm in this case. The linearity and repeatability of this model are 0.305 mm and 0.0061 mm, respectively.

Several adaptations were made to apply the linear-displacement transducer to portable lake-level measurements (fig. 16.6). The external magnet was mounted on a floating ring to represent water level accurately. A stilling well, needed to minimize wave effects and other small fluctuations in water level, was added to surround the transducer waveguide rod. A unit for vertically mounting the whole assembly (linear-displacement transducer, external magnet, and stilling well) from a standard surveying tripod was designed and fabricated. Care was taken to orient the transducer vertically, because a 3–4° deviation could cause an error of about 1 mm. A tripod with a domed head (the Kern system) was used so that the whole assembly can be rotated and tightened in the desired vertical position using a level bubble affixed to the horizontal base plate of the mounting unit.

Calibration

The linear-displacement transducer, like the pressure transducer, should be calibrated before and after each field survey. One method of calibration requires a tall container in which changes in water depth can be accurately measured. Tubing allows water to flow between the container and a transparent graduated buret permanently affixed to the outside of the container. The water level in the container is precisely read (to the nearest 0.5 mm) using the graduated buret, and the full range of the transducer can be tested. The electronics box of the transducer has adjustment potentiometers that can be used to adjust the null point and full-scale output of the transducer. Another calibration technique is to fabricate two different lengths of tube that can be used as spacers between the transducer head and the magnet ring. All the sensors used in the study can then be adjusted to have the same output with each spacer.

Measurement procedure

In the procedure for determining lake level with a portable system, the tripod is set up and the transducer and stilling well are mounted vertically using the fabricated mounting unit. The depth of water is not critical as long as the water surface is within the 60-cm length of the transducer waveguide. Three threaded bars (see fig. 16.6) connecting the lower end of the stilling

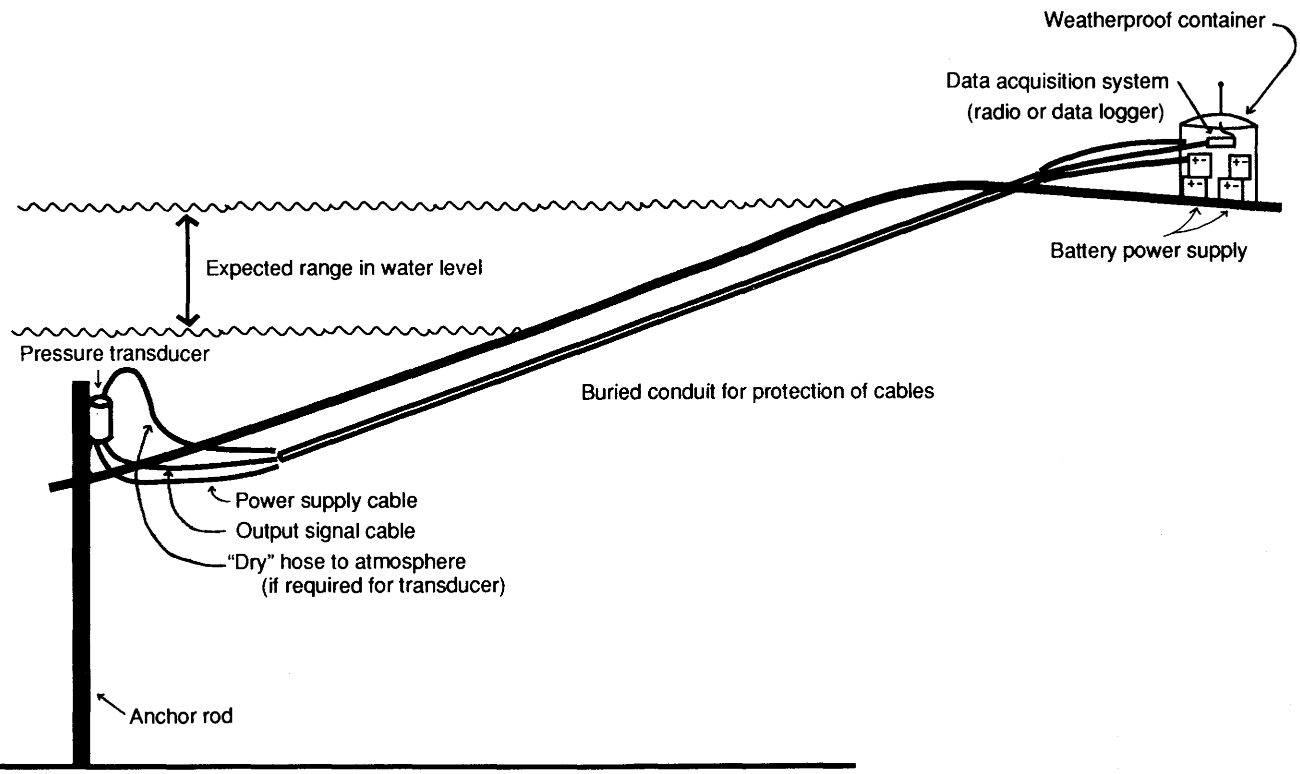

Figure 16.5. Sketch of a permanently installed lake-level monitoring system.

well to the legs of the tripod help stabilize the unit beneath the tripod.

Power is supplied to the transducer from a 12-volt battery on shore. A portable laptop computer is programmed to record the output data from the transducer and can also regulate the sample frequency. Alternatively, transducer-output data could be recorded manually at regular intervals with a voltmeter. The time needed and sample interval used to obtain an output voltage from the transducer that is representative of lake level depends on the specific application and the period of seiche oscillations. The final lake level is an average of transducer-output values through one to three complete seiche periods. When beginning a monitoring program, initial measurements must be made frequently over long time periods until the dynamics of the lake at each site are understood well enough to chose the most efficient sampling period and frequency required for accurate measurement.

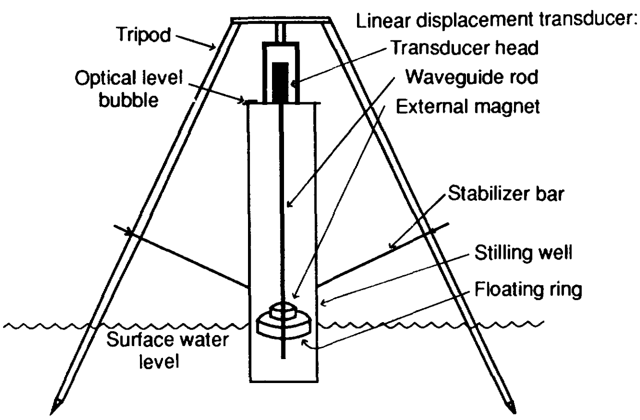

Figure 16.6. Instrumentation used for CVO portable system. Standard surveying tripod is used to hold gage.

Two separate measurements must be made with this portable monitoring system. The level of the lake surface is measured with the displacement transducer, and the vertical position of the transducer is measured relative to a reference point on the shore (fig. 16.7). The height of the transducer head above the water surface (the level of the floating magnet ring) is the averaged output signal from the transducer (1 in fig. 16.7). The output value of the calibrated displacement transducer (averaged for one to three seiche periods as discussed above) correlates with this height. The vertical distance from the transducer head to the top of the tripod (2 in fig. 16.7) should be constant for every setup. A 1.5-m section of fiberglass level rod is mounted onto the top of the tripod. Standard leveling techniques can then be used

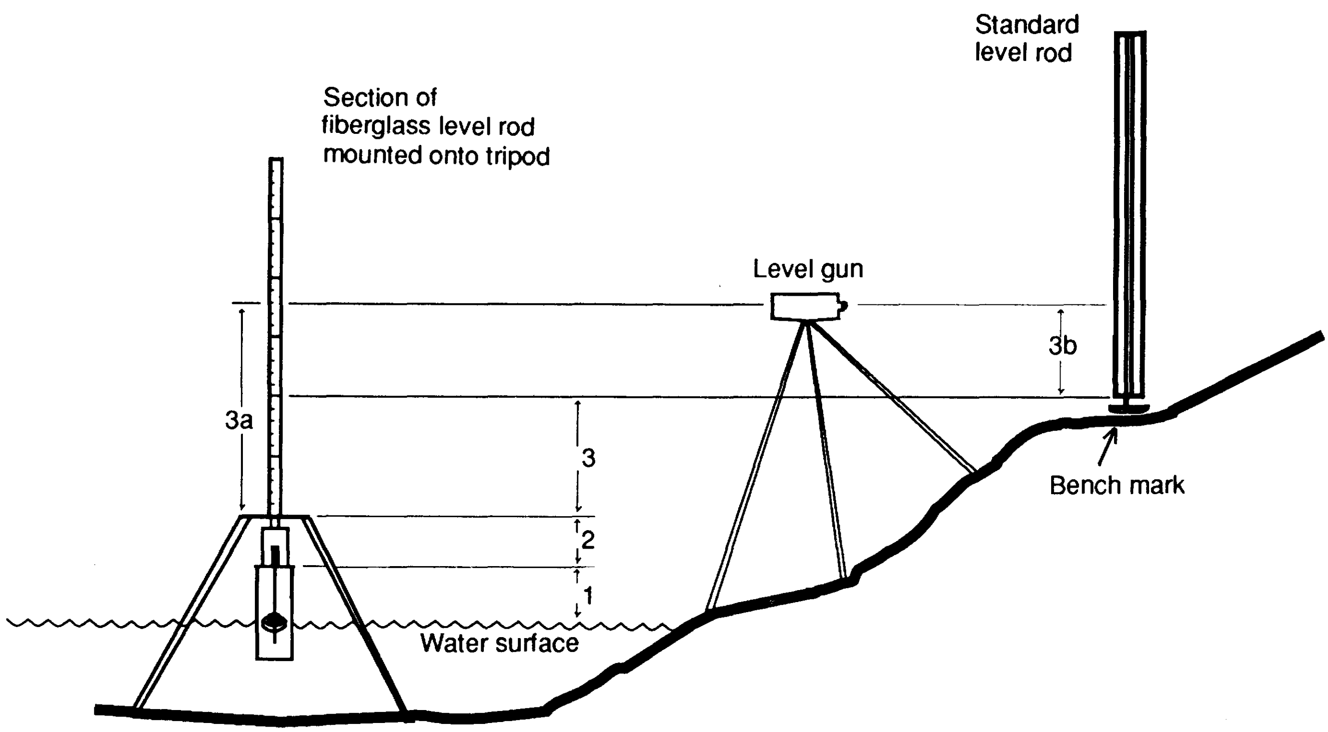

Figure 16.7. Water-surface elevation relative to a fixed point on land is equal to sum of height 1 (water-surface elevation relative to transducer) and heights 2 and 3 (position of transducer itself relative to bench mark). Height 1 is measured output from transducer. Height 2 is constant mounting-unit length. Height 3 is measured height to bench mark using standard leveling techniques. In this example, height 3 is equal to height 3a (height of level gun relative to tripod-mounted level rod) minus height 3b (height of level gun relative to bench-mark level rod).

to determine the height between the top of the tripod and the reference mark (3 in fig. 16.7). This measurement is made easier if the reference mark, preferably a bench mark cemented into bedrock or a large boulder, is as close to shore as possible and within the height range of the level rod on the tripod.

This procedure is repeated at each station around the lake. Ideally each station would have a gage, so that data could be collected from all sites synchronously. Alternatively, two sets of equipment can be used, one set in operation throughout the measurement period and the other moving to the different sites. This approach would minimize errors due to filling or emptying of the lake basin during the measurement period. If budget or personnel constraints prohibit such an approach, changes in basin filling can be found by reoccupying the origin at the beginning and end of each measurement day. Any ground tilting would most likely be negligible during such a short time period, and any changes found in lake level at the origin station would most likely be attributable to water inflow or outflow from the lake. Accuracy may be sacrificed, however, when conducting a monitoring program with only one instrument.

The measurements themselves can often be completed by one person while the portable computer is recording output from the transducer or between manual readings, so that the total time at each site is not much more than that needed to make a water-level measurement. Depending on the number of stations, their access, and the proximity of associated bench marks, a lake-level survey could be completed in one to four transducer days (that is, fewer days if two or more transducers are used concurrently).

Taupo System

Instrumentation

The water-level gage consists of a galvanized iron cylinder 0.6 m long and 50 mm wide (fig. 16.8). The cylinder hangs vertically by a chain from a hook and fills with water through a 1.5-mm orifice, effectively acting as a stilling well to damp out normal wave action (less than 0.5 m amplitude). When the tap is closed, the gage can be lifted and the inside water level read at eye level to within 1 mm by means of a clear viewing tube set against a scale on the outside of the gage. As an improvement, a pressure transducer (Honeywell Micro Switch 163PC) was mounted on top of the gage with one port extending below water level and the other open to the atmosphere; this provides an electrical readout capable of being logged automatically.

Attached to the gage is a motorcycle chain used for hanging the unit at each station. A station consists of a hook and reference mark set into a wharf or bridge piling or into a sheer rock face. A bench mark on shore can also be used if the gage is suspended from a temporary tripod set up in shallow water, similar to the setup with the linear-displacement transducer.

Procedure

The gage is hung from the hook located at each station or from a tripod in shallow water. The gage is positioned by choosing the appropriate link in its suspension chain so as to be approximately half-submerged. The tap is opened and the gage allowed to stabilize for several minutes. Readings are then made optically every 5 minutes or electronically every 2.5 minutes for a 30-minute period (one cycle of the predominant seiche on Lake Taupo). The readings are scanned for obvious anomalies before moving on to the next site. The height difference between the horizontal surface on top of the gage and the reference mark on the piling, rock face, or ground above is obtained either by direct taping or by precise leveling. The sum of this height difference and the manual-gage reading equals the elevation difference from the water surface to the reference mark. The reference marks are connected, where possible, to nearby bench marks by precise leveling and checked periodically for possible instability.

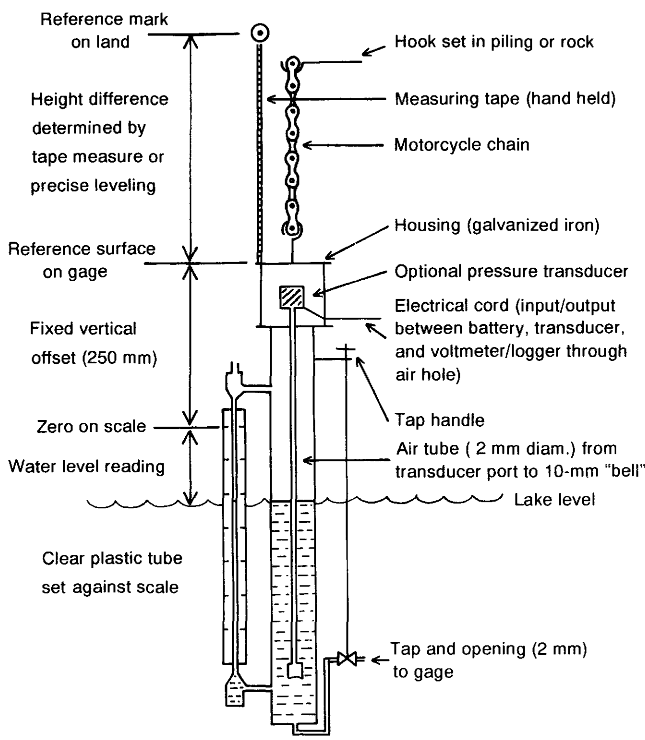

Figure 16.8. Portable water-level gage used at Lake Taupo. Modified from Otway (1989).

As with the CVO system, the observer both starts and finishes observations at the origin station. Before the introduction of the continuous recording gage in 1987, the manual gage was used to determine the water level at the start and finish of each day's work. Lake level at the time of each observation around the lake was then derived by interpolation that assumed a linear response during the day. Now the continuous recording gage is used at the origin, and lake level is computed by fitting a linear regression to recorded data.

POTENTIAL SOURCES OF ERROR

Data from ongoing lake-level studies demonstrate one particularly notable natural characteristic of lakes: their level continually fluctuates. In addition to natural fluctuations, measurement errors lead to inaccurate estimates of lake level. With reasonable care, patience, and experience, most of the errors can be either avoided or minimized, and the fluctuating water surface accounted for.

Natural Errors

Wind

Wind and associated waves are an obvious natural problem. Small waves can be adequately filtered, either electronically when permanently mounted transducers are used, or physically by a stilling well used with the portable systems. Large waves, however, may prevent reliable measurements of water-surface elevation. Wind-driven waves may appreciably raise lake level, especially in shallow bays; the effect in deep water is less pronounced. For example, a 12-knot wind (starting to form small whitecaps) on Lake Taupo, approximately 40 km long and more than 100 m deep, has been modeled and observed to produce a surface slope of about 0.07 μrad, or a height differential of 3 mm along the length of the lake at cliff faces or in deep sheltered bays. In shallow water the effect is commonly much greater because strong winds cause water level to rise on the exposed shore, which could erroneously be interpreted as ground tilt. Mueller and others (1989) found that strong wind effects also increase seiche amplitudes. Resolution of crustal tilt during periods of high wind is degraded by these effects.

Seiche

The seiche of a lake can be likened to the effect of slopping water in a saucer and takes the form of a relatively rapid, small tide whose spatial and temporal characteristics can vary greatly (fig. 16.9). A seiche is usually initiated by strong winds or a rapid pressure change and may last for days before either dying out or being superseded by a new seiche. Its amplitude and frequency are dependent upon the dimensions, shape, and depth of the lake. Most lakes, particularly if complex in shape, have multiple seiche modes; seiches travel along various axes, all with different characteristics. The resultant seiche at any point depends on the degree of exposure to each mode. In practice, recording lake level at each proposed site can identify those sites with unduly amplified or complex seiche. The periodicity of the most significant modes can be determined by analyzing the records with accuracy obviously increasing as more data are collected. From this preliminary work, the optimum observing time and frequency of sampling (if not using a continuous recording system) can be determined. The most effective method to filter the seiche can be derived

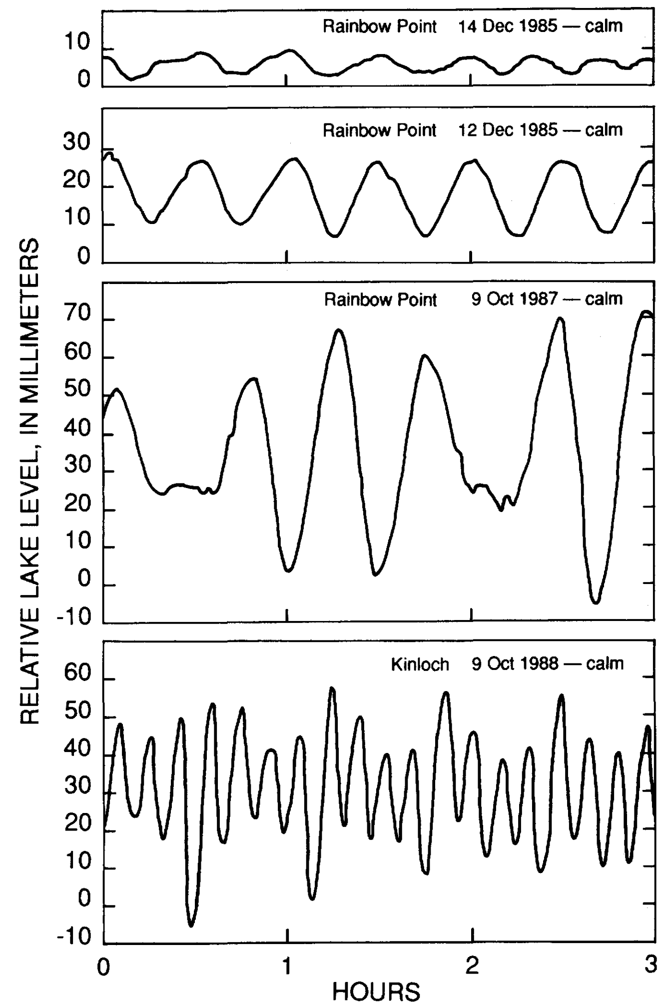

Figure 16.9. Lake-level records from Lake Taupo. The 30-minute seiche mode is clearly visible at Rainbow Point, but develops an unusual 10-minute resonance at Kinloch.

by experimentation and refined by mathematical modeling. For Lake Taupo, a wide heart-shaped lake, all but the southern arm of the lake is influenced primarily by a mode with a period of 30 minutes and 9 seconds. At the southern end a mode of 35 minutes and 35 seconds predominates (Gilmour and Butcher, 1987). Computing the mean of readings taken at regular intervals throughout one or more full seiche periods usually produces reliable data (within 1 mm of the mathematically modeled mean) for seiche amplitudes between 3 and 30 mm. For example, at Lake Taupo six readings are taken at 5-minute intervals for all but the southern stations, where an additional reading is taken. In complex lakes, however, more refined techniques may be required to filter other significant seiche modes.

Barometric Gradient

A differential in atmospheric pressure should result in a predictable response in water level across the lake. For example, personal experience has shown that a gradient of 0.02 mbar/km (common in middle and high latitudes in association with frontal weather systems) should produce a lake surface gradient of 0.2 μrad (a 2-mm height differential across a 10-km lake)[1]. Stress from the resulting wind may, however, greatly complicate the resulting lake level, particularly because the airflow tends to be at right angles to the pressure gradient owing to the Coriolis and frictional forces (Ahrens, 1982). Less well understood are the effects of localized weather systems, such as thunderstorms and squalls, with their associated low-pressure cells and sudden winds. It is usually much easier to avoid making measurements during unstable weather systems than to calculate their influences.

Variations in the Rates of Inflow and Outflow

Variations occur during and after heavy rainfall or when river-control structures are adjusted on lakes used for hydroelectric storage, irrigation, or flood control. Water levels may rise erratically during and immediately after heavy rain and consequently be difficult to predict. The rate of change becomes more regular as time passes following the rain, but the minimum waiting time required for any lake can best be determined only by observation. Lakes that are controlled artificially require consultation between the observer and the controlling authorities to determine the optimum periods when inflows and outflows will be most stable and, if the rates must be varied during this time, the effect this is likely to have on the lake level. Again, it is best to avoid such water-level variations if possible.

[1]Calculated with the approximates of 1 mb ~ 0.75 mm Hg ~ 10.2 mm H_2O.

Other Natural Influences

Currents, internal seiches, lunar tides, and density differences are all potential sources of error. Their effects are likely to be minimal in all but the largest lakes (more than 1,000 km^2 surface area) by exercising basic precautions. Currents can be produced by persistent winds that cause a slow rotation of some or all of the water in the lake. Currents tend to be strongest on promontories or in shallow water, where they may result in a significant gradient of the lake surface. Inlets and outlets are sites of local currents that should also be avoided. Internal seiches can occur along the boundary between a dense bottom layer and lighter surface layer of water but are thought to contribute generally small errors in lakes smaller than 1,000 km^2. Disturbances can also be caused by the Coriolis force and lunar tidal influences (Gilmour and Heath, 1989), but are not a significant source of error compared with wind, seiche, and barometric effects. Significant density differences owing to large volumes of meltwater or geothermally heated water may also cause lake-level anomalies, and should be avoided. It is possible that large gravity changes associated with tectonic or magmatic activity may also effect lake levels, but this effect has not been adequately researched or documented. For more precise work, therefore, further research is required on such effects, especially in large lakes. Until more is known, the observer should be on guard against any unusual systematic errors.

Measurement Errors

Calibration and Instrument Reliability

The instrument for measuring water level, whether it is read optically (for example a manual gage), mechanically (such as the floating ring of the linear pressure transducer), or electronically (such as the output from pressure transducers), must be calibrated and be capable of producing repeatable data. Each individual water-level reading should have a resolution and accuracy to within at most 1 mm, and preferably better.

Thermal Effects on Equipment

The accuracy of lake-level measurement is decreased if there are large temperature differences between (or during) readings. Electronic output and the relative dimensions of some materials can vary owing to changes in temperature. Calibration is recommended throughout the expected temperature range in which the equipment will be used. Most precision electronic instruments (including pressure transducers and linear position sensors) have manufacturer's specifications for temperature effects. The effects of variations in temperature depend on the type of instrumentation and on the climate in which the system is used, hence each monitoring program will have its own corrections applied to each application.

Instrument Setup

Errors associated with instrument setup are obviously not applicable to stable permanent installations, but could cause significant problems in portable systems. When using a tripod to support the gage, care should be taken to make sure that the legs of the tripod are stable with respect to the lake bottom. If the tripod sinks at all during the measurement, lake level will appear too high. The stilling well mounted beneath the tripod must hang vertically to ensure that all measurements are made at right angles to the water surface.

Leveling or Taping Errors

Adequate care and self-checking procedures must be taken to ensure that errors from leveling between the instrument and the bench mark remain less than 1 mm. Such errors will be negligible with strict adherence to precise leveling procedures and standards. In the CVO portable system, the leveling procedure deviates from first-order standards by using a fiberglass level rod mounted on the tripod instead of an Invar first-order quality rod (Yamashita and Kaiser, chapter 13). Errors in reading a fiberglass level rod can easily be kept under 1 mm. Likewise, great care and several readings must be taken to reduce error and eliminate blunders when using a tape to determine the height difference between the gage and a reference mark directly above it.

Bench-mark Instability

The permanent bench mark used as a reference for determining instrument height must be reliable. If there is doubt about its stability, the mark should be connected by leveling to at least one other bench mark as a check. When using a hook as a reference mark on a structure, it must be referenced to a bench mark where possible to prove stability. Alternatively, hooks and reference marks should be established on two independent nearby structures.

REDUCTION AND ASSESSMENT OF DATA

The recommended method of analyzing lake-level data begins with choosing one station as the origin. This station is considered "fixed" (that is, not undergoing any vertical displacement) throughout the study. Any changes in lake level found by reoccupation of this station, whether reoccupation occurs later in the day or over a year later as part of an annual survey, would by convention be attributed to changes in water volume of the lake, not to deformation.

The surface elevation of the lake relative to the origin must be determined at the time of each measurement of the other stations around the lake shore. To achieve this, the seiche effect is removed from the average lake level by computing the mean of regular readings over one or more complete seiche cycles, as described above. Then either a linear regression is fit to the record (if obtained continuously by electronic or mechanical means) or simple interpolation is used (if lake level at the origin is measured at the beginning and end of each day) to determine the lake level at the times of measurement at other sites around the lake. In either case, the lake level is assumed to respond linearly to steady inflow and outflow during the day.

Data from the other stations are then compared to the origin. An elevation is chosen for the origin either arbitrarily or derived from leveling to a bench mark. The water-surface elevation relative to that mark is then computed. The elevation difference between the bench mark or reference mark and the water surface at each measuring site is then added to this water-surface elevation. The elevation of each bench mark relative to the chosen elevation of the origin is then determined. This elevation can then be compared with any earlier set of data to determine apparent height differences relative to the origin.

Only the relative changes in water-surface elevation are measured. Therefore, changes in lake level owing to changes in water volume in the lake basin as well as to differential tilting can be ascertained only after reoccupation of the stations.

The reliability of the results can be assessed only after spending a considerable period carrying out frequent monitoring surveys of a particular lake under a wide range of conditions in order to determine means and standard deviations. A simple empirical formula can then be derived to estimate standard errors for future observations carried out by similar methods. As an example, the formula adopted at Lake Taupo since 1986, based on initial repeat observations and upgraded using more recent repeat observations at numerous stations, is as follows:

Standard deviation in mm for a single survey is

$$1.2 + (0.1 \times d)$$

where d is the straight line distance, in kilometers, from the origin. For a station 4 km from the origin, standard deviation is 1.6 mm (0.4 μrad); for a station 40 km from the origin, it is 5.2 mm (0.13 μrad). This provisional formula was derived from Lake Taupo data only; it may be a useful guide but is not necessarily applicable to other lakes because each has its own unique characteristics.

As a precaution, stations should be reoccupied when elevation differences indicate possible vertical crustal deformation. Despite precautions taken to minimize error, unexpected systematic influences related to localized pressure gradients, wind, internal seiches, and currents can still sometimes cause larger than usual errors. The best rule is to be vigilant and prepared to repeat observations whenever an anomaly becomes apparent.

EXAMPLES OF RESULTS

Yellowstone Lake

The Yellowstone Lake monitoring program is carried out by Wayne Hamilton from the Research Office of Yellowstone National Park in cooperation with the Cascades Volcano Observatory. Permanent lake-level systems have been established at five sites around the lake (fig. 16.2). The dashed line of figure 16.2 corresponds with the inferred rim of Yellowstone caldera (Christiansen, 1984); the Promontory station lies outside of the caldera. Figure 16.10 displays the data from stations Stevenson and Promontory from May 1988 to May 1989. In the top two curves, showing the transducer depth for the two sites, the seasonal variation in level is apparent. These data by themselves are not useful in detecting ground tilt. The bottom curve in figure 16.10 depicts the difference in depth between Stevenson and the Promontory reference station. The net difference over the year was about 1 cm. This difference is within the error of the transducers used in the study. Any ground tilt in the area of Yellowstone Lake over the year was below the detection level of the transducers. The 4 cm amplitude in the difference curve has not yet been fully explained. It may be due to poor calibration of the two transducers at different water depths, seasonal water currents as a result of geothermal activity, or possibly a seasonal ground-deformation pattern.

San Andreas Lake

The San Andreas Lake monitoring program shows a long-term tilt rate of 0.020±0.08 μrad/yr over the last decade (Mueller and others, 1989). This tilt is within the errors of the instrumentation and means that no long-term crustal tilting can be identified in the area.

Lake Taupo

Monitoring lake levels at Lake Taupo with a manually read portable gage has produced interesting results in the first 10 years the program has been in operation. Recorded changes between surveys are generally systematic both in time and space, with short-termanomalies generally within the range estimated by the standard deviation formula, indicating that the larger, long-term apparent changes are probably real. The annual trend since 1982 indicates subsidence of the northern shoreline, which crosses the Taupo Fault Belt (figs. 16.4 and 16.11). The rate of subsidence in the deepest part of the trough averaged 10±3 mm/yr (0.6±0.2 μrad/yr) relative to stations in the central and southern part of the lake. The movement has occurred without shallow seismicity and is interpreted to be due to tectonic extension affecting the whole volcanic zone. An even greater tectonic tilt rate (0.9±0.2 μrad/yr) was recorded during the same period by three permanent stations at Lake Tarawera, 70 km northeast of Lake Taupo (Scott, 1989). In addition, several other areas, ranging from 5 to 30 km in diameter, have exhibited episodes of uplift and

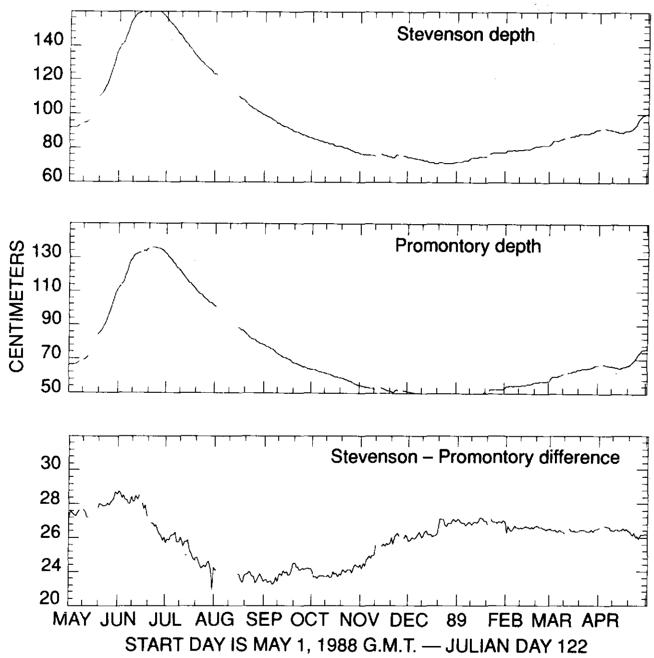

Figure 16.10. One year of lake-level data from two permanent sites on Yellowstone Lake. Top two plots are of transducer depth; seasonal fluctuation in transducer depth is readily apparent. Bottom plot depicts difference between Promontory and Stevenson sites.

subsidence of 5–20 mm over periods of up to 6 months; an example is in the southwestern area in figure 16.4. Shallow minor seismicity frequently occurs in the same general area (Otway, 1987).

The most dramatic example of vertical deformation associated with seismicity was recorded in 1983, when a swarm of frequent earthquakes of less than magnitude 4.3 occurred in the center of the Taupo Fault Belt, between Kinloch and Rangatira stations. Preseismic deformation over a 3-month period was recorded in the form of widespread uplift exceeding 40 mm at Kinloch (Otway, 1986a; fig. 16.12). Coseismic deformation during the month-long swarm consisted of rapid subsidence west of the Kaiapo Fault (between Whakaipo and Rangatira) and uplift to the east. A 50-mm displacement (down to the west) occurred on the fault a week after the swarm commenced (Hull and Grindley, 1984). Postseismic adjustment continued in the same sense but at a diminishing rate.

CVO System Results

The portable gaging system that uses linear-displacement transducers to measure water height relative to a stable point on shore has only recently been developed. Lake-level monitoring is concerned only with temporal changes in water height, so that deformation can be detected only after the gaging sites have been measured at least twice. The CVO system was initially used in September 1988 at Yellowstone Lake, Wyoming, as an independent check on the permanent system already established. Bench marks were placed on shore near the five permanent gaging sites, and the water-surface elevation relative to the bench marks was measured using the portable gaging procedure. Many improvements resulted from that survey. For example, the apparent water level fluctuated as much as several millimeters from one reading to the next, because the stilling well (and therefore the whole mounting unit assembly) was buffeted too much by small waves. The stabilizer bars now used were developed to eliminate this problem.

The gaging sites were reoccupied in June 1989 and the data compared with those from 1988. Differences in lake level were detected of as much as several centimeters. We suspect that the 1988 data set is not reliable. The data in 1988 were taken during windy conditions that were simply unacceptable for lake-level measurements. Because Yellowstone Lake is shallow, the water surface must be relatively calm for the data to be meaningful. One site is on the lee side of the lake, where conditions were calm at that location at that time, but the computed lake-level surface was not accurate because high winds elsewhere were tilting the lake surface. This problem emphasizes the need to measure lake level only on nearly calm days when portable equipment is used.

Despite this somewhat disappointing result, we are confident of the potential of this type of portable lake-level monitoring system. The linear-displacement transducer continues to function exceptionally well; its stability is extremely high and it exhibits no detectable instrument drift.

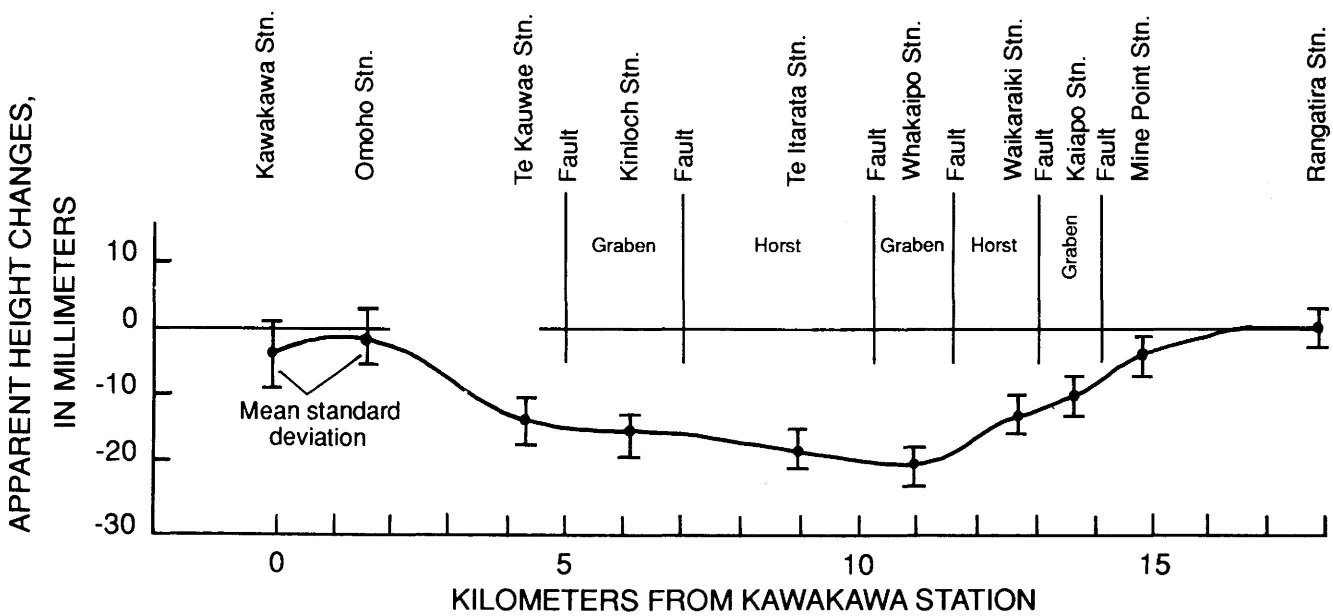

Figure 16.11. Profile (AA' of figure 16.3) of apparent height changes across Taupo Fault Belt, consisting of cumulative change at 10 stations along north shore of Lake Taupo over a 3-year period from November 1985 to November 1988 (see figure 16.3 for locations).

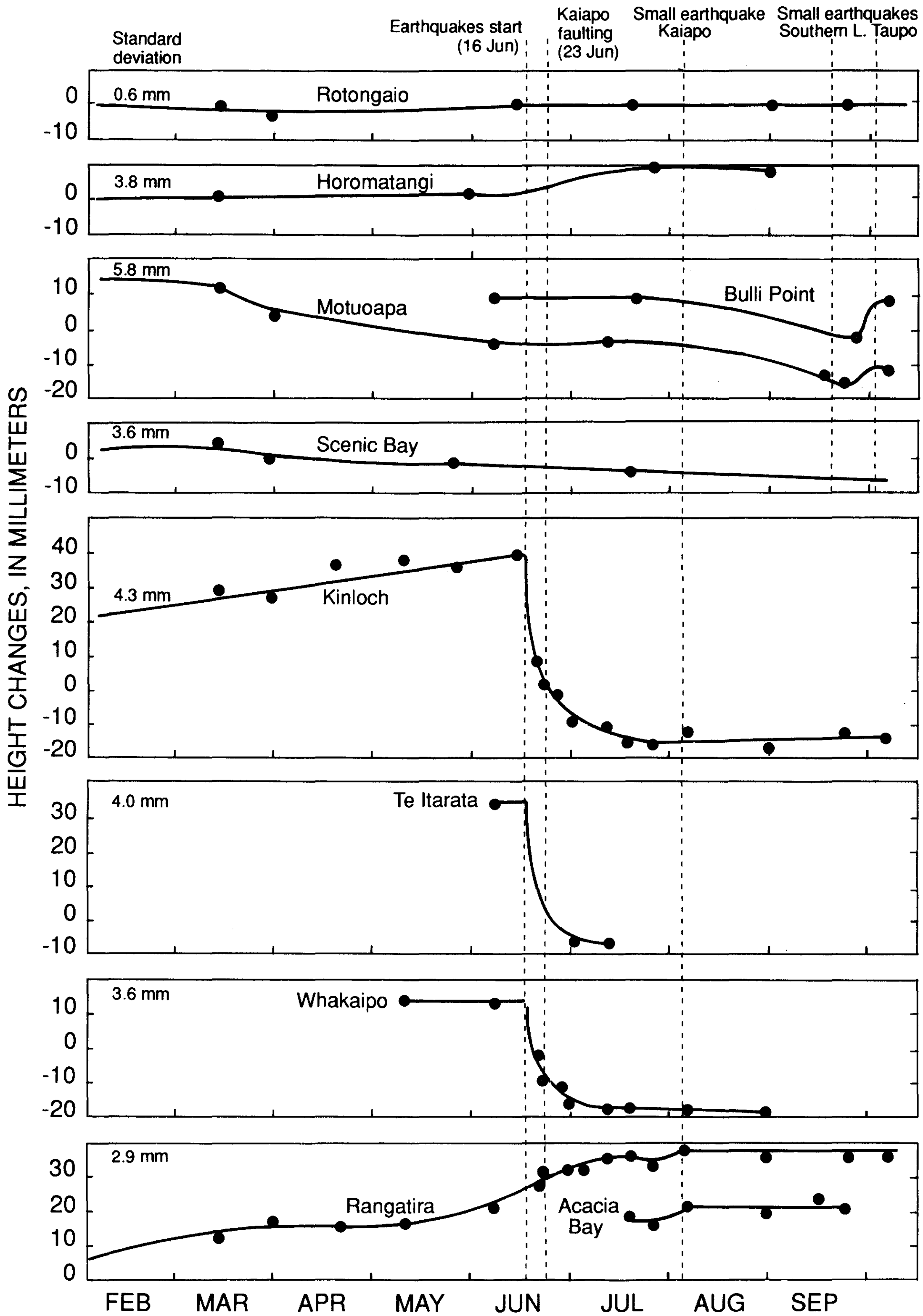

Figure 16.12. Record of height changes on northern shore of Lake Taupo, determined by lake leveling relative to Rainbow Point from February through September 1983 (see figure 16.3 for locations). A clear example of preseismic, coseismic, and postseismic deformation is associated with a major earthquake swarm located between Kinloch and Rangatira stations, which started on June 16, 1983.

DISCUSSION

There are advantages and disadvantages to both the permanent and portable types of lake-level monitoring systems. A permanent system has the obvious advantage of providing continuous data from all sites around the lake. Given continuous data, one can much more easily determine the periodicity and amplitude of the seiche and accordingly filter the seiche from the record. One also can more easily identify meteorological effects. Once established, permanent systems require field crews only for maintenance of the station, not for data collection unless a logger, rather than telemetry, is used and can in theory track rapid displacement events.

The use of portable gaging systems enables different lakes to be monitored with the same equipment. The goal of the portable lake-level program at CVO is to monitor crustal deformation using lakes near several different volcanoes. Except for the bench mark and any reference marks at each site, nothing needs to be permanently established around the lake, a desirable condition in wilderness areas or national parks. The short dynamic range of the displacement transducer used in the CVO system prohibits long-term installation, but the system can be easily converted to telemetered data collection; such conversion could be useful during a period of volcanic unrest.

Another advantage of a portable lake-level system is the ability to check and correct for instrument drift. The pressure transducers used in permanent installations are expensive, because they are designed to have a low instrument drift, but any possible instrument drift could be interpreted erroneously as ground tilt unless the transducer were removed from its permanent installation and recalibrated. The instrument used in a portable system, whether a pressure transducer or a linear-displacement transducer, can be checked and recalibrated in the office before and after each use in the field.

Permanent systems generate a larger data set than do portable systems, but portable systems have the advantage of being used only in known and suitable weather, assuming that observers don't push their luck in marginal weather. Consequently, data from a portable system should not be contaminated by strong wind effects or other meteorological noise as are data from a permanent system. On the other hand, the required good weather limits the days on which a portable system can be used. In deep lakes, such as Lake Taupo, meaningful data can still be gathered even in moderatly windy conditions. In shallow lakes, however, such winds can cause the lake surface to tilt. At Lake Myvatn in Iceland, the most reliable lake-level observations are made only if calm conditions prevail for 24 hours before the measurement (Tryggvason, 1987). Errors associated with measurements taken in adverse conditions can be unusually large. This is a problem for which there is only one simple yet exasperating solution: wait for a calm day. Such delays could add significantly to the time needed to complete a lake-level survey using the portable monitoring technique.

The reliability of data from permanent systems may be improved with the addition of meteorological observations to the data set. Weather observations (wind velocity in particular) could be arranged with volunteers in populated areas, or a weather station could be installed near a more remote lake. Transducer data from times of unfavorable conditions could then be filtered out.

The precisions of the two systems are comparable for large lakes. Both systems incur errors from climatic effects, variations in instrument precision, and bench-mark stability. Portable systems also have errors owing to instrument setup, seich effects and inaccurate leveling or taping, but these errors can be kept well within tolerance with proper care and adherence to standards. The imprecision associated with the smaller data set from portable systems decreases as experience increases. Permanent systems have a precision of 0.1 to 1.0 μrad, depending on the specific application (lake size and shape) and the precision of the transducer. Portable systems rival the permanent systems in terms of precision on larger lakes (greater than 100 km^2 in area), although the tilt precision decreases for smaller lakes. If measurements are made in favorable environmental conditions, the resolution of a portable system is about 1–3 mm. This corresponds to a tilt resolution of 1-3 μrad across a 1-km lake, or several tenths of a microradian across a 10-km lake. Precision is restricted by leveling and stability errors as well as those involved in the determination of water level, but these have the greatest effect on portable systems. Even on days when the environmental conditions seem perfect for measuring lake level (no winds, stable weather system), the lake surface may not be completely level owing, for example, to recent adverse wind conditions or unusually strong currents. As experience increases, reliability of the data will improve.

ACKNOWLEDGMENTS

We thank all those who have assisted in the Taupo lake-level monitoring project, in particular numerous colleagues in the Department of Scientific and Industrial Research (DSIR) for technical and scientific expertise in development work and interpretation of the results. Bill Chadwick and Don Swanson from CVO maintained continuity of monitoring during critical periods relating

to Taupo seismic activity in 1983 and 1984. Thanks also go to those who helped in developing the CVO lake-level monitoring program, in particular Gene Iwatsubo and Tom Murray, as well as those who were forced awake and onto the lake at ridiculously early hours to make measurements. We are especially grateful for the advice, patience, and encouragement of Dan Dzurisin.

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17. Techniques for Continuous Monitoring of Surface Water at Active Volcanoes: Examples From Loowit Drainage, Mount St. Helens, and Kelut Crater Lake, Indonesia

By Kenneth A. McGee, Andrew J. Sutton, David E. Wieprecht, *and* Mark E. Iven

ABSTRACT

Surface water associated with active or potentially active volcanoes can exhibit physical and chemical changes related to renewed volcanic activity. Measuring variations in parameters such as temperature, pH, conductivity, and water level on a regular basis can provide insight into the processes expected to accompany volcanic unrest. Continuous telemetered monitoring installations at Loowit Creek, Mount St. Helens, and Kelut crater lake, Indonesia, are examples of the techniques and equipment that can be used to monitor two different kinds of surface water at volcanoes.

INTRODUCTION

Springs, lakes, and streams associated with active volcanoes can exhibit both physical and chemical changes prior to renewed volcanic activity (Bercy and others, 1983, Giggenbach, 1983). Monitoring specific water parameters such as temperature, pH, conductivity, turbidity, concentration of dissolved gases, and water level can provide insight into the processes expected to accompany unrest or renewed volcanic activity, especially when these parameters are correlated with coincident seismic and other geophysical observations.

Lakes within volcanic craters may hide many of the physical and thermal features of interest. Fumaroles are likely to be actively discharging into a crater lake. During the days or weeks of unrest that might precede an eruptive episode, fumarolic discharge and heat transfer into the lake might increase and raise the temperature of the water. In addition, the pH would likely fall owing to an increase in discharge of acid gases into the lake, and the conductivity of the lake water would increase owing to the presence of more dissolved ions. The water level might change because of deformation of the lake bottom.

Thermal springs originating from a volcanic edifice can also show changes that reflect volcanic unrest. The extent of these changes depends upon the extent to which the hydrothermal system communicates with the subsurface springs. As with crater lakes, changes in the water chemistry, pH, temperature, conductivity, and discharge of springs can be expected to accompany the intrusion of magma into the shallow crust. A comprehensive monitoring program for volcanoes that have springs or crater lakes should include geochemical and hydrologic monitoring of these parameters.

DESCRIPTION OF EQUIPMENT

In summer 1989, a water-monitoring station was established on Loowit Creek approximately 2 km north of the active lava dome of Mount St. Helens. Loowit Creek is a small stream with a late summer discharge of approximately 7 ft^3/s containing surface-water runoff from the crater of Mount St. Helens as well as thermal water from at least three groups of hot springs. Steep topography and unstable ground prevent the hot springs from being monitored directly, so the monitoring site was located several tens of meters downstream from the most downstream hot spring. The monitoring station was established to record changes in water chemistry that might correlate with changes or unrest in the volcanic system.

Robust sensors for temperature, pH, and conductivity are mounted in a perforated polyvinyl chloride (PVC) housing 10 cm in diameter and suspended in the stream by cable (fig. 17.1). Signal output from each of the sensors is transmitted to a water-quality monitoring instrument called the "USGS Minimonitor." This device, developed by the U.S. Geological Survey's Hydrologic Instrumentation Facility, is designed to measure and record various water-quality properties (Ficken and Scott, 1988). The battery-operated (12 volts) minimonitor consists of a timer, signal conditioners for each parameter, and output circuitry.

The signal conditioners allow measurement of water temperatures in the range 0 to 50 °C (or 0 to 100 °C with a resistor change) and pH from 0 to 10 (or 2–12 pH units by changing a switch setting). Conductivity can be measured in any of four switch-selectable ranges from 0–100 to 0–100,000 micromhos. Sensor readings are each converted to output values in the range 0–5 volts.

The output from the minimonitor is connected to a low-data-rate telemetry system (Murray, 1988). Every 10 minutes, the telemetry system triggers the minimonitor to scan its sensor inputs and provide readings to the telemetry system. These data are then transmitted via VHF radio to the Cascades Volcano Observatory for analysis. Although the minimonitor was readily available to the authors for this application, any device capable of reading the outputs of water-quality sensors and converting these values to voltages usable by a telemetry system can be used. Typical data from the monitoring station on Loowit Creek are shown in figure 17.2.

LAKE MONITORING

Kelut volcano in east Java, Indonesia, has a history of ejecting water from its crater lake during eruptions and forming damaging lahars (Suryo and Clarke, 1985). Because of such behavior and the many fumaroles currently discharging into the lake, Kelut was chosen as a test site to develop the techniques and technology for monitoring crater lakes.

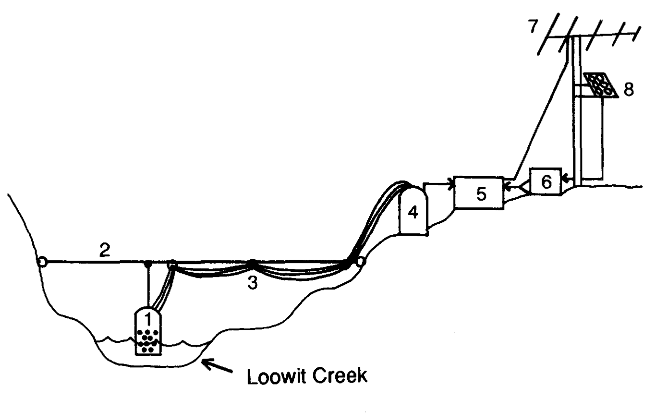

Figure 17.1. Schematic drawing of water-monitoring station at Loowit Creek: 1, temperature, pH, and conductivity sensor assembly in PVC housing; 2, suspension cable; 3, electrical lead cables; 4, minimonitor; 5, radio-telemetry box; 6, battery; 7, antenna; 8, optional solar panel.

In July 1986, a telemetered water-monitoring station was established at Kelut (Sutton and others, 1987). Sensors for temperature, pH, and conductivity are suspended from a floating platform in the lake to a depth of 2.5 m (fig. 17.3). The floating platform is located about 4 m from the edge of the lake and is stabilized with guy wires to prevent movement around the lake. The lake depth below the platform is 5–6 m. Lake level is monitored by a technique described in detail in the following section. Like the installation at Loowit Creek, signals from the sensors at Kelut are transmitted to a minimonitor for signal conditioning. At 10-minute intervals, these data are transmitted by radio telemetry through a signal repeater to Margomulyo Observatory, 6 km to the west and operated by the Volcanological Survey of Indonesia. A small computer records the transmitted data and computes both hourly and daily averages for all of the monitored parameters. These averages are then displayed on a printer and stored on cassette tape. Solar panels provide power for the monitoring site, repeater, and receiving station. Representative data from Kelut are shown in figure 17.4.

A SIMPLE TECHNIQUE FOR MEASURING WATER LEVEL

It is sometimes necessary to monitor water level in a crater lake or a stream. The depth of water can change in response to volcanic activity as well as other factors such as rainfall. The bottom of the crater lake at Kelut, for example, has undergone remarkable changes during several eruptive episodes (Hadikusumo, 1974). Although deformation of a crater floor covered by water is difficult

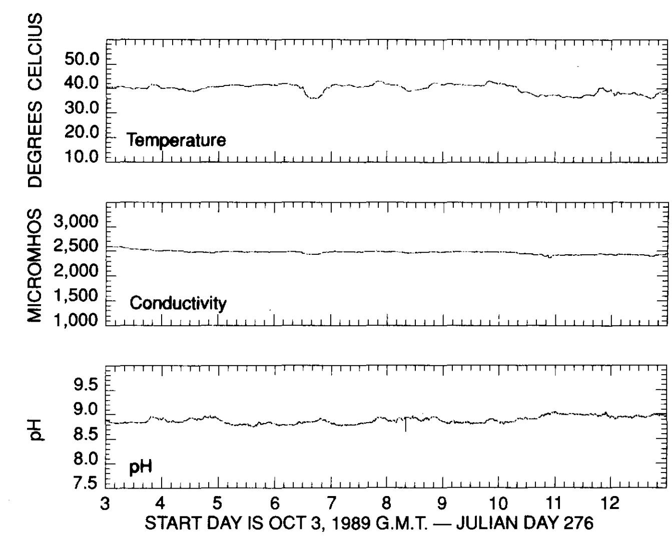

Figure 17.2. Representative data from monitoring station at Loowit Creek.

to detect directly, lake-level monitoring can provide some insight into this problem. Care should be exercised in interpreting lake-level data, however, because evaporation will occur in crater lakes heated above ambient temperatures as in the case of the crater lake at La Soufrière volcano on St. Vincent in 1971–72 (Aspinall and others, 1973).

We describe here a simple technique that can be used for monitoring water level of a crater lake or other bodies of water. It resembles the bubble-gage sensor described by Rantz (1982a) except that the mercury manometer is replaced by a pressure transducer. The apparatus consists of a cylinder of compressed gas (O_2, N_2, or air) with a standard regulator, a constant-flow regulator, a needle valve, a 0–200 kPa (0–30 psi) pressure transducer with 0–5 volt output, and a length of teflon tubing anchored at a fixed depth in the water (fig. 17.5). Gas is bubbled at a constant low flow rate through the tubing into the water. Changes in water level are reflected by changes in pressure measured by the pressure transducer. For example, as the water level rises, backpressure increases and pressure read by the transducer increases. The system may be calibrated before installation by inserting the end of the teflon tube to different depths in a water-filled pipe and reading the pressure-transducer output. The system can be normalized to any convenient zero point after installation in the lake. The lake-level system at Kelut can resolve changes in lake level to about 1 cm and has an absolute range of over 6 m. A typical pressure transducer calibration curve is shown in figure 17.6. Other pressure transducers with different response characteristics can be used to adapt the system to other depth ranges and resolution values. In areas with large diurnal or seasonal temperature changes, special care should be taken to select a pressure transducer with low temperature-coefficient characteristics. If a solar panel powers the monitoring station, a voltage regulator can be used to minimize cycling of the pressure-transducer output as the charge-discharge cycles of the solar-panel power supply cause swings in power supply voltage.

For long-term telemetered monitoring installations, a tank-pressure transducer with 0–5 volts output can be installed in parallel with the tank pressure gage. Data on the amount of gas remaining in the cylinder can then be transmitted through the telemetry system to reduce the number of required visits to the field site (fig. 17.4).

Besides the technique described here, many other techniques for measuring water level can be used. These include suspending a pressure transducer directly in the water from a fixed point (Kleinman and Otway, chapter 16), mounting an ultrasonic ranging device above the surface of the water, constructing a stilling well with float, or installing a load sensor in a stream bed (Rantz, 1982a). We believe, however, that the technique presented here is one of the simplest and easiest to implement.

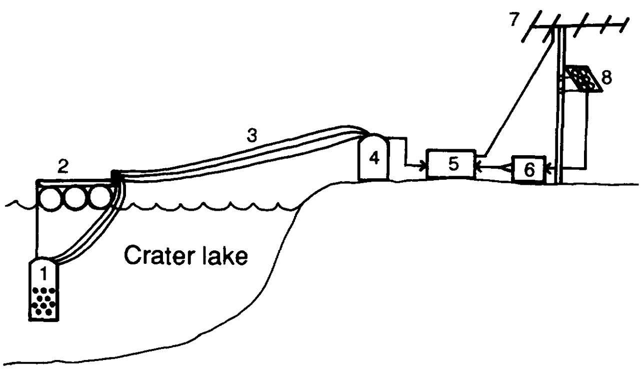

Figure 17.3. Schematic drawing of water-monitoring station at Kelut volcano: 1, temperature, pH, and conductivity sensor assembly in PVC housing; 2, floating platform; 3, electrical sensor leads; 4, minimonitor; 5, radio-telemetry box; 6, battery; 7, antenna; 8, solar panel. Water-level apparatus is shown in figure 17.5.

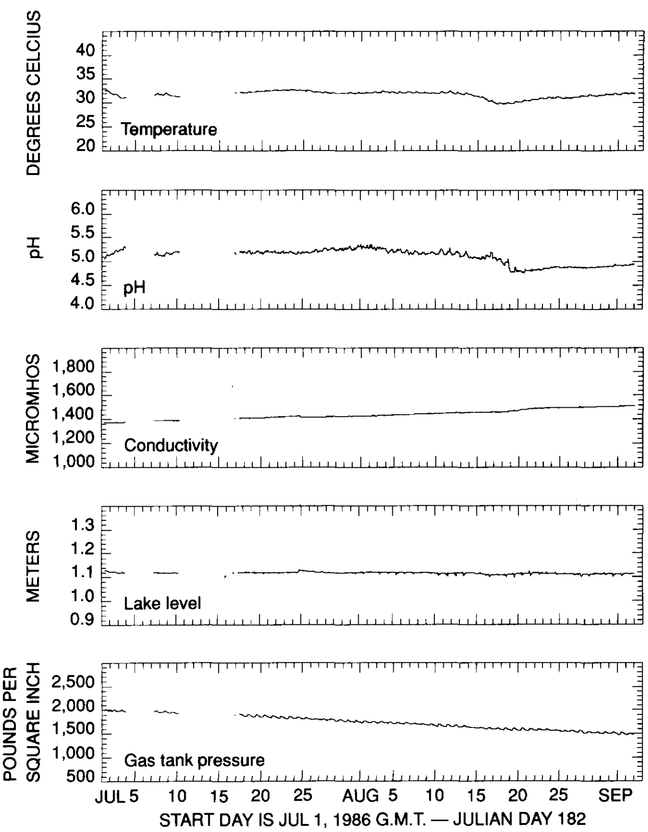

Figure 17.4. Representative data from crater lake at Kelut volcano. Lake-level data are corrected for swings in battery voltage owing to charging and discharging of solar panel.

DISCUSSION

Besides volcanic activity, other factors likely to have an effect on streams draining hot-spring areas or crater lakes are rainfall and melting of snow packs. For crater lakes, significant rainfall will tend to cool the lake, drive the pH toward neutral, and raise the lake level. The magnitude of the effect of rainfall on the monitored parameters depends upon the amount of rain and the size of the drainage system discharging into the lake as well as to the ratio of the volume of rain to the volume of the lake. The effect of rainfall on conductivity is uncertain. The addition of pure rainwater to the lake would lower the conductivity; however, an increase in water flow over soluble materials in the drainage system might increase the amount of dissolved ions present in the lake and might encourage mixing, thus disturbing preexisting thermal and chemical density gradients.

The effect of rainfall or melted snow on streams draining hot-spring areas is similar to that for lakes. Depending on local subsurface conditions, the direct effect of rainfall on hot springs will likely be less immediate and of smaller magnitude.

In any case, rainfall should be measured and recorded regularly when monitoring a crater lake or other surface water associated with a volcano in order to better interpret the water-property data. Rainfall can be recorded continuously with a tipping-bucket rain gage connected to the telemetry system, or can be measured once a day with a standard rain gage. In many areas, rainfall data are also available from other sources such as meteorological agencies, local radio and television stations, and forestry agencies.

Measuring stream discharge is another tool to provide information for interpreting the impact of rainfall upon water-monitoring data. Discharge measurements are a direct indication of the amount of water flowing past a particular point and are useful in assessing the effects of dilution on other parameters being monitored. Discharge measurements are particularly important for streams draining craters or hot-spring areas, as well as for streams flowing into and out of crater lakes. The techniques for measuring discharge are well known and are described in detail in Rantz (1982a, 1982b).

Conditions that can damage equipment or disrupt data must also be considered when establishing a water-monitoring station. Volcanic tephra and easily eroded deposits contribute to high suspended-sediment loads in streams, which can damage or destroy sensors. Thermal water commonly contains algae that can grow on sensors and inhibit response. Chemical precipitates can also form on sensors under certain conditions. Telemetry and electronic equipment should be located on high ground away from areas subject to damage from lahars or flooding. Lightning can be a problem at remote monitoring sites. Sensitive equipment should be thoroughly grounded and shielded to minimize damage from lightning (see Lockhart and others, chapter 3).

Many other observations and measurements can be made in conjunction with, or in place of, continuous

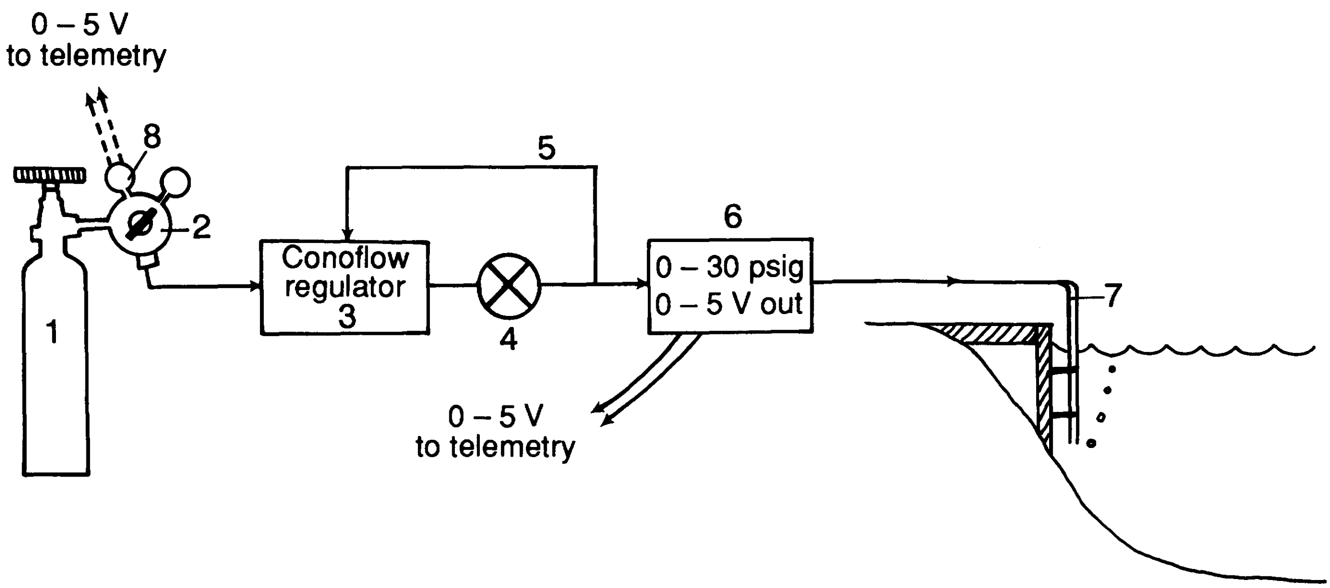

Figure 17.5. Schematic drawing of water-level apparatus: 1, cylinder of compressed gas; 2, tank regulator; 3, constant-flow regulator; 4, needle valve; 5, feedback loop; 6, pressure transducer; 7, teflon or other inert tubing anchored to piling in water; 8, optional tank-pressure transducer. Tubing from cylinder to pressure transducer (6) is 6.35-mm-diameter (1/4 inch) copper tubing.

telemetered monitoring stations. Measuring temperatures manually as often as possible, sampling for water chemistry, using portable instruments to measure pH and conductivity, studying the deposits around volcanic hot springs, and taking repeated photographs over time from established photo points are just some of the things that can be done to help provide a picture of current activity or inactivity. The important point is to be observant and document all changes.

CONCLUSIONS

Monitoring volcanic hot springs and crater lakes for changes that might accompany unrest or renewed volcanic activity is an important and challenging task. Relatively simple monitoring systems for pH, temperature, conductivity, and lake level can be established using off-the-shelf equipment. Crater lakes and volcanic hot springs commonly occur at high elevations and in difficult terrain, where the establishment of continuous-monitoring stations is difficult. Short of continuous monitoring, many periodic measurements or observations can be made to assess activity. The importance of integrating geochemical and hydrologic data from crater lakes and hot springs with seismic and other geologic and geophysical data in order to construct a complete model of volcanic activity cannot be emphasized enough.

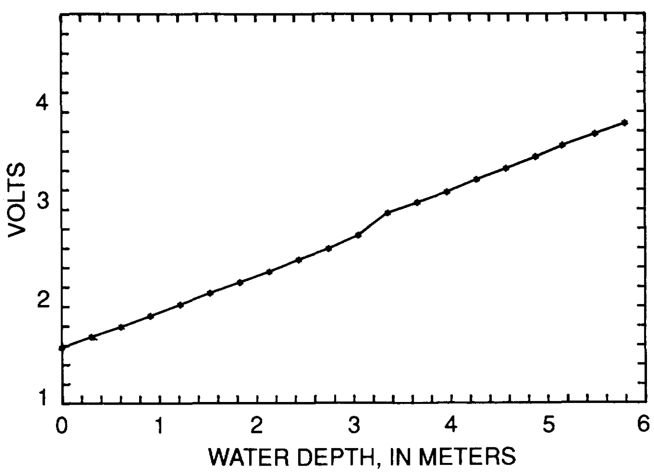

Figure 17.6. Plot of pressure-transducer output versus water depth for lake-level sensor.

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18. Fundamental Volcanic-Gas-Study Techniques: An Integrated Approach to Monitoring

By A. Jefferson Sutton, Kenneth A. McGee, Thomas J. Casadevall, *and* J. Barry Stokes

ABSTRACT

Fundamental gas-study methods for volcano monitoring include field sampling with laboratory analysis, measurements of volcanic-plume emission rates, and continuous on-site monitoring. Field sampling with laboratory analysis provides detailed chemical information about a specific location for a specific time. Gas-emission measurements reveal an average output commonly for SO_2 and CO_2. Continuous monitoring provides an understanding of temporal changes in gas concentrations. Each method has advantages and disadvantages, and a strong gas-studies effort for monitoring purposes is synthesized using all three approaches, along with conventional geophysical-monitoring methods.

INTRODUCTION

Gases dissolved in magmas are an important driving force of eruptive activity, even though they generally make up less than 5 weight percent of the melt for more silicic magmas, and 0.5 weight percent for basaltic magmas (Greenland, 1987). The solubility of a specific volcanic gas in a magma is a complex function of pressure, temperature, and bulk composition of the magma; moreover, different gases in the same magma have different solubilities and reactivities. As magma ascends, changes in subsurface conditions will likely be reflected as changes in emission rate or composition of gases issuing from surface vents and fumaroles, provided that the rock between the magma and the surface is permeable. Under these conditions, the ascent of magma may be detected by studying gases escaping from fumaroles, active vents, porous ground surfaces, and the volcanic-gas plume. Recently, Tilling (1989) cited gas geochemical studies as a promising, though still experimental, approach to volcano monitoring and eruption forecasting. Volcanic gas studies in the United States go at least as far back as the early 1900's in Hawaii (Jaggar, 1940). More recent volcano monitoring reviews that feature gas-studies techniques include a UNESCO volume (1972) and a special issue of Bulletin Volcanologique on volcanic gases (volume 45, no. 3, 1982). Gas geochemical studies require careful interpretation and evaluation of collected data (Casadevall and others, 1987; Giggenbach, 1989). In this paper we suggest that current volcanic gas study techniques for monitoring purposes are logically divided into three classifications. We emphasize the importance of each classification and how the synthesis of a comprehensive gas monitoring effort involves using these methods together.

Volcanic gas studies for monitoring purposes are conducted in several ways (fig. 18.1). Field sampling of fumaroles with laboratory analysis provides detailed information about vent-gas composition. Emission-rate studies of gases such as SO_2 and CO_2 can yield estimates of supply rate and other attributes of the magma system. Continuous on-site monitoring with gas sensors gives valuable information about temporal changes in gas composition in and around fumaroles, fissures, and porous volcanic soils. We discuss each of these gas-study techniques, and how they tie in with other volcano-monitoring methods.

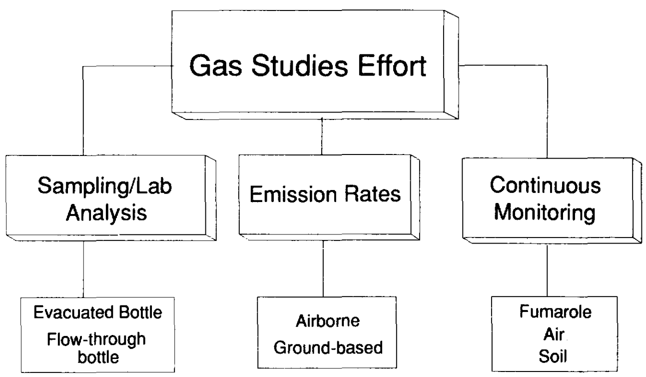

Figure 18.1. Fundamental gas studies for volcano-monitoring purposes should consist of integrated field and laboratory investigations involving periodic and continuous sampling and emission-rate measurements.

GAS STUDIES TECHNIQUES

Field Sampling with Laboratory Analysis

Two primary methods are used to collect and analyze fumarolic gases: evacuated bottles and flow-through bottles. The evacuated-bottle method was standardized by Giggenbach (1975; Giggenbach and Goguel, 1988). This method has the advantage of providing a detailed gas analysis using a minimum amount of equipment. It has been used to study many types of volcanoes and geothermal systems. In practice, a titanium, alumina, mullite, or silica sampling tube (chemically inert and physically durable) is inserted into the fumarole and allowed to heat until condensation in the tube reaches equilibrium, usually 5 minutes or less (fig. 18.2). Equilibrium is indicated by visible gas-flow from the exit of the sampling tube. Fumarolic gas is passed through a short length of teflon tubing to the sampling flask, which consists of a borosilicate glass bottle with a high-vacuum stopcock. The bottle is partially filled with concentrated (4*N*) aqueous sodium hydroxide and has been evacuated and weighed. The stopcock is opened, and gas bubbles into the bottle through the alkaline solution. Water, CO_2, H_2S, SO_2, HCl, and HF dissolve in the aqueous fraction, while N_2, O_2, H_2, CO, He, and Ne bubble through the solution and collect in the headspace. Many liters of fumarolic gas can be collected in a single bottle, because volcanic gas is typically composed mostly of water and condensable acid gases. This method concentrates gases in the solution and headspace, and thereby promotes better analytical precision. The headspace "permanent" gases are analyzed by gas chromatography on a molecular-sieve column with thermal-conductivity detection and argon carrier gas. Dissolved gases are analyzed by wet chemical and gravimetric techniques for CO_2, SO_2, H_2S, H_2O, and HCl and ion-selective electrode methodology for HF. Other evacuated-bottle sampling and analysis techniques are described by Piccardi and Cellini-Legittimo (1983) and Greenland (1986).

Flow-through-bottle collections are made more rapidly than the evacuated-bottle collections. They are used where a complete gas analysis is unnecessary, or where field conditions are too hazardous to safely make an evacuated-bottle collection. The sampling-tube arrangement is similar to that for the evacuated-bottle method, but the bottle has two stopcocks (fig. 18.3). A small hand-operated pump is used to flush and fill the sample bottle with gas. Samples are analyzed by gas chromatography for the gases listed in the preceding paragraph except water, HCl, and HF. Sulfur gases present in flow-through samples are stable for only about 6 hours, so analyses for these gases must be completed promptly after collection. Other gases present are stable for months. Hydrogen and helium are exceptions to this, owing to their small molecular size and high diffusivity. Permanent gases are analyzed as described above. Acid gases are also analyzed on a second chromatograph, using a helium carrier and a porous polymer such as Poropak-Q or Chromosorb 107 with a silica-gel precolumn to eliminate water-vapor interference during chromatography. This method, discussed by Greenland (1984), is used in Hawaii to measure carbon/sulfur ratios of Kilauea's summit-fumarole gases. These ratios have shown sympathetic behavior with inferred magmatic intrusions and changes in magma supply rates (Greenland and others, 1985).

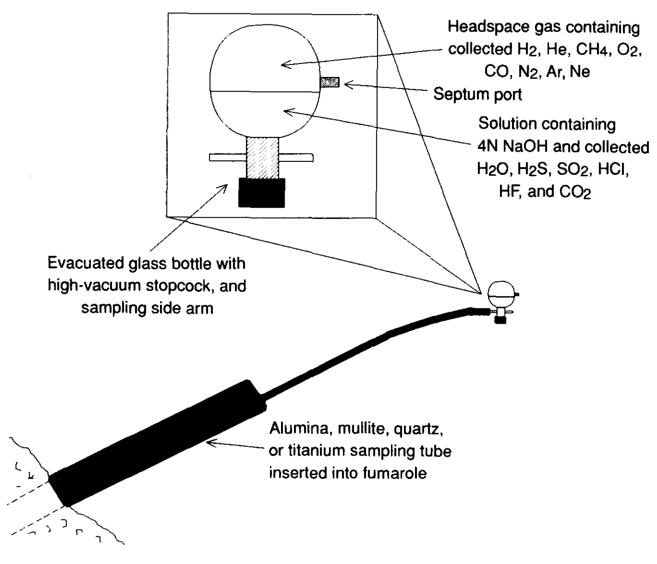

Figure 18.2. Evacuated-bottle sampling scheme, showing sampling tube and sample bottle.

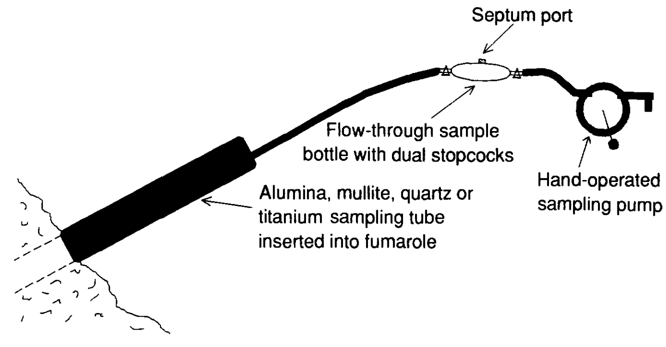

Figure 18.3. Flow-through sampling scheme, showing sampling tube, sample bottle and pump.

Emission-Rate Studies

Emission rates of gases are studied to estimate the quantity of SO_2 and CO_2 being emitted from a volcano, and are carried out by making measurements in the volcanic plume. Sulfur dioxide emission rates have been used to infer the volume of degassing magma (Casadevall and others, 1983) and magma supply rates (Casadevall and others, 1987). Sulfur dioxide and carbon dioxide measurements are both reported as fluxes with units of metric tonnes per day, although the two gases are measured in different ways.

Sulfur dioxide is measured remotely using a correlation spectrometer (COSPEC) (Barringer Research Ltd., Canada). Scattered solar ultraviolet energy of specific wavelengths is absorbed in proportion to SO_2 concentration and plume thickness. This absorption, with units of pathlength-concentration, is measured by the COSPEC and calibrated with the absorption of an SO_2 gas standard in the instrument. The product of the plume light-absorption profile and wind speed yields the SO_2 emission rate. The technique is described by Casadevall and others (1981; 1983; 1987), Stoiber and others (1983), and Millan and others (1976). This method is used routinely and worldwide to make volcanic SO_2 measurements. Measurements can be made from the ground or the air. Wind speed is determined by using a hand-held anemometer for ground-based measurements. Airborne SO_2 and CO_2 measurements use wind speeds measured by a variety of methods including those reported by local airports. Alternatively, wind speed is determined by comparing true air speed, flying with and against the wind, with true ground speed. Accurate determination of wind speed is critical for reliable emission-rate determinations (Casadevall and others, 1987). Airborne measurements of SO_2 tend to be more reliable than ground-based measurements, because wind speed is determined at the site of measurement.

Ground-based COSPEC measurements can be made from a vehicle by traversing beneath the plume while pointing the instrument up through it (fig. 18.4). Alternatively, the COSPEC can be mounted on a tripod near the vent (Chartier and others, 1988) to scan either vertically or horizontally through the plume (fig. 18.5).

Airborne SO_2 measurements are made by flying below and at right angles to the plume trajectory (fig. 18.6). Multiple traverses for either ground-based or airborne measurements are averaged to calculate SO_2 emission rates, which are then scaled up to a daily rate.

Carbon dioxide emission measurements are also made spectroscopically, but require measurements within

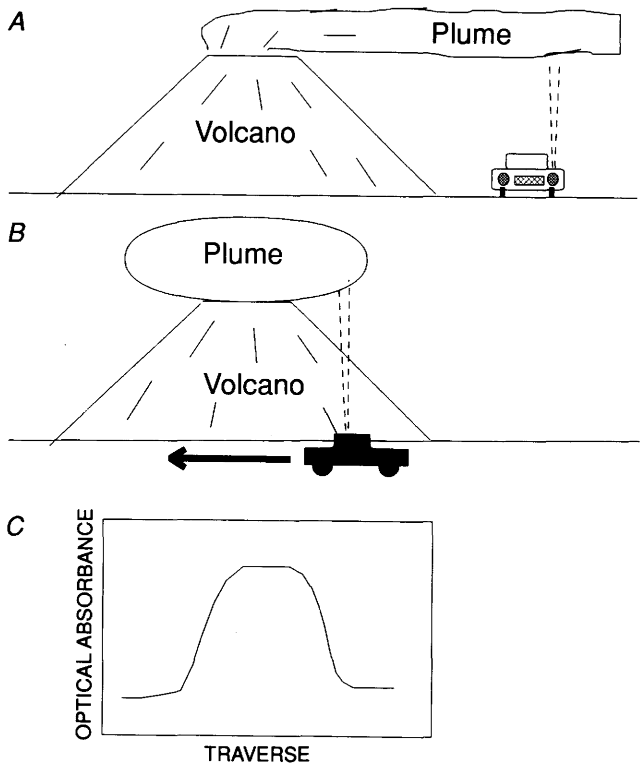

Figure 18.4. Ground-based (vehicle-mounted) COSPEC measurement of sulfur dioxide. *A*, Side view. *B*, Front view. *C*, Typical data.

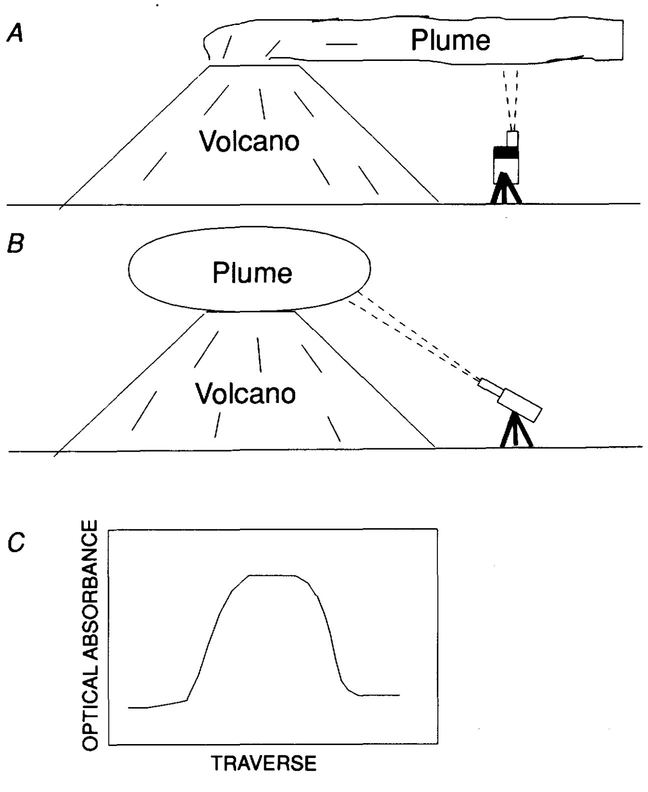

Figure 18.5. Ground-based (tripod-mounted) COSPEC measurement of sulfur dioxide. Dotted lines represent field of view for fixed angle of COSPEC. *A*, Side view. *B*, Front view. *C*, Typical data.

the plume. This is done by flying repeatedly through the plume at right angles to its trajectory (fig. 18.7). Infrared (IR) absorption measurements are made by pumping plume gas through a spectroscopically-tuned Miran IR spectrophotometer (Foxboro Company, Foxboro, Massachusetts) mounted in a fixed-wing aircraft. This method generates a concentration profile for the plume and is used along with wind speed to calculate CO_2 emission rates. The method, discussed by Harris and others (1981), has been used to make measurements at Mount St. Helens and in Hawaii (Casadevall and others, 1983, Greenland and others, 1985).

Continuous Gas Monitoring

Some gas-emission events have durations as short as a few minutes, and thus may not be detected by collection and analysis techniques involving periodic sampling or emission-rate measurements. Continuous measurements, however, can track fleeting concentration changes. Continuous gas monitoring involves using one or more sensors to measure gas concentration in situ. The technique was originally developed and tried in the mid-1970's by Sato and his colleagues (Malone and Frank, 1975; Sato and others, 1976) to monitor the activity of Mount Baker, Washington (Frank and others, 1977). Data are typically taken from the sensor(s) every 10 minutes and telemetered by radio, satellite, or telephone to a receiving site where they are available in near-real time (McGee and others, 1987). Continuous in situ gas-monitoring studies by scientists of the U.S. Geological Survey have used a fuel-cell type sensor, developed by the USGS, that is sensitive to reducing gases including H_2, H_2S, SO_2, CO, COS, HCl, and HF. The sensor, which is resilient under rough and corrosive field conditions, was described by Sato and McGee (1981). More recently, detailed studies of this sensor were reported by Sutton and McGee (1989) and McGee and Sutton (1990). Species-selective, rugged, commercially available gas sensors at reasonable cost have been difficult to find until recently. Chemical gas-sensing techniques and potentially useful commercially available gas sensors were summarized by Sutton (1990). Commercial sensors are now available for H_2, SO_2, CO_2, H_2S, CO, COS, HCl, and HF. Nearly all of these sensors require some modification before they can be used in volcanic environments, and species selectivity is a frequent problem that requires careful deployment. For example, an SO_2 sensor may show cross-sensitivity to H_2S. By deploying an H_2S sensor that has no SO_2 sensitivity along with the original SO_2 sensor, one can monitor both gases and construct an interference correction algorithm for the SO_2 sensor output.

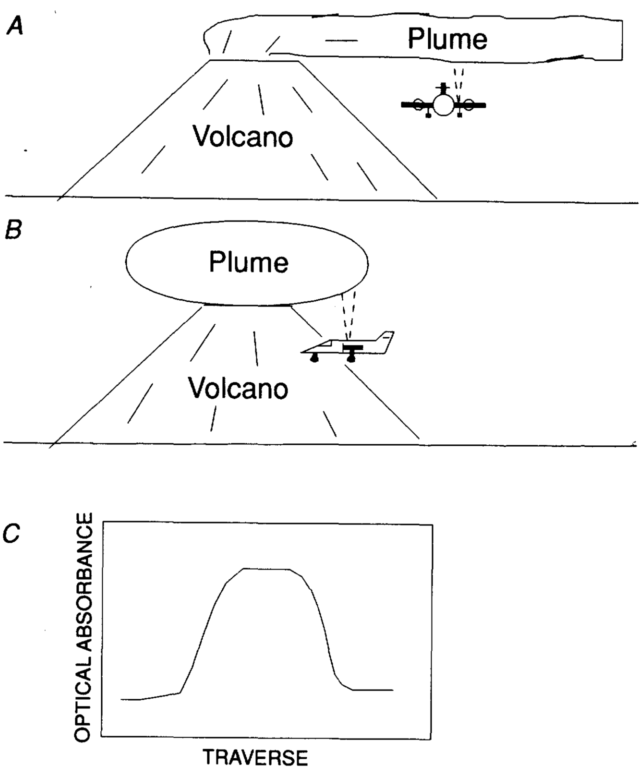

Figure 18.6. Airborne COSPEC measurement of sulfur dioxide. *A*, Side view. *B*, front view. *C*, Typical data.

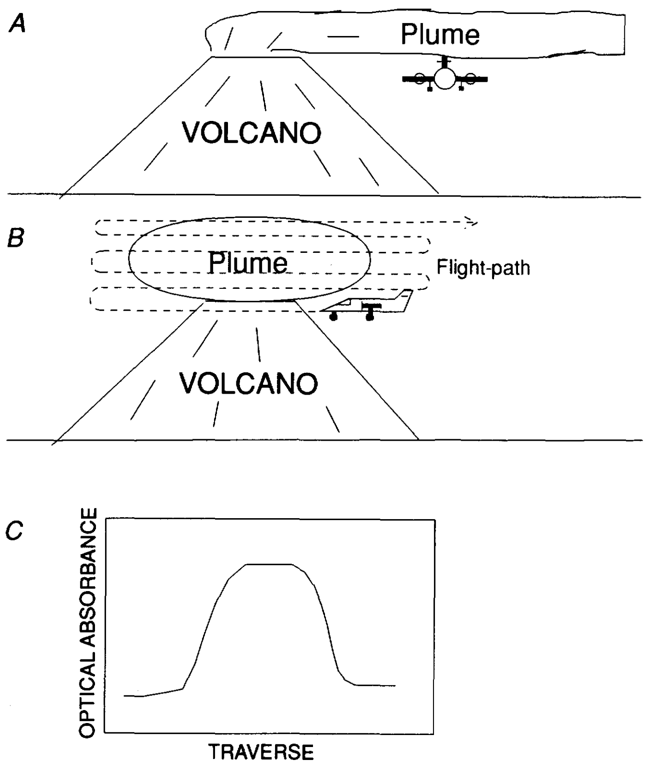

Figure 18.7. Airborne operation of Miran instrument for measurement of carbon dioxide. *A*, Side view. *B*, Front view. *C*, Typical data.

Continuous gas-monitoring measurements can be made in fumaroles, in the air near active fumaroles, and in soils near structural features (fig. 18.8). Continuous fumarolic measurements are made by placing gas sensors directly in the vent. A widespread gas event at Kilauea volcano, Hawaii, was detected before an East Rift eruption using gas sensors deployed in low-temperature fumaroles (McGee and others, 1987). This mode of deployment is useful when fumaroles are thought to be in good communication with the main conduit of the magma system.

Air monitoring is carried out by mounting gas sensors 1 to 2 m high on a strategically located wooden post near an area of active fuming. This method of sensor deployment has advantages over fumarolic monitoring. It avoids the possible error of selecting a rootless fumarole and provides an integrated gas-emission signal for multiple vents within an area, although it is subject to anomalous sensor readings as the wind direction varies. In addition, air monitoring permits the use of a larger variety of sensors, as many sensors cannot withstand harsh fumarolic conditions. Air monitoring on the south flank of Mount St. Helens was described by Sato and McGee (1981), and air monitoring on the active Mount St. Helens lava dome is in progress (McGee and others, 1986).

Continuous monitoring of soil gases involves burying a sensor at least one meter deep in an area of suspected faulting or in other gas-permeable zones. Favorable soil-gas monitoring sites may be located by surveillance methods. For instance, Allard and others (1989) used a portable infrared CO_2 detector to obtain information about geologic structure on the volcanic edifice of Mount Etna, Sicily. They determined that the integrated CO_2 emission from the soil gases was approximately equal to that of the summit craters at Mount Etna. Thomas (1987) determined that radon concentration in shallow ground gases changed substantially with both volcanic and seismic activity at Kilauea volcano. Continuous soil-gas monitoring studies have also been carried out at Long Valley Caldera, California (McGee and others, 1982; McGee and Sutton, 1990). Soil-gas sampling and continuous monitoring of helium gas were described by Friedman and Reimer (1987).

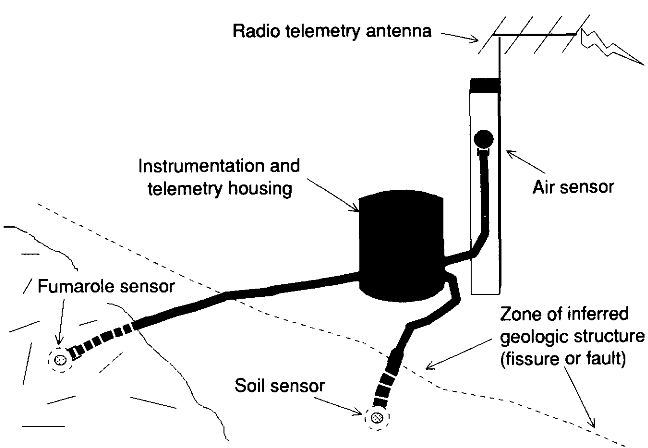

Figure 18.8. Continuous gas monitoring with air, fumarole, and soil sensors. Telemetry can be conventional ground-based radio, satellite relay, or telephone.

Table 18.1. Generalized Advantages and disadvantages for fundamental volcanic gas studies techniques

	Sampling/ Analysis	Emission Rates	Continuous Monitoring
Advantages	Very specific. Much data about single point in space and time.	Remote technique. Overall output of SO_2 and CO_2. Magma supply rate calculable.	Excellent temporal control on outgassing. Continuous dataset. True monitoring.
Disadvantages	Temporal, spatial holes in dataset. Labor intensive, possibly hazardous.	Two gases only. Requires site visit for each data point. Labor intensive. Weather dependent.	Small number of durable and selective sensors. Requires telemetry.

DISCUSSION

The fundamental gas-studies techniques for monitoring volcanic activity have advantages and disadvantages, summarized in table 1. Fumarolic sampling with laboratory analysis gives detailed chemical information, but only about a specific gas-vent location for a specific instant in time. Emission-rate studies reveal overall gas output for a volcano during a given measurement period but only for two gases, SO_2 and CO_2, using present-day techniques. Furthermore, high SO_2 emission values for certain volcanoes with renewed activity may indicate release of originally magmatic gases accumulated within an extensive but shallow hydrothermal system (Giggenbach, 1989). So, taken by themselves, high SO_2 values do not necessarily indicate a direct magmatic source. Continuous monitoring provides information about temporal changes in relative concentration of a few chemical species for fumaroles, air, and soils; however, currently used sensors are not very selective and hence rigorous interpretation is difficult. By using the three approaches together, a more complete picture of volcanic gas emissions can be obtained. Sampling with laboratory analysis provides fundamental information about the total composition and phase relations of the gas and checks the analytical accuracy of continuous monitoring studies. Emission-rate studies focus on overall gas-emission rates, which are checked qualitatively by continuous monitoring, and sampling with laboratory analysis.

Other direct-gas-study methods not described here include portable gas chromatographs for on-site gas analysis (LeGuern, 1982), and potentially useful isotopic gas studies to determine if gas species are of meteoric or magmatic origin (Evans and others, 1981). Indirect gas-study methods include ash-leachate studies, which are useful where direct gas sampling is not possible (Williams and others, 1986; Hinkley, 1987). Monitoring chemical and physical parameters of crater lakes and streams may indicate renewed movement of magma into these systems (McGee and others, chapter 17).

Results from gas studies can be used with other time-series data to help assess volcanic activity. Figure 18.9 shows monitoring data from dome-building activity at Mount St. Helens in October 1986. A reducing-gas sensor, tiltmeter, ground-temperature sensor, and seismometer located in the crater recorded the dome-building episode in real time. Sulfur dioxide emission rates were measured intermittently and show a similar pattern.

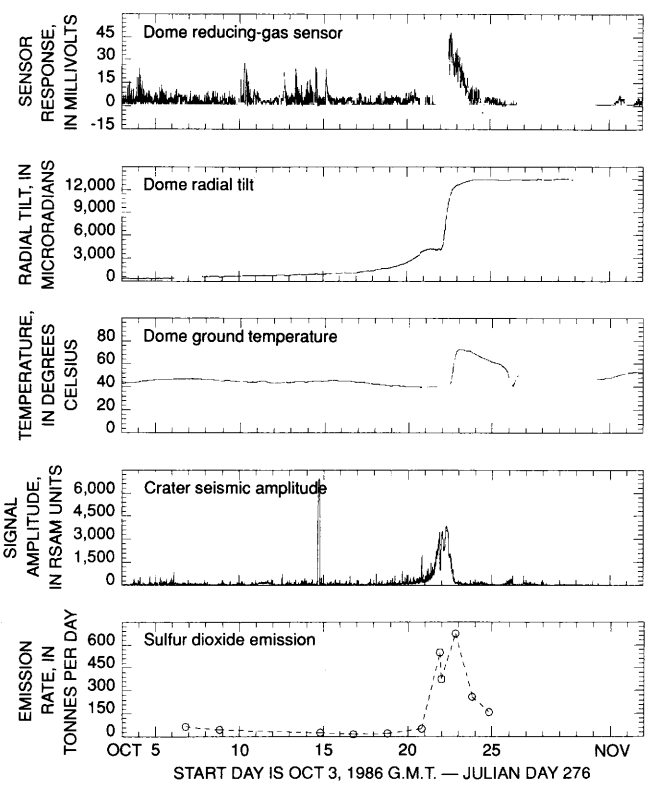

Figure 18.9. Comparison of telemetered gas-geochemical, tilt, ground temperature, RSAM, and intermittent airborne sulfur dioxide data for time period including October 22, 1986 dome-building eruption at Mount St. Helens.

CONCLUSION

Gas studies for volcano-monitoring purposes are conducted using three basic techniques: fumarole sampling with laboratory analysis for major and minor volatile species, emission-rate measurements of SO_2 and CO_2, and continuous on-site monitoring of gases using chemical sensors. Fumarole sampling and laboratory analysis techniques are well established and give the most complete information about specific vent compositions. Such techniques have also been used to infer magmatic gas compositions and volatile budgets (Gerlach and Casadevall, 1986; Gerlach and Graeber, 1985). Emission-rate measurements for SO_2 and CO_2 are similarly well established and can record changes in magma supply rate and the general level of activity of a volcano. Continuous monitoring establishes a temporal continuum for selected gas species in fumaroles, air, and soils and is also the monitoring technique most likely to experience growth in the near future, especially as commercial sensors for a wider variety of gas species become more readily available.

The gas-studies techniques described here are most valuable when used together, especially if in concert with time-series geophysical data. A successful volcano-monitoring effort should incorporate a balance of geophysical and geochemical methods to measure physicochemical changes in a magmatic system.

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19. Video Surveillance of Active Volcanoes Using Slow-Scan Television

By Bruce T. Furukawa, Thomas L. Murray, *and* Kenneth A. McGee

ABSTRACT

Video monitoring using slow-scan television has proved to be a valuable monitoring tool at Mount St. Helens. The system provides a permanent video record of events at the volcano and is also an important aid in planning field logistics and operations. Such a system is particularly valuable at remote volcanoes, where continuous observations are otherwise not feasible.

INTRODUCTION

Video monitoring of Mount St. Helens volcano using slow-scan television (SSTV) began on September 4, 1987. The system consisted of a video camera, a scan converter, a radio transmitter, and a power system, all located on a ridge 8.5 km north of Mount St. Helens; a radio repeater on a high point west of the volcano; and a scan converter, video monitor, and recording equipment at the Cascades Volcano Observatory (CVO) in Vancouver, Washington (fig. 19.1). After several months of operation, the system was modified to turn off at night and back on again in the morning in order to conserve power. A later enhancement included the capability to remotely control various other functions, such as zoom and pan.

Video monitoring of active volcanoes has several attractive benefits. First, there is the potential to significantly reduce the cost of monitoring a volcano. Adverse weather conditions as well as steam and dust conditions can be observed and considered before planning daily field activities. Second, the need for aircraft observation flights is reduced. Third, a reliable video system can significantly reduce hazards to field personnel during periods prior to and during eruptive activity, by supplementing on-site observations of field personnel. Remote variable-power zoom can allow observers to remain a safe distance from the activity. Fourth, video information available during daylight hours is easily correlated with other telemetered monitoring data to assess current conditions. At night, an SSTV monitoring system could utilize an infrared camera for monitoring hot spots. Or a video cassette recorder (VCR) could be connected at the output of the video camera in parallel with the output of the scan converter and triggered to turn on in response to either a control signal from a base station or a signal from a monitoring device in the field such as a seismometer or a trip wire, in order to continuously record events such as eruption plumes, debris avalanches, or lahars for subsequent detailed analysis. It is even possible to design a transportable SSTV system that could be rapidly deployed at volcanoes threatening to erupt. Finally, video information can be stored on magnetic tape for future analysis.

The earliest video system at Mount St. Helens was a closed-circuit television system installed in July 1980 in response to the onset of eruptive activity earlier that year (Miller and Hoblitt, 1981). This system was extremely valuable to scientists monitoring the ongoing eruptive activity at the time, but was hastily assembled under emergency conditions and operated for less than one year before succumbing to problems related to its complex microwave technology and large power consumption. In January 1984, an idea to use a microprocessor-controlled digital video camera with radio modem to obtain images from Mount St. Helens was proposed, but not acted upon. In the winter of 1985–86, CVO seriously considered a proposal to establish a permanent microwave link to Mount St. Helens that would carry telemetry and video signals from field monitoring stations. The idea was later abandoned because of the high equipment cost and system maintenance. Finally, in 1986, the idea of employing slow-scan television for video monitoring of Mount St. Helens was adopted as a goal for CVO. The system described in this paper is the result.

Slow-scan television, first developed by amateur radio experimenters in the 1950's, is a system whereby video images are converted line by line to a varying tone for transmission through a narrow-band radio system. Conventional television requires a bandwidth of 6 MHz for transmission of video signals, whereas SSTV requires only a standard 3 kHz voice channel. This critical difference in RF spectrum requirements results in many significant advantages for SSTV over conventional television systems (lower cost and power requirements, less complex radio-telemetry systems, and ease of servicing). Furthermore, because of the narrow bandwidth, SSTV images can be stored on standard audio magnetic tape rather than video tape. A disadvantage of SSTV is that the video information is discontinuous, because it is displayed as a time series of video snapshots. However, for volcano observatories which must monitor one volcano or several volcanoes over periods of years, slow-scan television may be the method of choice.

DESCRIPTION OF SYSTEM

The current slow-scan television system at Mount St. Helens consists of a camera, scan converter, and controller at the field site; a scan converter, remote controller, TV monitor, and recorder at the Cascades Volcano Observatory; and a radio system, including a repeater, for transmitting video and control signals (fig. 19.1). Appendix 1 lists the equipment used by CVO.

Any good video camera with a 12-volt DC operating voltage, or specifications similar to those listed in appendix 1, can be used in this application. CVO's camera, located 8.5 km north of Mount St. Helens, can be zoomed in to view only the interior of the crater or zoomed out to view the entire volcanic edifice and nearby terrain through the use of the remote control system described below. The camera is mounted on a pan and tilt servo-controller unit. When fully implemented, this pan-tilt unit will allow the camera to pan 150 degrees to the left or right from center and to tilt 30 degrees up or down from horizontal.

Video output from the camera is fed directly into a slow-scan video color converter that has been modified to operate from a 12-V DC power source. The

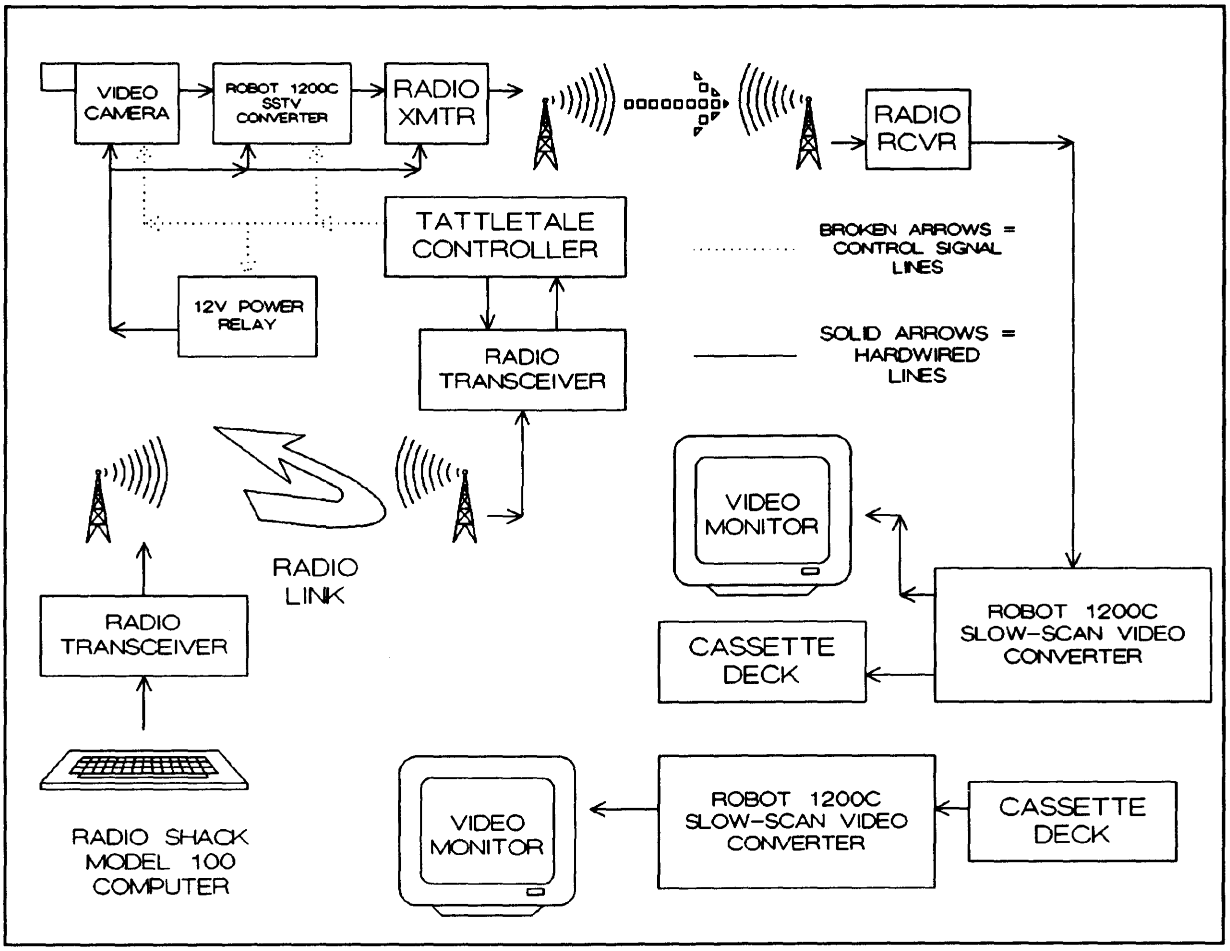


Figure 19.1. Flowchart illustrating components of CVO SSTV system.

SSTV color converter is actually an integrated transceiver capable of transmitting or receiving full color images over any voice-grade communications link. The converter digitizes the video signal from the camera and, after conversion to audio tones, transmits the image line by line using a process called time-multiplexed component color in 72 seconds. At the highest resolution setting, the converter can produce a digitized image composed of 61,440 picture elements in a 256 pixel by 240 line array. When operated unattended at a field location, the functions of the SSTV converter can be controlled by a computer through an RS-232 serial port. Two different control systems have been developed at CVO and are described below.

The digitized and encoded video signal from the SSTV converter is fed into a low-powered VHF or UHF radio telemetry transmitter. The use of standard radio transmitters similar to those used for seismic or low-frequency data telemetry represents one of the biggest advantages of SSTV over other types of video transmission. The antennas used throughout the system are standard radome-protected, UHF band, five-element yagis with 10 dB gain.

All of the equipment at the field site, except for the antenna and camera, is housed in a small building. Power for the equipment is provided by combining two sets of batteries. One set consists of four Delco 2000 high-capacity deep-cycle 125 ampere-hour (Ah) lead-acid batteries designed for use in solar-charging applications. The other set is composed of six Model KCP-SA-13, 2-V 560-Ah high-capacity wet-cell batteries, manufactured by C & D Batteries, Plymouth Meeting, Pennsylvania. Both sets are simultaneously charged during daylight hours by a bank of two 30-watt solar panels.

Video information from the field-monitoring site is received at the observatory via a standard telemetry repeater west of Mount St. Helens. At CVO, the audio output from the SSTV radio receiver is fed into another SSTV converter, where the signal is decoded, converted into a standard color video signal, and fed into a standard color monitor for viewing. The converter also feeds a signal into a standard audio cassette recorder. A separate SSTV converter with cassette player and color monitor is available nearby for off-line viewing of the tapes.

As of this writing (September 1990), a slow-scan television monitoring system for Mount St. Helens has been in operation for 3 years. The earliest version of the system operated in a continuous mode. Owing to excessive power consumption, a controller was added to turn the system off at night. However, power consumption was still a serious problem, and the program was later changed to transmit a single picture every 15 minutes during daylight hours. These were marginally acceptable, temporary solutions. Finally, a remote controller was developed and installed that allows all functions to be controlled from CVO.

SSTV CONTROLLER

Two controllers have been utilized with the SSTV system. The first, an on-site battery-powered laptop computer, turned the system on and off at programmed times (fig. 19.2).

Typically, the computer activated the system every 15 minutes to transmit a single picture of 2-minute duration. Turning the system on and off in this manner decreased the average power consumption of the system dramatically and allowed solar panels to substitute for the propane-fueled, thermoelectric-generator charging system.

The second controller, developed at CVO, allows users to remotely control the system by issuing commands from CVO to the controller over a radio link (fig. 19.1). This technique allows turning the system on and off, controls the picture resolution, monitors the battery voltage, and adjusts the zoom, pan, and tilt of the camera.

Battery-Powered Computer Controller

Figure 19.2 shows how a small computer at the camera site connects to the system as a controller. Pin 4 (RTS) of the computer's serial port controls the relay that switches power on and off to the SSTV converter, camera, and radio transmitter. Commands are transmitted from the serial port of the computer to the graphics input port of the SSTV converter.

A BASIC program running on the computer controls the sequence of events and the transmit times. A typical program is listed in appendix 2. With this program, the computer powers up the system every 15 minutes between 0600 and 2000 hours, sends commands via the serial port to the controller to transmit a single picture at the highest resolution, waits 2 minutes (long enough for the picture to be transmitted), and then powers down the system. Thirteen minutes later the process repeats.

Of the two controllers, utilizing a battery-powered computer is the simpler, less expensive method. Its major drawback is that changes to the program cannot be done remotely; the site must be visited to change the program. At sites accessible by vehicle this may not be a problem, and this system may suffice.

Remote Control System

The remote control system allows users to control the SSTV system from the observatory. A menu-driven program running on a laptop computer allows users to radio messages to the controller in the field (appendix 3). The messages instruct the controller to execute any of several desired options, so site visitation is unnecessary.

Observatory staff run the menu-driven BASIC program to indicate the desired action to be performed by the controller. User input initializes the computer, which then generates the appropriate instructional command for the desired controller action. This message is sent to the radio-interface circuit via the RS-232 serial port. The interface circuit reads the command, puts the radio into transmit mode, sets the modem to originate mode, and transmits the message in standard Bell 103 format. After the command is sent, the radio returns to receive mode, and the modem to answer mode. Messages and acknowledgments sent to the base station from the field are then received by the computer.

An Onset Computer Tattletale Model III single-board controller, a radio, and a CVO-designed interface circuit (fig. 19.3) make up the controller at the camera site. Messages sent from the observatory are received by the radio, demodulated by a single chip modem in the interface circuit, and sent to a serial port on the Tattletale. A BASIC program running on the Tattletale decodes the message and performs the correct action. The SSTV controller is directed by sending commands from the Tattletale's second serial port to the graphics input of the SSTV controller. MOSFETs attached to the Tattletale's digital I/O lines provide the contact closures necessary for the zoom, pan, tilt, and system on/off controls. The entire package is housed in a watertight case.

CONCLUSIONS

The use of video systems has the potential to reduce the operational costs and risks involved in monitoring active volcanoes, particularly dangerous volcanoes in rugged or remote terrain. Slow-scan

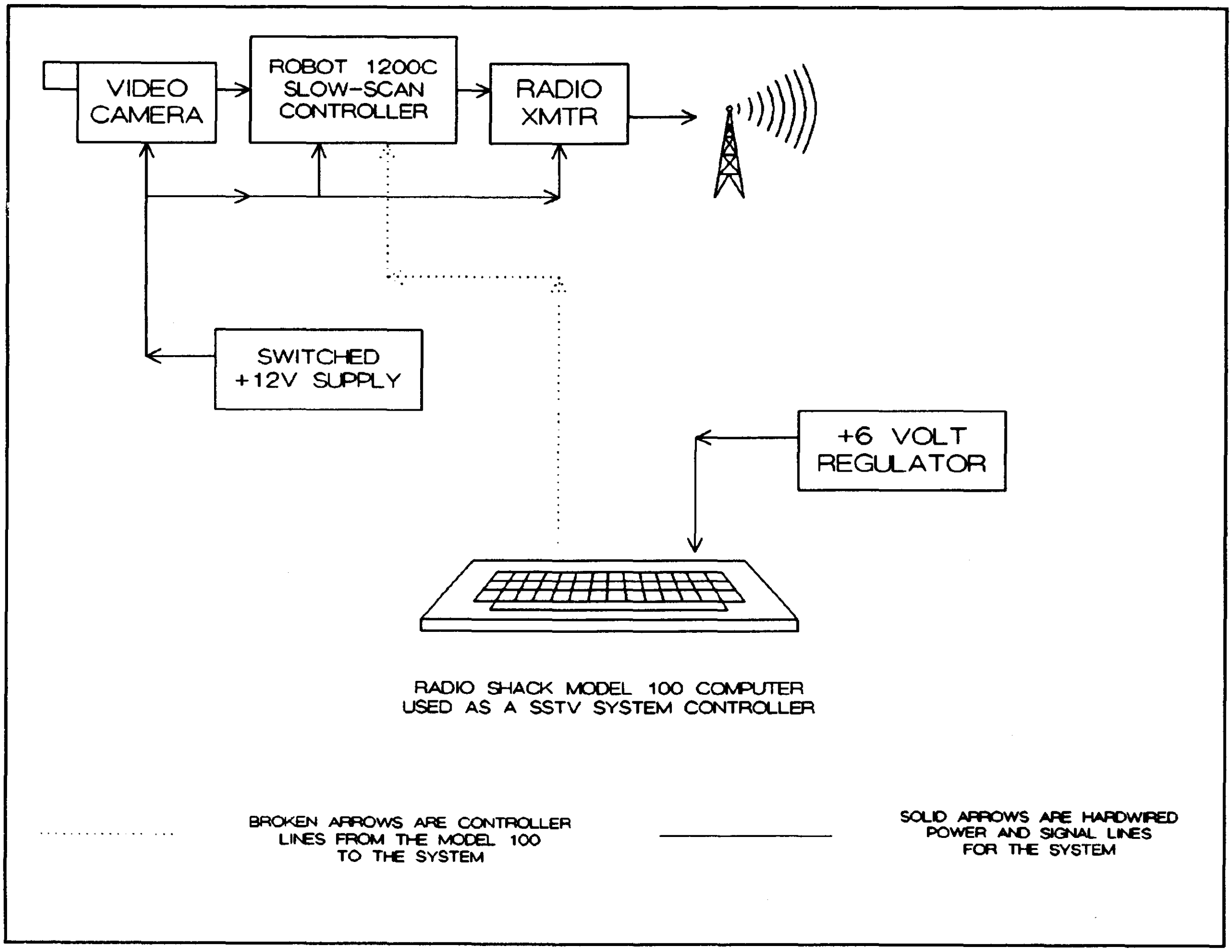


Figure 19.2. Schematic of original CVO SSTV controller.

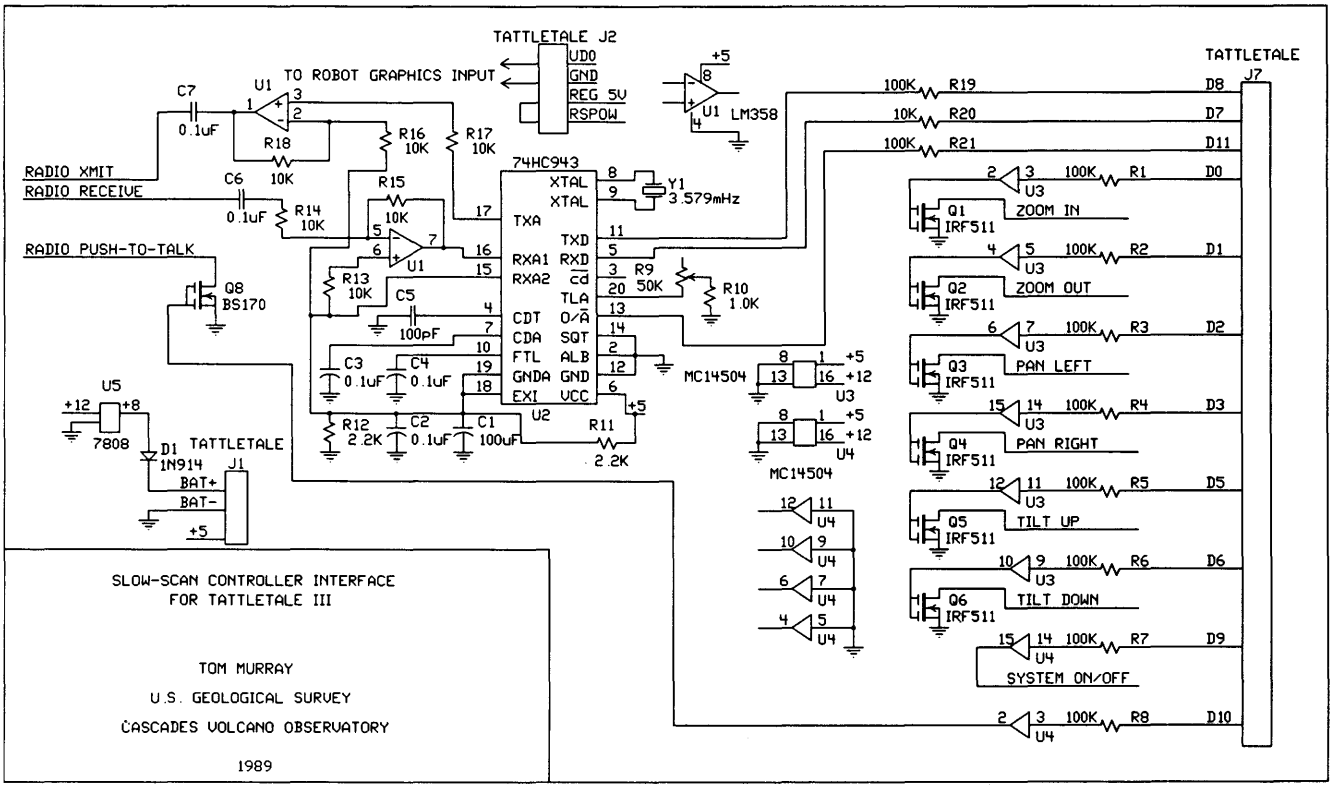


Figure 19.3. CVO-designed interface circuit.

television, with its simplicity and modest RF spectrum requirements, is an attractive low-cost alternative to conventional television systems. Although its power requirements are greater, a slow-scan television monitoring station is no more complex to install and operate than a seismic or low-frequency monitoring station, and can be optimized or enhanced for a particular application.

The slow-scan television system in operation at Mount St. Helens has evolved in design since its initial installation and has proved to be a useful and economical addition to the monitoring capability at the Cascades Volcano Observatory. Similar SSTV installations at other potentially active volcanoes should be considered.

REFERENCES CITED

Miller, C.D., and Hoblitt, R.P., 1981, Volcano monitoring by closed-circuit television, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 335–341.

APPENDIX 1

Equipment List

Video camera	JVC Model TK-860U color video camera head, with a Sanyo TV Autofocus, f 1.2, motorized zoom lens with a focal length of 12.5 to 75 mm.
Pan/tilt controller	Daiwa Model MVH-2D pan and tilt unit, with pan of 150 degrees laft and right from center and tilt of 30 degrees up and down from horizontal.
Slow-scan video converter	Robot Model 1200C Color Scan Converter, modified to operate from a 12 VDC power source.
Telemetry radios	Monitron T40F-1 UHF radio telemetry transmitter.
	Monitron R40F UHF radio receiver.
	Synthex Model LM4400 VHF radio tranceiver.
Computers	Radio Shack Model 100 (or 102)
Field controller	Onset Computer Tattletale Model III single-board controller.
Antennas	SCALA, model RA5-450, radome-protected, five-element yagi, with 10 dB gain.

APPENDIX 2

Typical BASIC program on Radio Shack Model 100

A program for the Radio Shack Model 100 to control the slow-scan video system. The program transmits a picture every 15 minutes between 0600 hours and 2000 hours.

set the automatic running of this program on reset

```
20 IPL "SLOSCN.BA"
21 PRINT "THE SLO-SCAN WILL BE TURNED ON EVERY"
22 PRINT "15 MINUTES (XX:00, XX:15, XX:30, AND XX:45) AND "
23 PRINT "TRANSMIT ONE PICTURE. CURRENT TIME IS"
24 PRINT TIME$ : FOR I=1 TO 2000: NEXT I
26' always transmit a picture on start-up
30 GOSUB 200
```

now just loop around waiting for a 15 minute mark between 06:00 and 20:00

```
40 IF (MID$(TIME$,1,2)<"06") OR (MID$(TIME$,1,2)>"19") THEN GOTO 40
41 IF (MID$(TIME$,4,2)="00") OR (MID$(TIME$,4,2)="30") THEN GOSUB 200
42 IF (MID$(TIME$,4,2)="15") OR (MID$(TIME$,4,2)="45") THEN GOSUB 200
45 GOTO 40
50' the subroutines for delays between commands (a short and a long)
180 FOR I=1 TO 2000:NEXT I:RETURN
185 FOR I=1 TO 300:NEXT I:RETURN
190' the turn-on subroutine
191' opening the com port turns on the relay to power the system
200 BEEP : PRINT "POWER ON" : OPEN "COM:77N2D" FOR OUTPUT AS 1
205' power up delay
210 GOSUB 180 :GOSUB 180
215' issue the commands to put in the correct configuration to
216' transmit 1 (one) picture
220 PRINT "36/72" : CALL 28210,25 : GOSUB 180
230 PRINT "TRANSMIT" : CALL 28210,16 : GOSUB 180
235' do a double-push on the "camera" button
240 PRINT "CAMERA" : CALL 28210,42 :GOSUB 185 : CALL 28210,42 : GOSUB 180
245' wait until 2 minutes later and turn off.  the turn-off has the return
250 SC$=MID$(TIME$,7,2)
251 MN$=CHR$(48+((2+VAL(MID$(TIME$,5,1))) MOD 10))
252 IF (MID$(TIME$,5,1)=MN$) AND (MID$(TIME$,7,2)>=SC$) THEN GOTO 300
255' go back to the wait loop
260 GOTO 252
270' the turn-off subroutine
275' closing the port deactivates the relay that powers the system
300 BEEP :PRINT "POWER DOWN AT "+TIME$ : CLOSE
305' go back
320 RETURN
```

APPENDIX 3

Commands available in the Base Station Computer Program

Picture transmission control instructions

- Power down the system
- Transmit a single picture
- Transmit continuously
- Transmit one picture at intervals of either 5, 10, 15, 30, or 60 minutes
- Set the picture resolution

Miscellaneous instructions

- Set the Tattletale's clock
- Transmit the battery voltage

Instructions for controlling the camera

- Zoom in or out from the current position
- Zoom to an absolute position
- Pan left or right from the current position
- Pan to an absolute position
- Tilt up or down relative to the current position
- Tilt to an absolute position

Note: Zoom, pan, and tilt positioning is measured in the length of time (in hundredths of seconds) the motor drive is engaged. For example, an absolute zoom position of 125 indicates the zoom was driven completely out and then driven back in for 1.25 seconds. A relative zoom in of 25 means the zoom is driven in for 0.25 second. Pan and tilt positions are measured in the same fashion.

20. Basic Photography at Mount St. Helens and Other Cascades Volcanoes

By Lyn Topinka

ABSTRACT

During the last decade, researchers at the Cascades Volcano Observatory (CVO) in Vancouver, Washington, have taken thousands of photographs of Mount St. Helens and the surrounding area, and hundreds more of other Cascades volcanoes. They have used a great many types of cameras. Cameras are one of the most versatile and useful tools available to document changes around volcanoes. Still cameras take one picture at a time and can be divided on the basis of film size into small format, medium format, and large format. There is also an instant-processing still camera which produces a single image within 30 seconds. Video and movie cameras are used for many of the same applications as still cameras and are especially useful in oblique and illustrative terrestrial photography. Video or movie footage is valuable when studying dynamic events such as ash plumes or pyroclastic flows, or calculating the speed of lahars or floods. Vertical and oblique aerial photography, repeat and illustrative terrestrial photography, and time-lapse photography are all techniques available for documenting changes occurring on or around volcanoes. The resulting photographs and footage can be used for interpretation, illustrations in publications, scientific talks and public slide shows, quantitative measurements, and historical documentation of volcanic processes.

INTRODUCTION

Active volcanoes are capable of producing great changes in themselves and the surrounding landscape. To illustrate, document, and to better understand these changes, photographic records should be kept.

On May 18, 1980, over 400 m of Mount St. Helens collapsed as a series of great landslides, releasing pressure which produced a 20 km-high plinian ash column, and leaving behind a crater 1.5 km wide and 600 m deep. Over 650 km^2 of recreation, timber, and private lands were damaged. Approximately 60 km^2 of the Toutle River valley was buried by 2.8 km^3 of debris from the collapsing cone (Tilling, 1984). The magnitude of change is clearly illustrated by comparing photographs taken from a site 10 km northwest of Mount St. Helens on May 17, 1980, the day before the devastating eruption (fig. 20.1*A*), and from the same location on September 10 (fig. 20.1*B*). The same view taken on March 30, 1987, illustrates the continuing changes to the landscape after 7 years of dome growth and river channel erosion (fig. 20.1*C*).

During the last decade, personnel at the Cascades Volcano Observatory (CVO) have taken thousands of photographs of Mount St. Helens and the surrounding area, and hundreds more of other Cascades volcanoes. These photographs are used for illustration in publications, scientific talks and public slide shows, quantitative measurements and interpretation, and historical documentation of volcanic processes. Many camera types are used including still cameras, video cameras, and movie cameras. Many techniques are employed including vertical and oblique aerial photography, repeat and illustrative terrestrial photography, and time-lapse photography. The type of equipment and the purpose for which the equipment or technique is used largely depend upon the scientific need, budget limitations, location accessibility, and the scientist's personal preference. This chapter covers possible combinations of cameras and techniques and cites examples of what has been useful at Mount St. Helens and other Cascades volcanoes. There is no correct or universal way to photograph volcanoes; how little, how much, or of what quality depends upon variables unique to each volcano and to the scientists involved.

STILL PHOTOGRAPHY CAMERAS

Cameras are one of the most versatile and useful tools available to scientists monitoring volcanoes, and still cameras are the most commonly used. Still cameras take one picture at a time resulting in either positive or negative images, and can be divided on the basis of film size into small format, medium format, and large format.

A

B

Figure 20.1. Mount St. Helens as viewed from 10 km to the northwest, showing development of lava dome and drainage channels. *A*, One day before devastating May 18 eruption. *B*, Four months after May 18 eruption. *C*, Seven years after May 18 eruption.

There is also an instant-processing still camera, which produces a single image within 30 seconds. The scientists at CVO use all four.

Small-Format Cameras

The most common small-format cameras use 35-mm-size roll film, producing 12-36 frames per roll. These cameras are readily available, economical, convenient to use, and offer a wide variety of lenses and accessories. Film is available in a wide range of types and speeds, and processing is quick, with certain films able to be processed in the office. For a detailed scientific study, however, the small images may not have sufficient resolution to show the detail needed to compare landscape changes, and high-quality enlargements are often difficult and expensive to obtain. Two styles of small-format cameras used at CVO are the 35-mm lens/shutter and the 35-mm single-lens reflex (SLR).

The lens/shutter is a camera where the user looks through a viewfinder, not the lens, resulting in a photo that is slightly offset from what is actually viewed. The lens/shutter cameras at CVO are usually auto-load, auto-focus, and auto-rewind, and are often referred to as "point-and-shoots." Lenses are either a single fixed focal length or zoom between two focal lengths. The cameras are generally small and lightweight, and are easily carried in pockets or packs. Because the cameras are typically cheaper than SLR's, they are often considered "disposable" cameras, and are used while stream-gaging, surveying drainage-channels, working in dusty or ashy areas, or doing activities when there is a chance of the camera (or the scientist) falling into a river or becoming covered with dust and ash.

The camera most commonly used at CVO is the 35-mm SLR. In the SLR, the image coming through the lens is reflected to the viewfinder by a mirror and a prism, so the user sees exactly what the film records. These cameras are relatively compact, lightweight, and can use a large selection of interchangeable lenses and accessories. Many different brands of SLR's are used, as each researcher buys camera equipment to fit his or her scientific needs, project budget restrictions, and personal taste. For example, many use the Olympus OM2 or the Nikon FE, both of which have proved dependable in Mount St. Helens's ashy environment. Others use the Minolta X700 with its optional multifunction programmable data back. This data back can record hours, minutes, and seconds on the film, a valuable feature when documenting dynamic events such as ash plumes, pyroclastic flows, lahars, and floods. The Minolta data back can also be programmed to trigger the camera every 1 second to every 99+ hours, or an optional motor drive can be set to trigger 2 or 3.5 frames

C

Figure 20.1. *Continued*

per second, options that have been important in time-lapse photography sequences.

The standard 50-mm focal-length lens is most commonly used with the SLR's. This lens is ideal, as it provides approximately the same magnification as the human eye. The wide-angle 28-mm focal-length lens is also popular and forms an image of a subject which is approximately half the size of that formed by the standard lens.

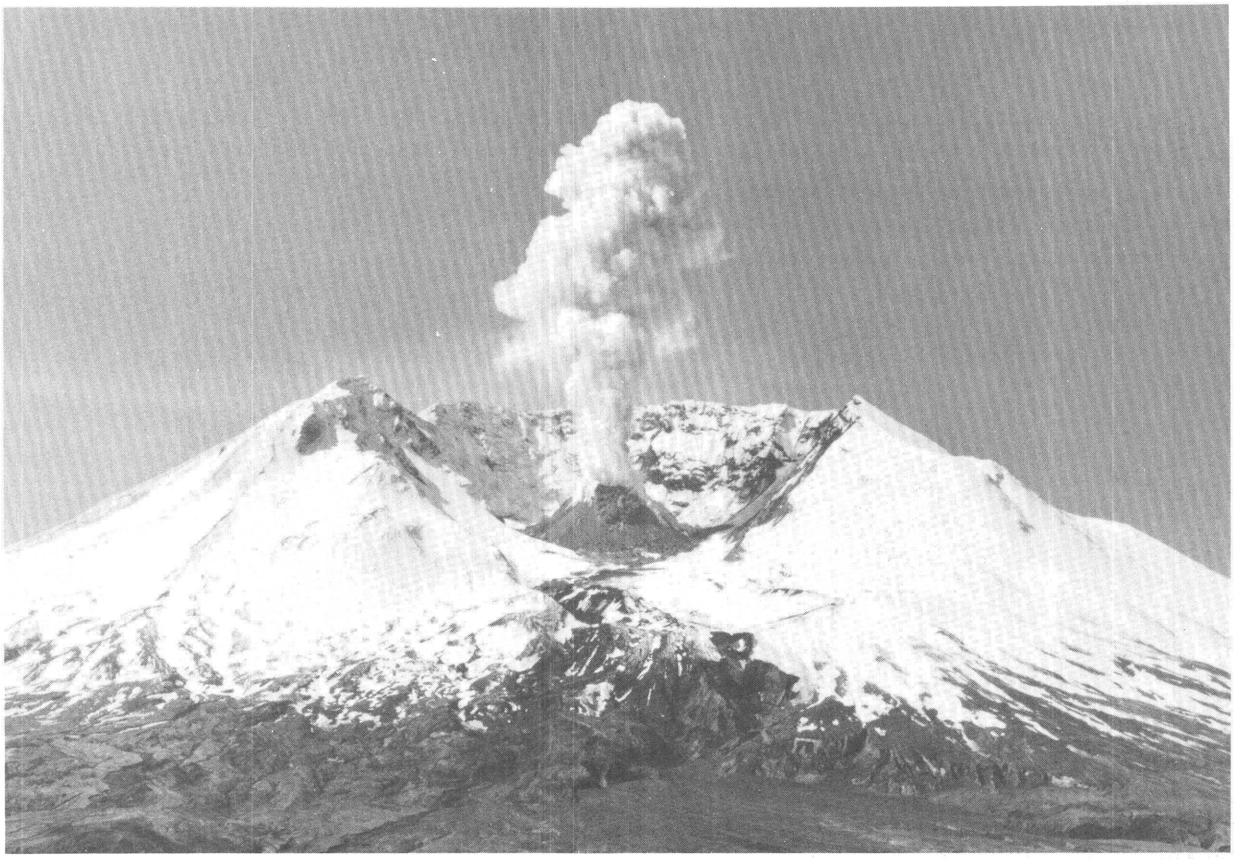
Only a few scientists use medium-range telephotos (100 to 300-mm focal-lengths), long-range telephotos (300 to 1000-mm focal-lengths), or zoom lenses, as these lenses are expensive and bulky. In the field, most scientists usually carry only one camera body and lens, as extra bodies and lenses take up room and add extra weight; moreover, it is often unwise or difficult to change lenses in ashy, dusty, or winter environments. Occasionally field crews carry a variety of cameras and lenses, resulting in different scale photographs of the same subject on the same day, a convenience when choosing photographs for publication or slide shows. For example, one member of CVO's deformation monitoring crew routinely uses a Nikon with a 28-mm lens, while another uses a Nikon with a 50-mm lens.

The CVO staff photographer uses a Nikon FE with a Vivitar 17-mm lens, and Nikkor 28-mm, 55-mm, and 200-mm lenses. The 17-mm is a super-wide-angle lens with a field of view of approximately 100° (as measured from corner to corner) and is useful when photographing scientists working in their environment (fig. 20.2*A*). The 28-mm is a wide-angle lens with a field of view of approximately 75° and is useful when photographing aerial views of the crater or dome (fig. 20.2*B*). The standard 55-mm lens has a field of view of approximately 45° and is an excellent all-around lens, useful for all types of photography (fig. 20.2*C*). The 200-mm lens is a medium-range telephoto lens with a field of view of approximately 12° and is useful when photographing the dome from a distance (fig. 20.2*D*). During critical periods, the staff photographer also carries a Minolta X700 with its hours-minutes-and-seconds data back, a motor drive, and an MD

A

Figure 20.2. Mount St. Helens photographed using different focal-length lenses. *A*, A 17-mm lens was used to photograph researchers making measurements to dome. *B*, A 28-mm lens was used to photograph an aerial view of Mount St. Helens crater and dome. *C*, A 55-mm lens was used from 8 km away to photograph a small steam and ash burst. *D*, From same location, a 200-mm lens was used to photograph steamy lava dome and remnants of a rockslide down its north face.

B



C

Figure 20.2. *Continued*

50-135-mm zoom lens, or an extra Nikon FE body and Nikkor 35-105-mm zoom and 100-300-mm zoom lenses. Multiple cameras allow the simultaneous use of different types of films and provide an extra camera should the primary camera be inoperable.

A wide selection of film types is available to users of 35-mm small-format cameras. At CVO, most scientists participate in scientific talks and slide shows and thus prefer color transparency (slide) films over color or black-and-white (b/w) negative films. Transparencies are also economical, easy to view, convenient to store, and for most applications can easily be made into b/w or color prints. Kodak brand film is generally used, with Kodachrome 64 and Ektachrome 200 transparency films being the most popular. Both of these films provide good color and show little grain. The faster speed Ektachrome 400 transparency film is often used when photographing during overcast or rainy periods.

Very little black-and-white film is used by CVO researchers, as they usually carry only one camera and have it loaded with color. The staff photographer, however, routinely carries two cameras, one loaded with color slide film and the other loaded with a fine-grained b/w negative film. The b/w film is used when shooting specifically for publication photographs or historical documentation. Black-and-white film is very important for historical archiving. According to Eastman Kodak Co. (1979, p. 32):

> When black-and-white negatives on acetate or polyester film base are processed properly, and are protected in storage from the effects of heat, moisture, oxidizing gases, and reactive storage materials, they are extremely stable articles. They will outlast most other photographic records and, since they can be duplicated with very little loss of quality by a comparatively simple process, they constitute the best material for archival purposes.

Medium-Format Cameras

Medium-format cameras typically use 120-size roll film, produce 12–15 frames per roll, and provide 57-mm (2¼ in.) square or 60×70-mm rectangular transparencies or negatives. These cameras offer handling convenience similar to that of the 35-mm cameras, some have interchangeable lenses and film backs, and the larger film provides for greatly improved image detail. However, medium-format cameras are generally more

D

Figure 20.2. *Continued*

costly, larger in bulk and weight, and lack an extensive or readily available selection of lenses and films.

Few medium-format cameras are used at CVO. One scientist uses a Pentax 6×7 with a standard Takumar 105-mm lens. The staff photographer uses a Hasselblad 500C with a standard Planar 80-mm lens and a wide-angle Distagon 50-mm lens. Since most medium-format photographs are used for publication or historical documentation, fine-grained b/w films are generally used. A second Hasselblad film back is carried loaded with either color slide or color negative film.

Large-Format Cameras

Large-format cameras typically use 102×127 or 203×254-mm (4×5 or 8×10 in.) sheet film or 241-mm (9½ in.) size roll film, and are heavy (some weigh in excess of 130 kg), bulky, and not readily available. The cameras require a tripod or are mounted in an aircraft, and are generally used for vertical aerial photography. Film processing is specialized and expensive, but film resolution is excellent. The 241-mm size roll film also has the convenience of more than 300 frames per roll, although smaller rolls are available.

At CVO, large-format cameras are used for vertical aerial photography and most CVO requirements are contracted to professional aerial photography companies. In 1985, "in-house" large-format vertical aerial photography was attempted with a borrowed Fairchild camera. A local aircraft company was contracted to cut a camera port for the camera in the belly of its airplane. The project was abandoned after a short time, however, owing to the poor quality of the camera and the resulting photographs.

Instant-Processing Cameras

The instant-processing cameras used at CVO are the Polaroid SX-70 instant cameras. The Polaroid SX-70 Land Camera Model-2 folds to approximately 100×200×40 mm and is convenient to carry. Final print size is approximately 80×80 mm. Although the film is expensive, the advantage of seeing prints in 30 seconds to 8 minutes (depending upon the film used) outweighs the disadvantage of expense for some uses. Instant prints allow scientists the luxury of photographing an outcrop or stratigraphic section and within minutes writing field notes pertaining to that feature directly on the print. The print is then secured in the field notebook and becomes a part of the field records. Polaroids, like other color prints, will fade with time.

VIDEO AND MOVIE CAMERAS

Video and movie cameras are used for many of the same applications as still cameras and are especially useful in oblique and illustrative terrestrial photography. Video or movie footage is valuable when studying dynamic events such as ash plumes or pyroclastic flows, or for calculating the speed of lahars or floods. When shown at talks or seminars, video or movie footage allows the scientific and public community to feel what it is like to be at an active volcano.

CVO has made only limited use of video or movie cameras as an illustrative tool, and numerous public-education opportunities have been lost simply because video or movie cameras were not taken into the field to take appropriate footage of the crater, dome, or scientists working. Such cameras have been and are being used in individual scientific projects, however. One project was the 1980–82 closed-circuit television/video system installed on Harrys Ridge (Miller and Hoblitt, 1981), and a similar project currently in use employs a slow-scan video system to relay real-time images of the crater to the offices at CVO (Furukawa and others, chapter 19). In 1986–87, a low-light television/video system was installed on the Toutle River for viewing the river channel during lahars or floods (Jon Major, oral commun., 1990), and from 1981–86, a night-vision system consisting of video and still cameras was used to monitor changes in the system of hot cracks on the lava dome (Robin Holcomb, oral commun., 1990). A 16-mm movie camera was used in 1981–83 to study debris flows originating from Shoestring Glacier on Mount St. Helens (Tom Pierson, oral commun., 1990), and in 1988 and 1989, 8-mm movie cameras were used to monitor glacial outburst floods originating from South Tahoma glacier on Mount Rainier (Joe Walder, oral commun., 1990). Movie cameras were also successfully used to photograph sequences of active dome growth during the 1982 and 1986 dome-building episodes at Mount St. Helens.

Video cameras are available in 1-inch, ¾-inch, ½-inch, and 8-mm tape formats. They offer the luxury of convenience; footage shot on videotape can be instantly reviewed and studied back at the office, thereby offering quick interpretation and response to possible hazards. Prints can be made from a single video frame, a technique that has been used to compare hot cracks on the dome preceding an eruptive episode. Such prints are generally of much lower resolution than either still or movie film however. Most video cameras also record sound simultaneously with the video, so that the photographer can narrate the scene and describe exactly what is being observed.

There is no one ideal video camera system among the many types of video cameras available; cost and personal preference are major factors in deciding which camera to purchase. One popular video-camera design is the "camcorder," a system where the recording tape is mounted in the camera body. In 1989, four camcorder systems in use at CVO were: ½-inch Panasonic AG-160 ProLine VHS, JVC GF-S550 SuperVHS, and JVC GR-S77 SuperVHS "Compact," and an 8-mm Sony Handycam "Environmental Quality" system. One-half-inch VHS and SuperVHS systems are economical, readily available, and offer good quality images; their tapes can be purchased at nearly every camera store or supermarket (a useful feature when in the field). The ½-inch JVC "Compact" and the 8-mm Sony "EQ" systems are small and lightweight and fit easily into backpacks. The Sony "EQ" camcorder is weather resistant and ashproof. Its 8-mm blank tapes are not as readily available as are ½-inch format tapes, however. This camera is popular with the scientists, as they do not have to carry a bulky camera around yet can still enjoy viewing the scene immediately when back in the office.

CVO uses two formats of movie cameras, a 16-mm and an 8-mm-size format. The 16-mm offers better quality, but the 8-mm is lightweight, economical, and more convenient to use. In 1989, three types of movie cameras in use at Mount St. Helens were a 16-mm Canon Scoopic, an 8-mm Canon Auto Zoom 518 Super-8, and three 8-mm Eumig 128 XL Super-8 movie cameras, modified for time-lapse by Timelapse, Inc. The Eumigs are in weatherproof housings that can be easily mounted on a tripod, and the time-lapse feature is programmable from one frame every 0.5 second to one frame every 99.5 minutes.

CVO has used movie cameras to obtain "one-of-a-kind" footage. On May 18, 1980, a CVO geologist shot 700 ft of 16-mm movie film of Mount St. Helens's eruption plume. This footage has been repeatedly requested by video and movie companies and television producers during the past 10 years. For security and protection against damage to the film, the original is now kept under lock and key and a copy negative is kept on file. Duplicate films and videotapes are sent to prospective users, and all reproductions of the footage are made from the file negative. This procedure is highly recommended to anyone obtaining irreplaceable footage. In 1982 and 1986, one-of-a-kind dome-eruption footage was filmed using the modified Eumig 8-mm movie cameras. The cameras photographed growth of emerging lobes on the lava dome.

Unfortunately, movie-camera formats are becoming more difficult to effectively find and use, owing to the popularity of video camera systems with the general public. Some camera companies that manufactured 8-mm movie cameras are simply no longer doing so, and some film laboratories are phasing out the processing of movie film.

TECHNIQUES

Vertical and oblique aerial photography, repeat and illustrative terrestrial photography, and time-lapse photography are all techniques available for documenting changes occurring on or around volcanoes. Any and all types of cameras can be used. To ensure a successful photographic trip, pay attention to four main points.

Camera Protection

Volcanic ash and gases destroy cameras. Ash scratches camera lenses and film and can jam the camera's internal mechanisms, while volcanic gases corrode the camera body and the delicate circuits of electronic cameras. To protect the camera against ash and gas, keep it in a case or camera bag when not in use and load film in a protected environment. Use clear filters (such as "UV" or "Skylight" filters) to protect the lens surface. Filters are expendable and more economical to replace than the camera lens. Have the camera system cleaned regularly. Take extreme care when using video systems in the ashy volcano environment, as even the slightest dusting of ash can interfere with the recording heads.

Low-temperature Photography

Volcanic activity occurs during cold winter months as well as warm summer ones, creating a problem with camera operation in freezing weather. Cameras continually exposed to freezing temperatures become sluggish as mechanical reaction time increases (shutter speeds lengthen). Film freezes and becomes brittle, and camera batteries lose their efficiency at low temperatures. To alleviate these problems, keep camera and extra film warm by carrying it near the body under outer garments, and if available, install fresh silver oxide or lithium batteries before venturing into the field. Silver oxide and lithium batteries perform better in cold temperatures than the regular alkaline types (Gillsater, 1985, p. 33). Always carry extra batteries. Frozen film should be thawed at least an hour before using.

Bracketing Exposures

When photographing volcanoes, film is usually the cheapest factor involved, so take many frames of the same subject using different exposure settings. Shoot one frame as the camera lightmeter indicates, then bracket exposures by increasing exposure (overexposing) and decreasing exposure (underexposing) for the next frames. In extreme conditions, increase or decrease exposures by one and two stops, depending upon the subject. For example, the correct exposure for dark objects (as Mount St. Helens's dome) surrounded by brightly-lit snow will generally be one or two stops of increased exposure from that which the lightmeter indicates. Conversely, photos of a snow-covered peak surrounded by blue sky and green forest often are washed-out if shot at the exposure the lightmeter indicates. Therefore, decrease exposure by one or two stops to properly expose for the snowy peak. Ash, mud, and snow are difficult subjects to photograph, for they have very little inherent color and contrast, and in these situations, most camera lightmeters have difficulty indicating the correct exposure. By bracketing exposures, the proper exposure—not necessarily the one the camera meter indicates—may be obtained. To bracket exposures on automatic cameras, use the "exposure-compensation dial" and adjust to the plus side to increase exposure and to the minus side to decrease exposure.

Accurate Notes

Keeping accurate notes may be the most important aspect of volcano photography, other than the actual shooting of the photograph. Keep notes on cameras, lenses, and filters used, film type, exposure, date and time, weather and lighting conditions, the height of the tripod, the subject being photographed, and the location from where the photograph was taken. Keep notes on everything and anything that might be important, for they may prove useful years later.

VERTICAL AERIAL PHOTOGRAPHY

Vertical aerial photographs (figs. 20.3, 20.4) are taken when the camera's optical axis is pointing downward, within 20° of vertical (Ray, 1960, p. 2). The cameras (usually large format, occasionally medium format, and rarely small format) are mounted in the belly of an aircraft and shoot through a camera port. The aircraft flies in straight lines back and forth across an area, following predetermined flightlines. A flightline consists of three or more photographs taken in measured succession, with each photograph overlapping adjacent ones by 30 to 60 percent. Vast areas of ground can be photographed in a few minutes. The flightlines at Mount St. Helens were designed to document the impact of volcanic eruptions on the peak and the subsequent changes occurring within the crater and surrounding river valleys after the May 18 eruption.

The photographic scale of vertical aerial photography varies and is determined by the focal length of the lens used divided by the altitude of the aircraft above the ground, expressed in a ratio. The lower the altitude or the longer the focal length, the larger the photographic scale is and the more detail that can be seen (fig. 20.3).

Photographic scale is only an approximation at best, as topographic relief of the terrain photographed and the inclination of the optical axis of the camera are two major factors that cause variation in scale (Miller and Miller, 1961, p. 8). For example, at Mount St. Helens a flightline over the crater and north to Spirit Lake is flown at an altitude of 7.6 km (25,000 ft). A 152-mm (6-in.) focal-length lens is used, and approximately six frames are photographed. A single frame can cover the entire dome, crater, and flanks of the volcano (fig. 20.3*A*). Photographic scale of that frame ranges from 1:42,000 around the flanks of the volcano, to 1:40,000 across the crater floor, to 1:34,000 at the crater rim. Another flightline is flown at an altitude of approximately 2.7 km (9,000 ft) and photographs are taken using the same lens. A single frame covers the dome (fig. 20.3*B*). This photograph has a larger scale than the previous photograph (hence more detail can be seen), and its scale ranges from approximately 1:8,000 at the base of the dome to 1:6,000 on top of the dome.

By 1990, the flightline over Mount St. Helens crater and dome had been rephotographed over 150 times. All photography was contracted to professional aerial photography companies, altitudes and photographic scale varied, and b/w and color negative film was used. In June 1980, over 100 flightlines specifically designed to document drainage-channel development around Mount St. Helens were established (fig. 20.4), and these flightlines were rephotographed yearly during the low water season and after major hydrologic events. Scale was 1:9,600, and b/w film was used (with color film being used occasionally in 1980). Flightlines varied in length from 3 to over 20 frames depending upon the straight length of the drainage reach. Large drainages would typically have many flightlines, whereas small drainages were covered by one flightline (fig. 20.5).

The individual photographs from flightlines can be pasted together and read like a map. The overlapping areas of two adjacent photographs form stereoscopic pairs that can be used to directly see elevation differences in the photographed terrain. With the proper support equipment, stereoscopic pairs can be used to create

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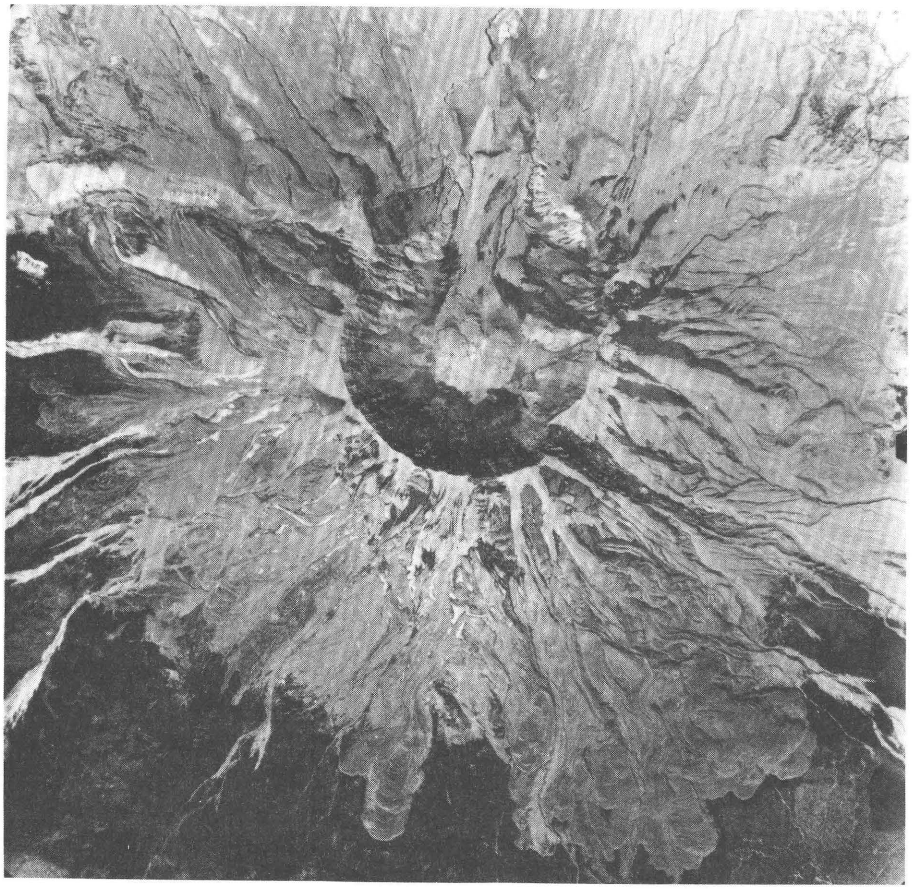

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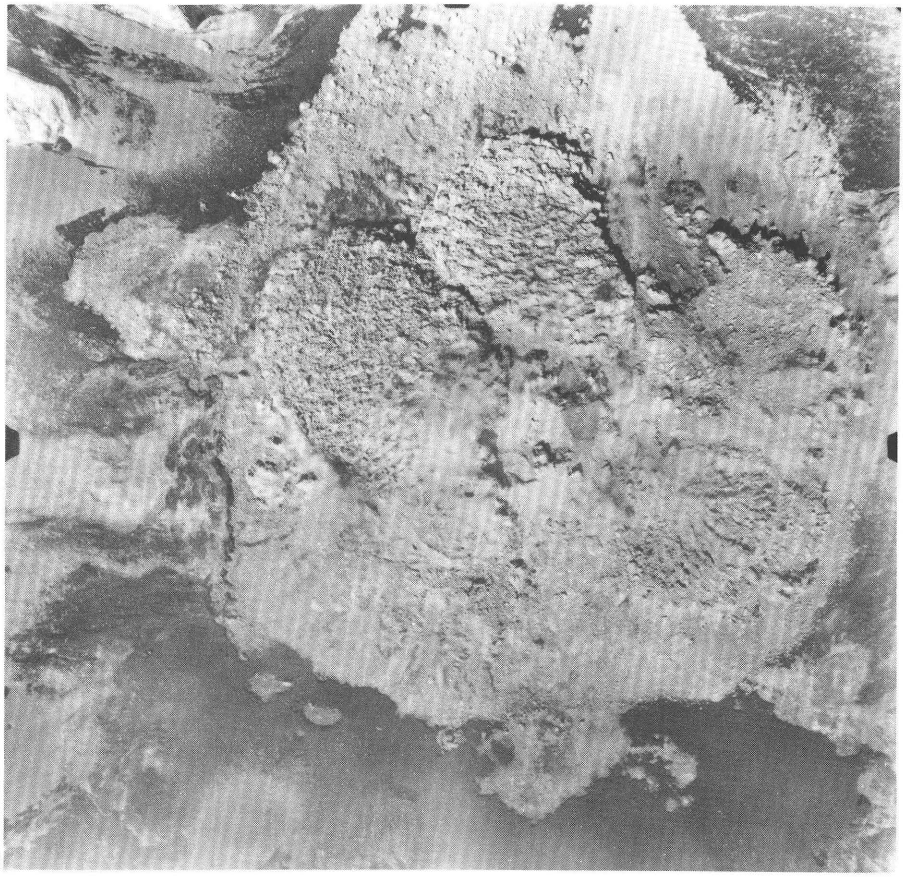

Figure 20.3. Large-format vertical aerial photographs, reduced 50 percent, illustrating different photographic scales. *A*, Mount St. Helens crater and dome photographed from 7.6 km (25,000 ft), showing crater floor at a scale of approximately 1:40,000. *B*, Lava dome photographed from 2.7 km (9,000 ft), showing top of dome at a scale of approximately 1:6,000.

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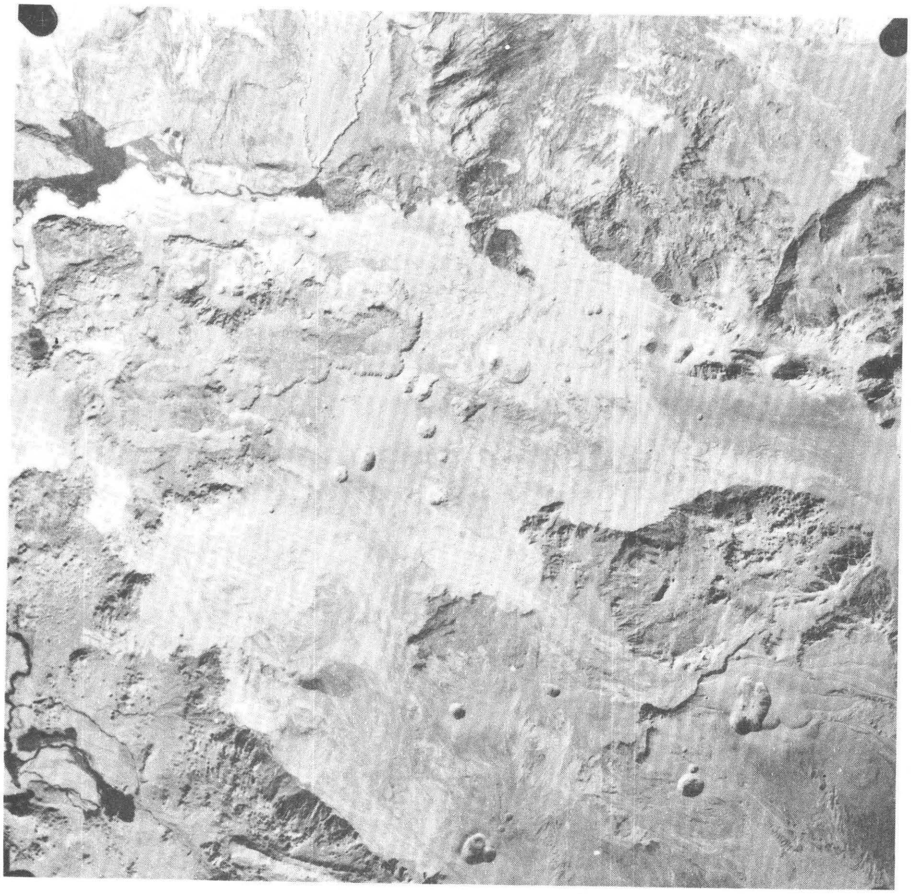

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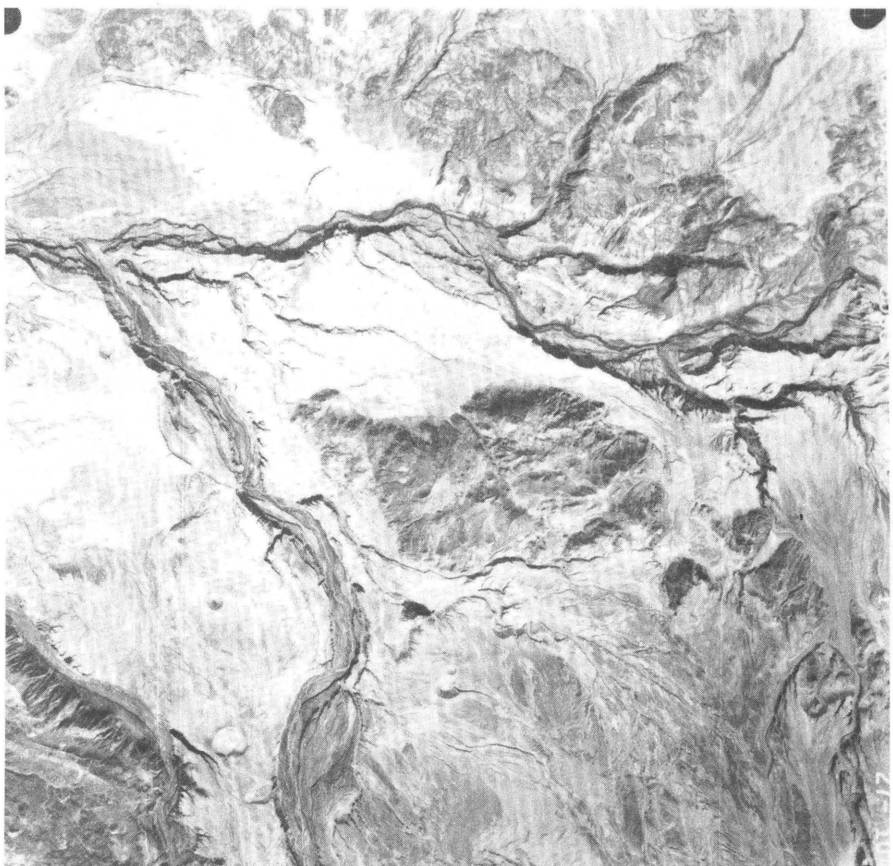
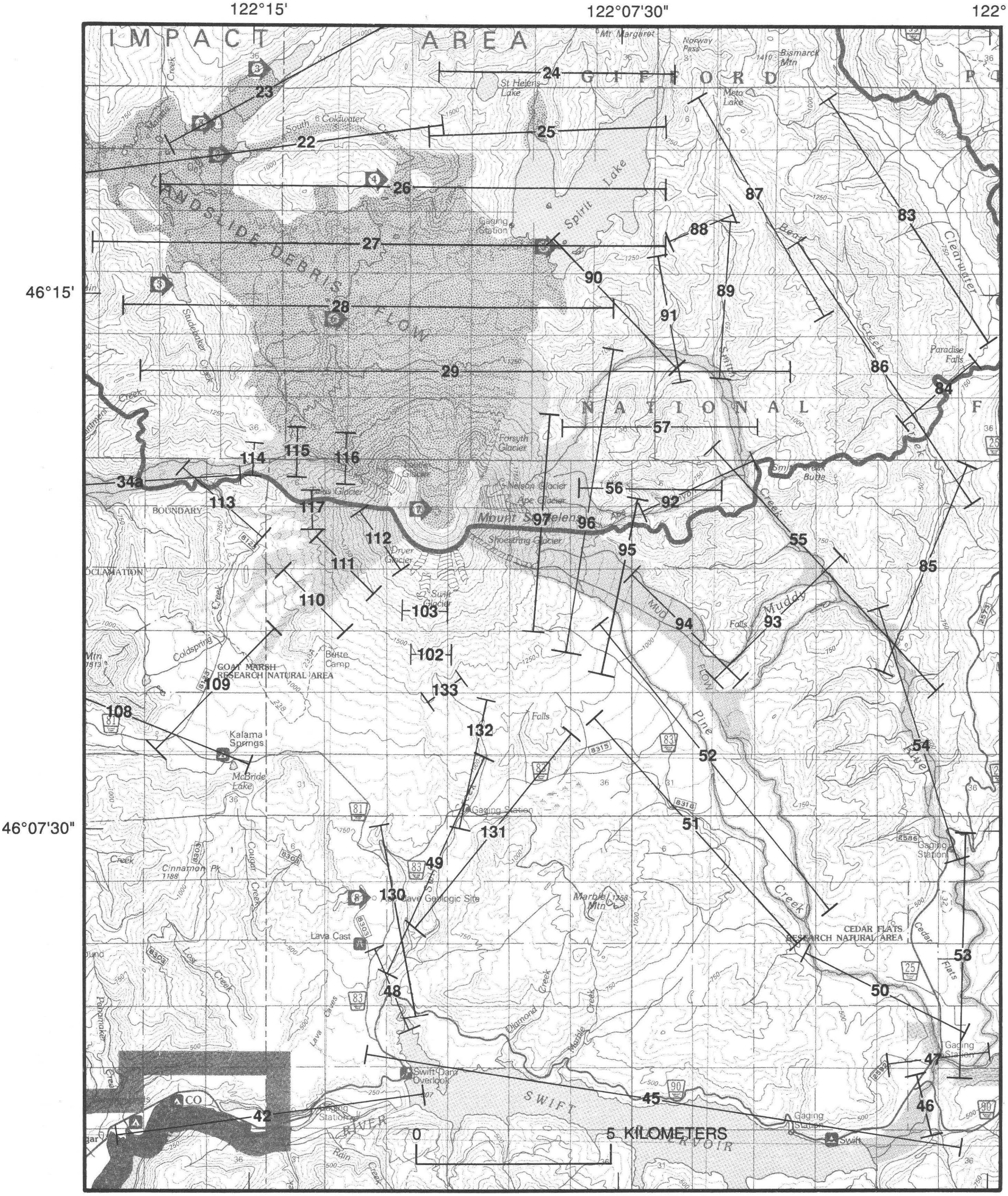


Figure 20.4. Large-format vertical aerial photographs, reduced 50 percent, illustrating drainage channel development around Mount St. Helens at a scale of approximately 1:9,600. *A*, Section of debris avalanche photographed September 15, 1980, shows absence of drainage channel development. *B*, Same area photographed September 28, 1985, shows establishment of major drainage channels.


122°15'
122°07'30"
122°
46°15'
46°07'30"
IMPACT AREA
GIFFORD
NATIONAL
LANDSLIDE DEBRIS FLOW
MUD FLOW
Mt Margaret
Norway Pass
Bismarck Mtn
Meta Lake
St Helens Lake
South Coldwater Creek
Spirit Lake
Gaging Station
Studebaker Creek
Clearwater
Bean Creek
Smith Creek
Paradise Falls
Smith Creek Butte
Forsyth Glacier
Nelson Glacier
Ape Glacier
Mount St Helens
Shoestring Glacier
Dryer Glacier
Swift Glacier
Muddy
Pine Creek
BOUNDARY
Butte Camp
GOAT MARSH RESEARCH NATURAL AREA
Coldspring
Kalama Springs
McBride Lake
Falls
Gaging Station
Cinnamon Pk
Cougar Creek
Cave Geologic Site
Lava Cast
Lost Creek
Marble Mtn
Diamond Creek
CEDAR FLATS RESEARCH NATURAL AREA
Cedar Flats
Swift Dam Overlook
SWIFT
RESERVOIR
RIVER
Rain Creek
Swift
0
5 KILOMETERS
22
23
24
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26
27
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29
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topographic contour maps. At Mount St. Helens, photography flown after each dome-building episode or after major hydrologic events has been used to produce numerous topographic maps of the crater, dome, and debris avalanche.

The value of vertical aerial photography was proved at Mount St. Helens in 1980 (Moore and Albee, 1981). A topographic map was made from photography flown across the volcano on April 12, 23 days after earthquake activity began. This map was compared with a published 1958 contour map (based on 1952 photographs) and significant topographic differences were noted. To eliminate possible changes due to glacial action during the 28-year span covered by the maps, a new topographic map was "hastily prepared" from photography of August 15, 1979, and compared with the April 12, 1980 map. Differences in elevations of the summit graben and bulge area on the north side of Mount St. Helens were apparent. According to Moore and Albee (1981, p. 127):

> The photogrammetric data *** in conjunction with ground geodetic measurements *** were of prime importance in understanding the processes acting within the volcano and in assessing the hazard due to oversteepening of the north slope. In retrospect, the photogrammetric data set was acquired at low risk, and consequently should be an important element in monitoring future activity of potentially explosive volcanoes of similar type.

OBLIQUE AERIAL PHOTOGRAPHY

Oblique aerial photographs (fig. 20.2*B*) are taken when the camera's optical axis is considerably inclined from the vertical, generally 20° or more (Ray, 1960, p. 2). Krimmel and Post (1981, p. 31) believe that this technique is one of the more useful photographic techniques used at volcanoes:

> Oblique aerial photographs offer many advantages over vertical photographs for documentation of volcanic events; these include more natural perspective, greater aerial coverage from low altitude, greater flexibility in aircraft operation, coverage of specific localities during periods of partial cloud or ash obscuration, and lower cost.

Figure 20.5. (facing page) Section of a location map showing layout of flightlines over drainage channels southeast of Mount St. Helens. Contours in feet. Numbers on the flightlines are indexed to the CVO photo library. Circled numbers within bold arrows refer to interpretive features described on original base map (U.S. Geological Survey, 1981).

Small-format 35-mm cameras loaded with color slide film are the most common camera format and film used at CVO for oblique aerial photography of the Cascades volcanoes. A medium-format camera loaded with b/w film is also used by the staff photographer. (Although not common, a large-format camera can also be used for oblique aerial photography; see Krimmel and Post, 1981). Video or movie cameras are occasionally used. The cameras are always hand-held (except for the large-format camera used by Krimmel and Post, which is mounted in the airplane). The most useful lenses for oblique aerial photography are the standard and wide angle, as the telephoto lens magnifies aircraft vibrations, making it difficult to use with complete success.

The following are a number of helpful points to remember when photographing from an aircraft.

1. Set the camera focus on infinity. Since virtually all aerial photographs will be taken at infinity, tape the focus ring at infinity before the aircraft leaves the ground. This will ensure that the focus is not accidently bumped during the excitement of volcano photography. Vinyl plastic electrical tape works well, as it is easily removed without breaking or leaving residue.

2. The shutter speed of the camera used in aerial photography should be at least 1/250 second, and preferably 1/500 or 1/1000 second. A slower shutter speed may introduce motion, resulting in blurred photographs. Motion during exposure is one of the main problems of good aerial photography and is caused by the camera being hand-held, the forward speed and mechanical vibration of the aircraft, and the smoothness of the flight relative to how much turbulence is in the air (Eastman Kodak Company, 1985, p. 8). To reduce the effects of motion, use as fast a shutter speed as possible and keep the camera from touching the aircraft. Use a faster film instead of a slower shutter speed if the day is overcast (at CVO, 200 or 400 speed films are used on overcast days). To obtain a fast shutter speed with an automatic camera, use as fast a film as possible.

3. Shoot through open windows or remove the helicopter door before takeoff. Aircraft windows have distorting curves and hundreds of scratches, so that shooting through plastic windows severely limits the quality of the photographs. If possible, shoot through an open window or have the helicopter pilot remove the doors, thereby leaving an unobstructed view. If you must shoot through windows, hold the camera as close to and as perpendicular to the window as possible. This will minimize the possibility of unpleasant reflections from the windows. With auto-focusing cameras, shooting through an open window is a must, as many auto-focusing cameras may focus on the window instead of the volcano.

4. Keep airplane wings and helicopter blades out of the view. Photographs with airplane wings and

helicopter blades are less pleasing than those without. Airplane wings and helicopter blades also can cause auto- focus cameras to focus on them instead of the view.

5. The location of the sun is an important factor when shooting aerial photographs. Aerial photographs taken with a sun angle of 20-30° above the horizon are the most satisfactory (Hackman, 1967, p. B157); photographs taken when the sun is 10° or less above the horizon produce long shadows. In areas of high relief, such as volcanic terrain, shadows of large topographic features often obscure too much of the area unless the sun is well above the horizon. This has proved to be a major problem when photographing the Mount St. Helens dome, as the crater wall casts its shadow on the dome during winter months, or early or late in the day. In the summer, photography taken at midday produces little shadow and shows almost no relief at all, making details harder to see.

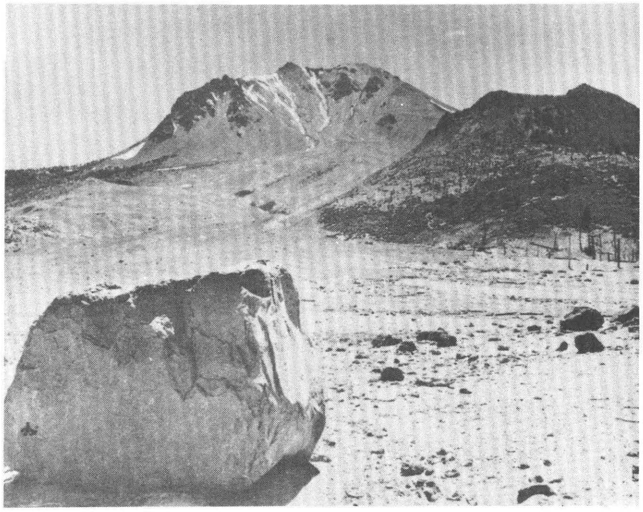
REPEAT TERRESTRIAL PHOTOGRAPHY

Repeat terrestrial photographs are taken over a period of time from a permanent mark and are used to document long-term landscape change, such as biological (fig. 20.6), erosional (fig. 20.7), and geological (figs. 20.1, 20.8) development around volcanoes. Repeat photographs can also be combined into one composite diagram to illustrate years of cumulative landscape evolution (fig. 20.9). Since 1980, more than 100 repeat terrestrial photography stations (photo stations) have been established at Mount St. Helens and the other Cascades volcanoes.

Ideally, repeat terrestrial photographs are taken from the same point, using the same camera and lens (or at least the same camera format and focal-length lens), with the camera at the same height above the ground, and aimed in exactly the same direction. This results in the same photographic view each time. At Mount St. Helens, this goal has not been fully achieved. Many photo stations are sporadically visited by different people with different camera, lens, and film combinations, and who stand in slightly different locations. Harrison (1974, p. 469) stated: "Retrieval of information from old photographs of geological features will be enhanced if the photographs are repeated from the same site. Reoccupying the exact site may not be essential, but it makes the interpretation of the photographs more convenient." What has resulted at CVO is a collection of photographs that are not all perfectly repeated views, yet nonetheless document changes around the volcano (fig. 20.7).

When establishing or reoccupying a photo station, a number of ideas should be kept in mind:

1. Numerous photo stations should be established. According to Veatch (1969, p. 51), "it is better to establish too many rather than too few photographic stations. Some stations can always be dropped, but once any photographic records are missed they are lost forever." Over the years at Mount St. Helens, many different photo stations have been established, often within sight of each other, but not all stations have survived. Some have been destroyed by volcanic activity and river channel migration; the locations of others have been forgotten. A few were established for short-term



A

B

Figure 20.6. Two repeat photographs of Lassen Peak illustrate biological development occurring around volcanoes. *A*, Lassen Peak after May 22, 1915 blast. B.F. Loomis photograph, courtesy of Loomis Museum Association, Mineral, California (Loomis, 1926). *B*, View from same location 69 years later.

projects, occupied for a few days, weeks, months, or even years, and then abandoned when the project ended. Some stations have turned out to be good photo stations and have been reoccupied many times over the past 10 years, and others, while being visually and informationally good, have not been reoccupied consistently because of cost or difficulty of access.

2. Each photo station should be a permanent mark on the ground. Permanent marks should be established so photographers know exactly where to place the tripod to repeat the photographs. At Mount St. Helens, fence posts, steel towers, large rocks, bridge supports, established USGS bench marks, and, as a last resort, spots on the ground located a known number of paces from a permanent object have been used as permanent markers. During one dome-building episode, a short-term permanent mark was established using a 55-gallon drum as a camera mount (fig. 20.10). Long-term permanent marks at other Cascades volcanoes are often established CVO bench marks (fig. 20.11).

3. Tripods are a must. A tripod facilitates aiming the camera, helps to ensure that the camera is correctly aligned over the permanent mark, and is necessary to maximize photo sharpness by reducing camera vibrations. Very few people can hold a camera sufficiently still during an exposure longer than 1/60 second. Camera movement results in blurry photographs. At CVO, Bogen 3020 "Professional" tripods with Bogen 3025 "3-D" or 3028 "Super 3-D" three-way-tilt heads are used. At other Cascades volcanoes, the staff photographer uses a Bogen 3058 "Super Pro" tripod with a 3047 "Deluxe" heavy-duty three-way-tilt pan head, or

A

B

Figure 20.7. Although taken from slightly different positions, two repeat photographs of Upper Muddy River at Mount St. Helens illustrate erosional development around volcanoes. *A*, October 1980, five months after May 18, 1980, eruption. *B*, Same area photographed one year later.

A

B

Figure 20.8. Repeat photographs of Mount St. Helens lava dome illustrating importance of choosing correct focal-length lens. *A*, In 1981, dome was photographed using a standard 55-mm lens from a photo station approximately 1 km away. *B*, When photographed 4 years later, dome had outgrown field of view of 55-mm lens.

the head is mounted on the Kern tripod used in the deformation network (Iwatsubo and Swanson, chapter 10).

4. Take along a copy of the photo taken previously at the photo station to aid in exact framing of the same scene.

5. To ensure successful repeat photography, keep accurate notes on cameras and lenses used, film type, date and time, the height of the tripod, the angle of tilt of the camera if not level, and the azimuth of the camera. Record detailed descriptions on how to get to the photo site and how to identify the permanent mark. These will all be important when repeating the photograph at a later date. If the photo station cannot be reoccupied on a particular visit, note why.

6. Take a photograph of the camera setup at the photo station. This greatly facilitates reoccupying the exact site and is an invaluable aid to the next person sent to occupy the site. Many of the photo stations at other Cascades volcanoes are official U.S. Geological Survey bench marks that do not protrude above the surface of the ground. Photographs showing where the tripod is, with nearby rocks, vegetation, or outcrops visible (fig. 20.11), have saved considerable time when searching for the station.

7. Shoot the scene with both color slide and b/w negative film, so that the same scene can be photographed in slide format for talks and shows and in b/w format for publications and historical archiving. Although b/w prints may be derived from color slides, they are inferior to a print from an original b/w negative and therefore not as desirable for historical purposes.

8. If possible, use the same focal-length lens each time a photo station is occupied. This helps to facilitate quick comparison of images without having to manipulate the photographs, but it is not absolutely necessary. According to Malde (1973, p. 198) "views made with cameras of different focal lengths from the same lens position will always match exactly, provided that both are printed and cropped to the same size."

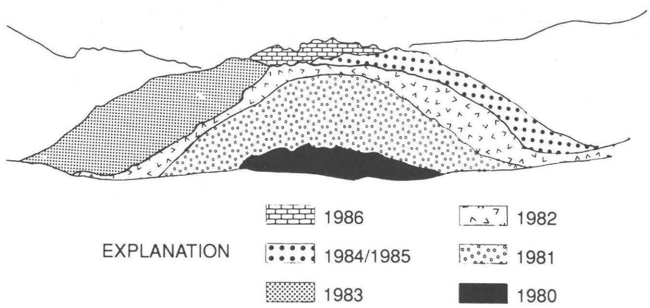


Figure 20.9. Composite diagram of dome growth, made from 6 years of repeat terrestrial photography, taken from a photo station approximately 1 km north of dome.

During eruptions and floods, however, there is no time to print and crop photographs. Also, when different people are reoccupying the photo stations, having one "project camera" available to give to the field crews results in more consistent photographs. For example, many CVO photo stations were established at cross-section survey points along the stream drainages. Repeat photography is shot upstream, downstream, and across the drainage while hand-holding the camera and standing at the channel edge near the cross-section marker, or near the edge over the instrument stake. The field crews doing the

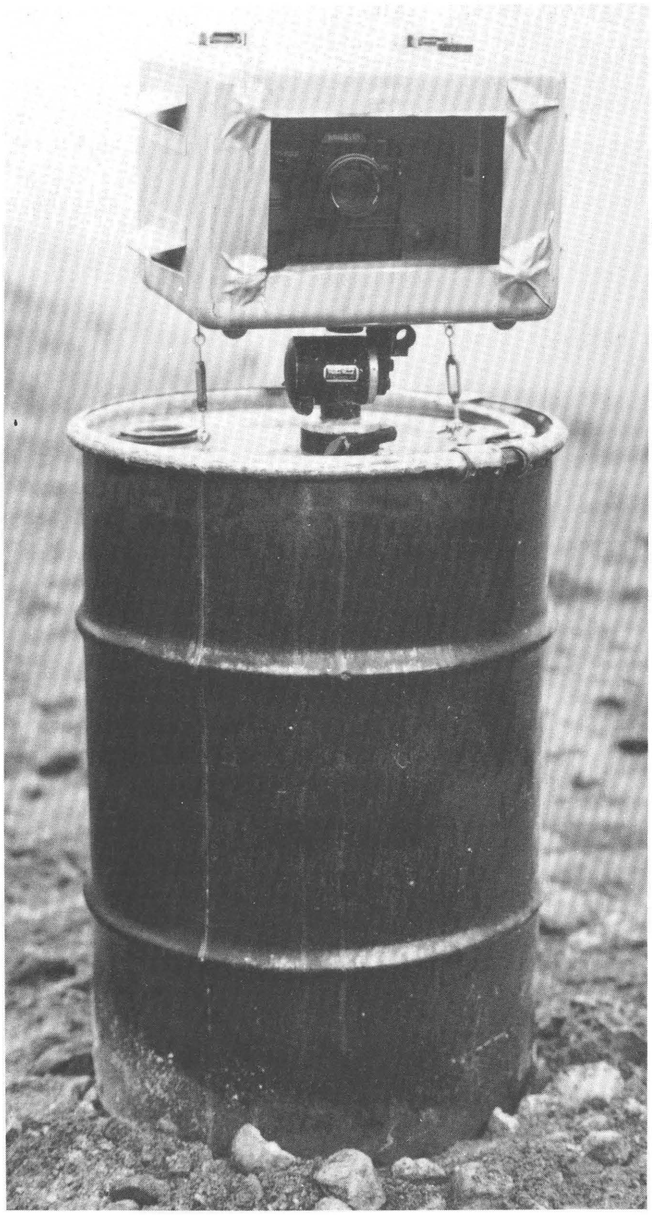


Figure 20.10. A 55-gallon drum filled with rocks was used as a camera mount and a permanent mark for a short-term photo station. Drum was filled with rocks for stability, a tripod head was secured to lid, and camera's protective metal housing was attached to tripod head.

surveying (and the photography) are seldom the same each time. By eliminating one variable, that of the different fields of view of different cameras and lenses, the resulting images have been easier for researchers to study later.

9. Lenses of different focal lengths should be used on the same subject at each photo station during each visit. Shooting a photo station at only one focal length might present irreversible difficulties in the future. On August 22, 1981, the dome was approximately 163 m high and 400 m wide when photographed from a station 1 km north of the dome. The dome fit within the frame of the 35-mm camera using a standard 55-mm focal-length lens (fig. 20.8*A*). By August 12, 1985, the dome was 230 m high and approximately 800 m wide, and no longer fit in the frame (fig. 20.8*B*). Unfortunately, it was too late to capture the 1981 scene with the wider-angle 28-mm focal-length lens.

10. When possible, the photographs should be taken about the same time and date each year. "In this way, because the shadows and highlights are then faithfully reproduced, the old and new photographs can be better compared." (Rogers and others, 1984, p. xxvi). At Mount St. Helens this often is not possible; many of the photo stations are reoccupied only after eruptions or floods, regardless of the time of the year. Other photo stations visited several times a year offer better opportunities for getting photographs at nearly the same date and time.

11. If the weather or lighting conditions are not perfect, take the photograph anyway. Because film is inexpensive compared to the cost of getting to a photo station, a large number of photographs are taken at Mount St. Helens photo stations even if the weather or lighting conditions are not perfect. That way, if the station cannot be reoccupied during better conditions for some reason, at least something has been recorded. At the other Cascades volcanoes, photographs are always taken when a photo station is reoccupied because it may be years before we visit it again.

12. Consider the future. Try to imagine what the photo station will look like in the years to come. Will there be any small trees in the foreground that will one day grow up to block the view (fig. 20.6)? Is the station so close to the edge of an active channel that it may be eroded away? Is the station directly in the path of

Figure 20.11. Tripod setup at South Sister volcano facilitates relocating that site years later. At South Sister, same tripod is used for photo station and deformation network's surveying instruments.

potential lahars, pyroclastic flows, or rock avalanches? If so, perhaps consider establishing another photo station in a more secure spot.

ILLUSTRATIVE TERRESTRIAL PHOTOGRAPHY

Illustrative terrestrial photography is perhaps the most common photographic technique employed by scientists. Illustrative terrestrial photographs (figs. 20.2*A*, *B*, *D*, and 20.12) are taken from the ground of any subject, with no plans to ever reoccupy that exact photographic spot again, and with no other purpose except to document and illustrate some natural or man-made feature. Every year at Mount St. Helens hundreds of illustrative terrestrial photographs are taken of the crater, dome, drainage channels, erosion, rockfalls, returning plant life, scientific equipment, researchers at work, and other topics.

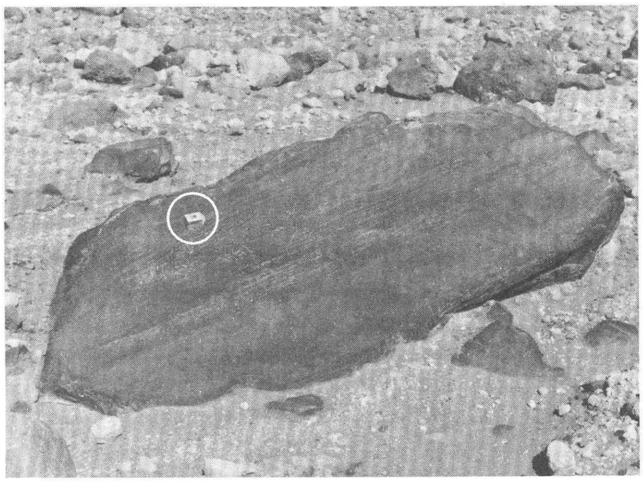
Occasionally place a "ruler" in the scene when photographing close-in subjects and include a recognizable object in the scene when photographing a distant subject. Measurements can then be calculated from the photograph, or at least a general idea of scale of the image can be obtained. Rock hammers, shovels, ice axes, camera lens caps, or film boxes are useful when photographing close-in subjects (fig. 20.12*A*), and fellow researchers, helicopters, and automobiles work well in wider views (fig. 20.12*B*).

TIME-LAPSE PHOTOGRAPHY

Time-lapse photography is another technique useful when photographing volcanoes. For purposes of this report, time-lapse photography is defined as repeat terrestrial photography taken in a short period of time with programmable cameras. The cameras are programmed to photograph an important geologic or hydrologic event by shooting a roll of film in predetermined time intervals. At Mount St. Helens, time-lapse photography has been successfully used to photograph dome growth during dome-building episodes and debris flows originating at Shoestring Glacier.

In August 1982, an 8-mm Eumig movie camera, modified for time-lapse, was installed at a photo station approximately 1 km from the dome and used to photograph an emerging lava lobe. A frame was shot every 5 minutes, resulting in nearly 5 days of lobe growth condensed on one 50-ft roll of film. In October 1986, the camera was placed on top of the dome and aimed at an actively extruding lobe. The camera was programmed to shoot a frame every 10 seconds, resulting in a roll of spectacular footage of the lobe's active spreading center.

Minolta X700 cameras with programmable data backs were also used during the same two eruptive episodes. On August 19, 1982, a camera was mounted in



A

B

Figure 20.12. "Rulers" help illustrate size in photographs. *A*, Film box (circled) shows relative size of boulder. *B*, Two scientists (circled) show relative size of trees devastated on May 18, 1980.

a protective housing and set on a tripod approximately 0.5 km north of the dome. Throughout the next two days, five rolls of film were shot, at different time intervals. The site was then reoccupied and photographed sporadically during the next two weeks. Figure 20.13*A* shows tracings of the August 19 lava lobe taken from the time-lapse frames, and figure 20.13*B* shows tracings of the new lobe on August 19 and 20 and September 1.

On October 21, 1986, two Minolta X700's were installed 8 km north of the dome in an attempt to photograph the predicted emergence of a new lobe during the night. One camera was programmed to take an exposure 10 minutes long every 2 hours, and the other camera was programmed to take a 20-minute exposure every hour. A 20-minute exposure taken at 0500 hours

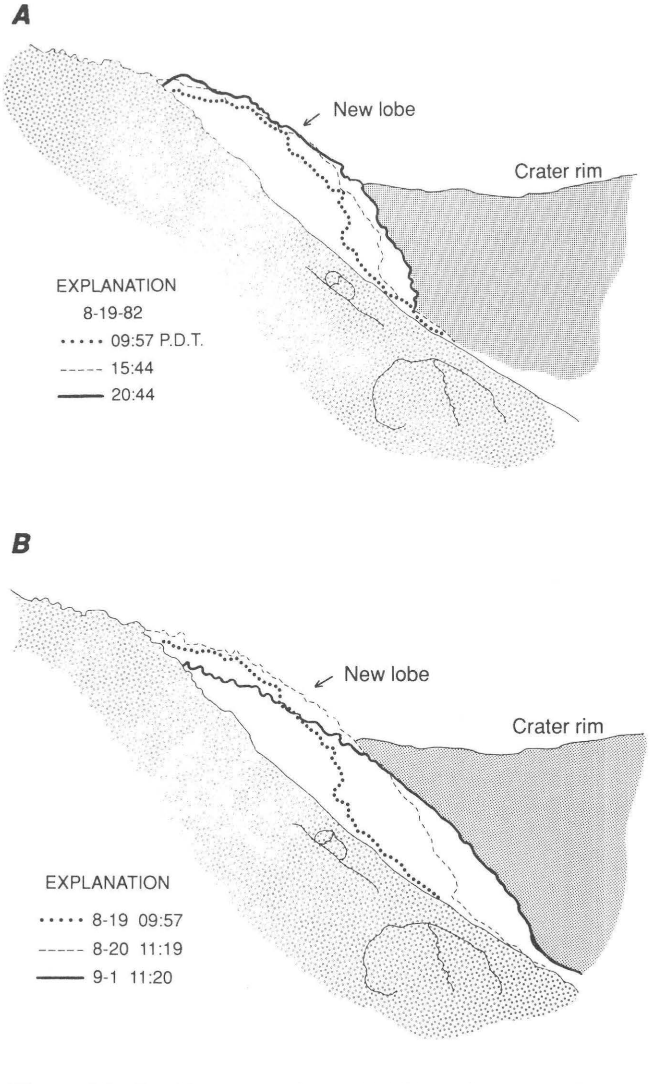


Figure 20.13. Between August 19 and September 1, 1982, a 35-mm time-lapse programmable camera was used to photograph dome growth. Resulting photographs were later used to sketch growth. *A*, Tracings of lobe during August 19. *B*, Tracings of lobe on August 19 and 20 and September 1.

(local time) the morning of October 22 shows no hint of a glowing lobe while the next frame taken at 0600 hours clearly shows glow from a hot dome. The camera documented the emergence of the lobe, consistent with the interpretation of seismic records (Elliot Endo, oral commun., 1986). The next night, October 22, the cameras were programmed to take 30-minute exposures of the new lobe (fig. 20.14).

In 1981-83, the Minolta X700 camera was also used to photograph sequences of debris flows originating from Shoestring Glacier. The camera's motor drive was set to shoot 3.5 frames per second when remotely triggered by an infrared beam (Tom Pierson, oral commun., 1990). This setup was successful three times.

Time-lapse cameras left at photo stations create a new set of photographic problems. Rain, snow, ice, and ash can coat camera lenses or housing windows, clouds can obscure views, wind can blow cameras over, and eruptions, lahars, or floods can destroy cameras. Camera batteries can die with no warning; cold weather is the major reason for the failures. Numerous attempts at photographing emerging lobes on the dome have been ruined by blowing ash during the summer, cold, snow, and ice during the winter, and clouds obscuring the view at all times of the year. Attempts to photograph drainage-channel development during major storms have been unsuccessful due to wind and rain. One of the Eumig 8-mm movie cameras was swept away at Mount Rainier during a glacial outburst flood.

To ensure the best possible chances of obtaining good time-lapse volcano photography, mount the cameras at secure locations in environmentally sealed camera housings, keep the cameras warm during colder months, and provide enough power to keep the system running. At Mount St. Helens, an unheated plexiglass box and an unheated metal box with an inset glass window (fig. 20.10) are used to protect the Minolta X700's. The Eumig movie cameras have their own weatherproof housings, which still need to be sealed with duct tape to prevent blowing ash from entering the system (fig. 20.15). All cameras are generally mounted low to the ground, and rocks or sandbags are placed around them to provide stability in winds (which can exceed 100 km/hr). Although the Eumig movie cameras have not been heated, they have usually remained running even during the winter. Ice quite often forms on them, however, making the footage unusable. The Eumigs run on one 6-volt "lantern" battery, and the cameras have been modified to accept a parallel battery setup. The Minolta X700's will not stay running during periods of cold, and they have not been modified to accept parallel batteries. In the warmth, at 20°C, one lithium battery (3 volts) will operate a Minolta X700 for approximately 6 hours of exposure time.

The Minolta X700's used to photograph the night scene of the growing new lobe (fig. 20.14) were mounted in an unheated observation building, with camera ports cut into the walls. Winter temperatures in the building have been recorded as low as -15°C, necessitating an inexpensive method to keep the cameras warm. A camera-heating system using electric socks (such as those worn by hunters and fishermen) was devised. Electric socks have a heating element sewn into the sock toe and are powered by a 1.5-volt "D"-cell battery. The socks are modified to accept up to four batteries in parallel, therefore providing over 30 hours of heat. Two socks are used per camera. The socks are turned inside-out and the heating elements placed next to the camera, data back, and motor-drive batteries. The rest of the sock is then wrapped around the camera to provide extra insulation, and the entire setup is covered with waterproof nylon. Only the front of the camera lens is exposed.

QUANTATATIVE MEASUREMENTS

The capability to make quantitative measurements from photographs is an important application of photography. The researchers at CVO have used this capability extensively with vertical aerial photography and occasionally with terrestrial or oblique aerial photography. The dimensions of the dome (Swanson and others, 1987) are routinely calculated with the help of photographs.

Quantitative measurements and calculations are based on four variables: h, the subject size; h', the image size (size of the subject as measured on the negative or transparency); F, the lens focal length; and v, the lens-to-subject distance (Blaker, 1976, p. 343). Their relationship is

$$h'/F = h/v.$$

This formula can be used not only for obtaining measurements from photographs but also to determine what focal-length lens is needed, or how far away a photo station must be from a subject in order to have that subject fill the frame.

Measurements are usually obtained from large-format vertical aerial photographs. The lens focal length and lens-to-subject distance (altitude of the aircraft above the ground surface) are routinely recorded, image size is easily measured off the large negative or transparency, and subject size is then computed. Image size can also be determined from photographic prints if

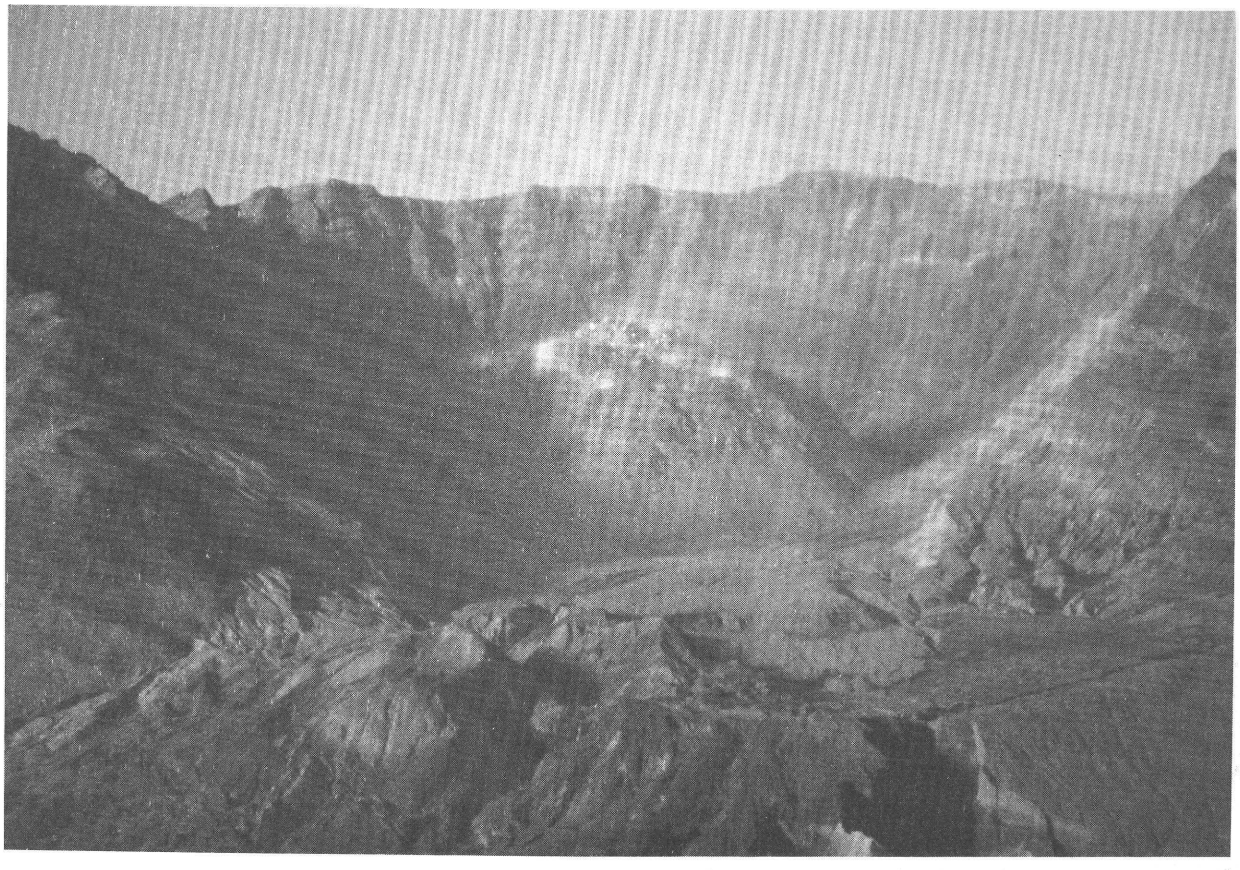


Figure 20.14. A programmable 35-mm time-lapse camera was used to shoot this 30-minute evening exposure of the October 22, 1986, dome growth, resulting in this moonlit view of a 15-hour-old lobe.

the relationship is known between the print and the original negative or transparency (amount of enlargement or reduction). Image size is then calculated as if measured from the negative or transparency.

If the scale of a vertical aerial photograph is known, two variables can be deduced. Since scale is represented as a ratio against 1, the image size (h') is the "1", and the subject size (h) is the other number. If either the altitude of the aircraft or the focal length of the lens is known, the remaining variable can then be solved for. This is useful in determining at what altitude the aircraft should fly to obtain the desired scale. If a 1:10,000-scale photograph of the dome is desired and the camera has a 152-mm (6-in.) lens, the aircraft will need to fly approximately 1.5 km (5,000 ft) above the top of the dome to obtain the desired scale

$$1/152 = 10{,}000/v = 1{,}520{,}000 \text{ mm} = 1.5 \text{ km}.$$

Measurements can also be obtained from oblique aerial or terrestrial photography, although the process is more difficult and not as exact. In an oblique photo the distances in the photo generally increase from the bottom (nearest the camera) to the top (farthest from the camera), thus making it difficult to calculate subject size. Image size is readily obtainable from the negatives or transparencies, and lens focal length should be written in the notes. Unfortunately, both the subject size and the lens-to-subject distance are variable across the film and are often unknown. One of these needs to be obtained to complete the equation.

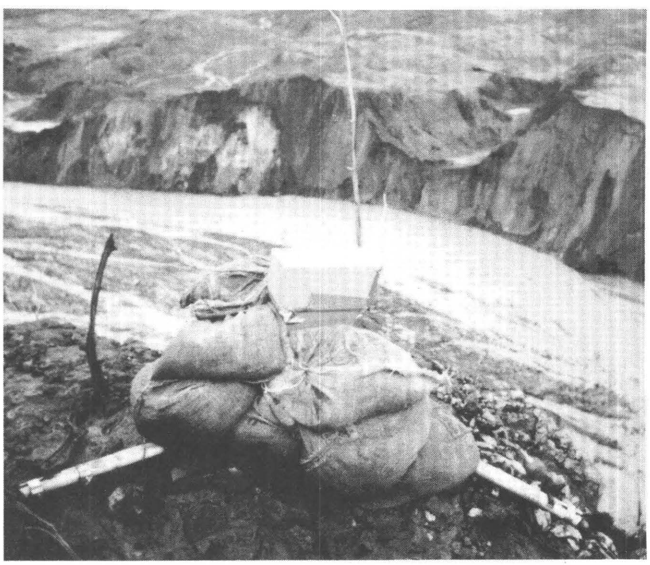


Figure 20.15. For camera protection, this time-lapse movie camera has its housing edges taped for ash protection and tripod sandbagged for wind protection.

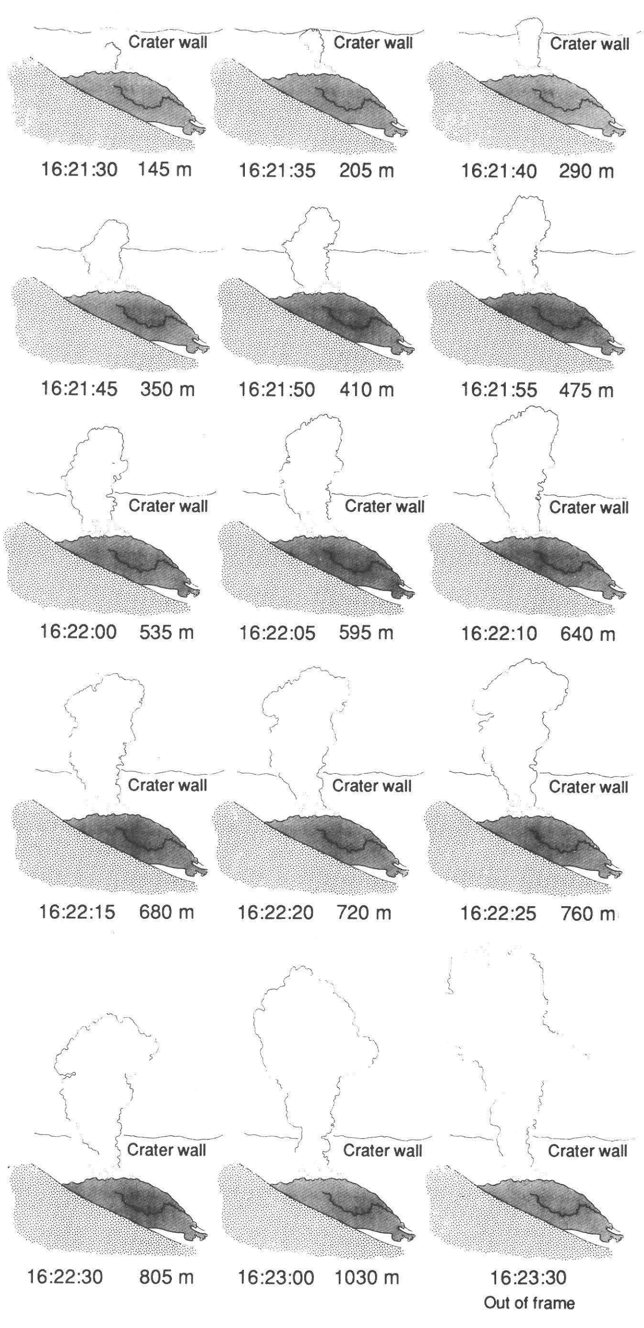
An easy method to obtain lens-to-subject distance for terrestrial photography calculations is to measure the distance between the photo station and the subject using topographic maps or vertical photography. Another method is to use surveying equipment and accurately measure the distance from the camera to the subject. When surveying cannot be done, rough estimates of the lens-to-subject distance can be made if the distances of at least two known objects (control points) roughly in the same plane as the main subject are obtained. The distance to the original subject can then be estimated geometrically between the control points. The equation can also be solved if the subject size or the control-point sizes are known or can be measured or estimated, leaving the lens-to-subject distance to be calculated. The surveying or measuring of the control points does not have to be done when the photo station is initially established and it does not have to be done each time a photograph is taken, so long as it is completed sometime during the life of the photo station (Malde, 1973, p. 197).

Once the distances to, or sizes of the control points are known, distances and sizes of many features within any photograph taken from that photo station can be calculated, although the exactness of the calculations depends on the number and location of the control points. The greater the nmber of control points measured, the more exact will be the calculated subject size. Approximate size can still be determined if only one control point is available and often this rough estimate is all that is needed to help illustrate an idea. For example, on April 16, 1983, 35-mm photography from a photo station was used to calculate the rate of rise of a small plume of steam and ash (fig. 20.16). This particular photo station was chosen because of its location of approximately the same elevation as the dome, thus offering a nearly perpendicular view of the dome providing one known control point. The photo station was also close enough to be able to measure the plume images on 35-mm film, yet far enough away to minimize the effect of varying distances between the plumes and the camera. A Minolta X700 camera with motor drive and data back was programmed to shoot a picture every 5 seconds and was manually turned on at the first sign of a plume. For this situation, the focal length of the lens was known, the image size was measured from each frame. The lens-to-subject distance of the "center-of-dome" control point was measured from topographic maps. The unknown variable, the height of the plume, was then calculated and the rate of rise was plotted.

CONCLUSIONS

Personnel of the Cascades Volcano Observatory have used a variety of cameras and techniques to document changes and events at Mount St. Helens and other Cascades volcanoes. The selection of camera equipment has been largely decided by scientific need, budget limitations, and personal preference. Still photography, especially small-format, has been used most extensively, while video and movie photography has been underutilized. A variety of techniques has been used involving aerial and terrestrial photography, and numerous photo stations have been established. Use of photographic products include illustrations for publications, transparencies for slide shows, maps made from vertical aerial photography, and diagrams made from repeat terrestrial or time-lapse photography. We have learned that photography in any form is better than no photography at all.

A



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B

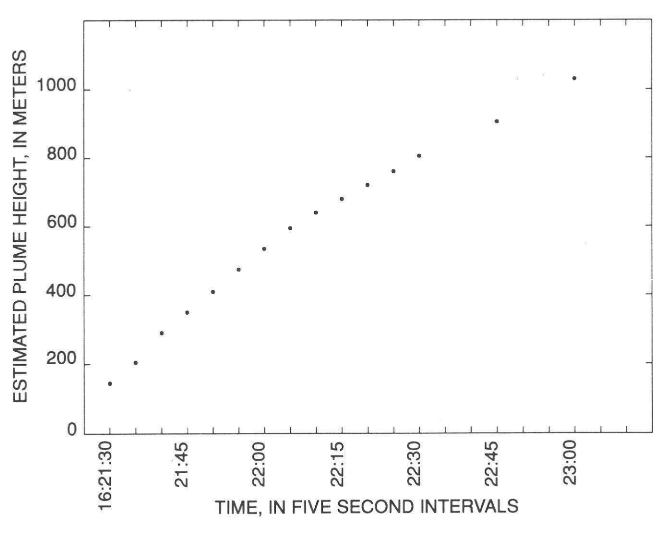

Figure 20.16. Two minutes of time-lapse photography help illustrate rate of rise of a small plume of steam and ash. *A*, Height of rising plume sketched and calculated from oblique photographs. *B*, Plume height plotted against time.

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21. The Importance of Field Observations for Monitoring Volcanoes, and the Approach of "Keeping Monitoring as Simple as Practical"

By Donald A. Swanson

ABSTRACT

Geologic field observations form an important part of any volcano-monitoring program yet are often overlooked in lists of monitoring techniques. Such observations provide the opportunity to integrate many different kinds of data on the spot and to design simple measurements to test key questions resulting from the observations. Field observations go hand in hand with more sophisticated equipment and techniques to form a complete system for monitoring volcanoes. Monitoring programs should explicitly include provisions for geologic field observations and instill in field workers, scientists and technicians alike, the need to be flexible and clever in designing simple experiments and measurements to test important field observations on the spot.

INTRODUCTION

Other chapters in this bulletin describe the many different methods of monitoring volcanoes that have been used by the on-site and affiliated research staff of the Cascades Volcano Observatory (CVO). Most of these methods involve relatively sophisticated equipment, training, or data analysis. Many of the methods have been used successfully at a number of volcanoes around the world in various environmental conditions. They are largely proven commodities that can be put to use for study of active volcanoes anywhere. They reflect the remarkable ingenuity and significant advancement in monitoring volcanoes that characterize the past decade in volcanology.

My aim in this essay is to highlight another means of monitoring that is the oldest that volcanologists have and yet is commonly overlooked in establishing a monitoring program. It cannot take the place of the more sophisticated techniques but can augment them and help guide their use. It is the only means that allows instant on-the-spot integration of a number of parameters that characterize the volcano, and instant reevaluation of that integration. It is old-fashioned yet up-to-date, operates in all but the most extreme environments, and is as durable as the remarkable machine that runs it. The means is direct field observation, and the machine is the observer.

The simplicity of geologic field observations belies their significance, and I provide three examples to demonstrate that fact. I also try to make the point that even simple measurements made on the basis of the observations can be sufficient, and that making the measurements more sophisticated than required does not necessarily improve their value—and in fact can even undermine their utility.

EXAMPLES

Three examples from Mount St. Helens illustrate my thesis that observations and simple measurements can be effective under the right circumstances. They are representative but not exhaustive examples of the importance of this thesis at Mount St. Helens. The examples are some of those with which I am most familiar.

Spirit Lake as a Tiltmeter

The first explosion from Mount St. Helens took place on March 27, 1980, and immediately thereafter volcanologists began to wonder if a magma body were rising beneath the volcano and, if so, what were its depth and volume. The volcano was covered by deep snow, but it was possible to drive to its base and a short distance up its northeast flank. Hence plans were quickly made to initiate tilt measurements by both single-setup leveling and electronic tiltmeters. But it would take time to acquire the necessary equipment, wait for new bench marks and foundations to stabilize, and obtain data. Moreover, the thick pumice blanket at the base of the volcano near Spirit Lake made it difficult to find stable sites for instruments and bench marks.

Why not use Spirit Lake as a giant carpenter's level? This idea had several advantages. The lake was far enough from the foot of the volcano to be an effective monitor of deep-seated changes under the volcano. The lake was oriented with its long direction radial to the volcano, and quick calculations suggested that tilts on the order of 2 μrad would be detectable with reasonably careful measurement procedures. The lake was covered with ice, so that wind-related waves would be damped out. Boat docks and partly submerged stumps in small areas of open water provided sites to install measurement devices.

But what devices could be obtained quickly? We couldn't afford the time to obtain normal water-level sensors and install them. An inexpensive and readily available alternative was immediately apparent. A visit to a local lumber yard resulted in an outright gift of several wooden yardsticks (metersticks), which were easily nailed to piers and stumps. Within a day the level of the lake was monitored by individuals visiting each site, reading the level of the lake on the partly submerged meterstick, recording the time of their visit, and closing back on a station chosen as a reference point. Later we used several observers with synchronized watches, but the results were the same: The shore of Spirit Lake was *not* tilting. This told us that a large volume of magma was not intruding under the volcano, so that we could concentrate our attention on the edifice of the volcano itself (Lipman and others, 1981).

The North-Flank Bulge

In mid-April, 10–12 days after monitoring of the lake began, several different geologists viewing the volcano noticed that its upper north flank had apparently deformed relative to its pre-1980 shape. Earthquakes recorded on portable seismographs were located beneath the north flank, so it seemed reasonable that the deformation was related to shallow intrusion of magma into the edifice. But the observed deformation was obvious only on glaciers, which apparently were buckling and bulging upward. Was this deformation confined to the glaciers and the result of rapid advance caused by subglacial melting, or was the underlying edifice also taking part in the deformation?

The obvious way to test for deformation of the edifice was to make repeated measurements to targets on snow-free parts of the volcano. Quickly a standard theodolite used by most surveyors was obtained and angles measured to prominent natural features on the volcano. The data suggested outward movement of the north flank, but aiming on natural features was difficult and subject to considerable error. Within a day or two an electronic distance meter (EDM) arrived, and reflectors were placed on the mountain. The EDM is a sophisticated instrument, but the targets were nothing more than clear plastic highway reflectors screwed to boards that were lashed to steel fence posts hammered into the ground. A combination of the theodolite and EDM measurements to these targets soon indicated that the north flank was moving northward at a steady rate, so that clearly the volcanic edifice was deforming in response to intrusion of magma (Lipman and others, 1981). The theodolite measurements to the wooden targets provided sufficient data by themselves to define the rapid displacements of as much as 2.5 m/d. The EDM data were useful adjuncts to the theodolite measurements but were not necessary to trace the movements at all but the least sensitive targets.

Measurements of Cracks and Thrust Faults Used for Prediction of Dome Growth

Geologists first observed cracks on the crater floor in mid-September 1980. Would they continue to widen, or had they formed quickly in response to some short-lived but unknown event? Simple measurements provided the answer. Short stakes of steel reinforcement rod (rebar) were pounded into the ground on either side of several cracks, and the distances between the stakes were measured with a carpenter's steel tape. Repeated measurements showed that some of the cracks widened with time, and that the rate of widening accelerated before the explosive event of October 16–18 and the dome-growth event of December 27, 1980–January 3, 1981 (Swanson and others, 1981).

During the December-January event, geologists were surprised to find two thrust faults on the crater floor north and northwest of the dome. The thrust faults faced outward, away from the dome. The same questions arose with these faults as with the cracks: were they still moving and, if so, might they provide an indication of future eruptive activity? Again rebar stakes were driven into the upper and lower plates of each thrust, and the distance between them was measured with the steel tape. The distance between each pair of stakes shortened with time and indicated that the upper plate was moving across the lower plate. Repeated measurements of the thrusts and associated radial cracks soon showed a distinctive pattern. Rates of displacement were slow after a dome-building episode but increased nearly exponentially as the onset of the next dome-growth event neared (Chadwick and others, 1983). This pattern and various other details of the entire deformation process of the crater floor were nicely traced with the simple rebar-and-tape method and formed the basis for a series of predictions of dome growth in 1981–1982 (Swanson and others, 1983). Moreover, the simple measurements with a steel tape provided the primary data for two interpretative papers about how and why the crater floor deformed (Chadwick and others, 1988; Chadwick and Swanson, 1989).

DISCUSSION

These three examples each show the value of on-the-spot field observations and the application of simple measurement techniques to resolve important questions and stimulate significant interpretations. Within hours to several days the basic questions raised by each set of field observations were answered, although of course refining the details took much longer. The answers came quickly, in part because the questions were easy (yet very important), but in part because the measurements could be started quickly owing to the simplicity of the methods used. Moreover, the simple methods were reliable and didn't depend on a complex chain of equipment, any link of which could fail unexpectedly. Total reliance on sophisticated equipment can backfire if the means is unavailable for its rapid repair. In general, a good guide to follow for devising a monitoring method is to "keep it as simple as practical."

Since 1980 notable improvements have been made in portable electronic-monitoring equipment, as several chapters in this bulletin show. Nonetheless, given the same circumstances as those in the three examples, I believe that the answers would still come faster with the simpler methods, largely because the sophisticated equipment requires significant installation and "settling-in" time. There is no question that the more sophisticated techniques fill important gaps, because most have the capability to acquire data almost in real time, 24 hours a day under any weather condition. But one of the principal limitations of these techniques is one of the principal strengths of field observation and simple measurements: flexibility and the ability to integrate several observations on the spot and to design a measurement to test that integration. Continuous measurements often can proxy for an on-site observation, but even the most broadly based—television monitors—are less adaptable and ingenious than a human observer in the field.

The flexibility provided by field geologic observations cannot be overemphasized. Most electronic sensors are designed to detect and report one parameter, such as tilt, displacement, seismicity, or changes in a particular species of gas. If some unmonitored parameter changes, the sensor either doesn't detect it or may provide spurious information. On-the-spot geologic observation clearly is not restricted to a single parameter, although of course it *is* restricted to what can be observed with the eyes, ears, and nose. Small changes may go unnoticed by field observers, but large changes may go unnoticed by electronic sensors not monitoring the proper parameter. Only on-the-spot observers can quickly assess the situation and determine which parameters are likely to provide vital information. Measuring an unimportant quantity accurately and continuously using sophisticated equipment can be a waste of time and resources; it is much better to get to the heart of the matter by the simplest means possible.

Another important point is that even the best remote-monitoring techniques require verification by on-site field observations and integration with other data. For example, an electronic tiltmeter may indicate a change, but this change could reflect an electronic problem, an unstable installation, or real deformation of the volcano. Only independent information can determine which interpretation is most likely. As a rule of thumb, never blindly accept data obtained remotely until on-site verification can be made. **Accept no substitute!**

Many colleagues emphasize the importance of sophisticated equipment and telemetered data during times of great hazard to field workers, and I agree with their reasoning. It is far better to lose a piece of equipment than a life. No reasonable person would advocate fieldwork under conditions that he or she feels are life-threatening. But there are many times in the activity of a volcano when conditions are not so hazardous, and it is these times that are suitable for field observation and indeed would benefit from such observations. Moreover, those of us who study active volcanoes must admit that certain risks exist, just as they do for firefighters and police officers. An integral part of our job is to assess those risks and establish personal guidelines for the relatively safe conduct of our research.

I see no point in providing further discussion of putative advantages and disadvantages of geologic field observations versus electronic measurements. The real point to be made is that we should think not in those terms (although many of us do), but instead in terms of an integrated monitoring effort that incorporates the best of all observations into unified interpretations. No one approach is inherently superior. There is a tool for every job, and the trick is to find the best tool or set of tools, whether they are close-in observations, complex equipment, sophisticated telemetry systems, or a combination of all three.

Nothing is new in this discussion, but the emphasis on sophistication and telemetered data in this bulletin seems to me to require a counterpoint, even though an obvious one. Field observations and related measurements are a vital component of volcano monitoring, just as are electronic sensors, radios, and high-priced surveying equipment. In fact, the two approaches commonly merge.

For example, sophisticated (and expensive) EDM's measure to painted wooden boards with plastic reflectors screwed on them—a real marriage of the aristocracy and the proletariat!

Indonesia provides a remarkable example of how a combination of simplicity and complexity has saved lives. In 1988, Indonesia experienced seven explosive eruptions, all of which had seismic precursors. As a result of the warnings and preliminary, closely observed, minor eruptive activity, 33,000 people were evacuated from their homes, and only four lives were lost (all on Banda Api, where those who were killed were knowingly evading the evacuation order) (T. J. Casadevall, written commun., 1989). Indonesia has about 150 active volcanoes and 50 volcano observatories. Each observatory has from two to four observers, generally only one seismometer with a smoked-drum seismograph, and typically only radio contact (a few have telephones) to central headquarters in Bandung. Nonetheless, the observers are well trained to note changes in seismicity and many other parameters (such as the presence of new ejecta, changes in plume behavior, fumarole temperatures, characteristics of crater lakes, and other factors), and they are from the region around the observatory, know the local people well, and have their trust. Perhaps there are lessons here for all of us. One lesson is that *the simplest kind of monitoring and warning system that works is the best one to use*; in this example, the monitoring system consisted of the simplest kind of complex instrument—a single seismometer and smoked-drum seismograph, and the warning system involved the observers who were intimately familiar with the monitored volcanoes and with the people of the region. Another lesson, not germane to the theme of this chapter yet of great importance, is that *the familiarity (and even closeness) of the observers to the local populace is a key that we should consider more in our efforts to save lives.*

During some volcanic crises, many scientists and technicians converge on the scene (or to a field observatory) but may stay for only short periods of time, returning to other duties as required. Continuity of observations and data gathering is difficult to maintain with such a rotation of staff, especially for field observations that commonly involve relatively subjective descriptions. One way to minimize such problems is to develop and use a check list of the kinds of field observations that should be made routinely. Such a list would in detail be specific to each volcano and would be susceptible to modification as the activity of volcano developed. Another key element in maintaining continuity of field observations is the thorough transfer of information between departing and arriving observers, preferably by visits to the volcano together.

CONCLUSIONS

My purpose in writing this essay is not to minimize in any way the modern monitoring techniques that are helping make volcanoes safer and better understood. I have used many of these techniques myself and have championed their implementation by others. Instead I simply want to point out that any monitoring effort is incomplete if trained observers are not made a part of it, and if the opportunity is not given for these observers to influence the gathering and interpretation of the data acquired by sophisticated techniques. In my view a volcano observatory or monitoring program of any sort starts with the people on its staff, not with the equipment in its locker or planned in its budget. Each geologist or geophysicist who spends much time on a volcano should be trained to observe field conditions, to think about those observations while in the field, and to be flexible and clever in devising simple measurements that can be made quickly and definitively once changes are noted. Those scientists and technicians should not have tunnel vision for only their specialty but instead should integrate all available information and be ready to respond to observable changes of any significant parameter. These individuals should be given the field time to spend on active volcanoes, and in fact such time should be an integral part of the monitoring program. Nature is too complex for us to learn enough about a volcano by monitoring it only remotely; we must also observe and monitor it personally and closely.

A volcano is too complex to be understood by individuals working alone. Free communication and exchange of data, observations, and ideas *among all workers* involved in monitoring are essential. Integration of field observations with telemetered data is vital to preparing a unified assessment of the volcano and its hazards. The stakes are so high that the data and observations, and the resulting development of interpretations, *must* be shared in an atmosphere of intellectual curiosity and social responsibility, rather than compromised in an atmosphere of competition or one of conflict among senior and junior scientists and technicians.

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