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The changing shapes of active volcanoes: History, evolution, and future challenges for volcano geodesy

Michael Poland [a,*], Michael Hamburger [b,1], Andrew Newman [c,2]

[a] *U.S. Geological Survey, Hawaiian Volcano Observatory, Crater Rim Drive, Hawaii National Park, HI 96718-0051, United States*
[b] *Department of Geological Sciences, Indiana University, 1001 East Tenth St., Bloomington, IN 47405, United States*
[c] *School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA 30332-0340, United States*

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1. Introduction

At the very heart of volcanology lies the search for the ‘plumbing systems’ that form the inner workings of Earth’s active volcanoes. By their very nature, however, the magmatic reservoirs and conduits that underlie these active volcanic systems are elusive; mostly they are observable only through circumstantial evidence, using indirect, and often ambiguous, surficial measurements. Of course, we can infer much about these systems from geologic investigation of materials brought to the surface by eruptions and of the exposed roots of ancient volcanoes. But how can we study the magmatic processes that are occurring beneath Earth’s *active* volcanoes? What are the geometry, scale, physical, and chemical characteristics of magma reservoirs? Can we infer the dynamics of magma transport? Can we use this information to better forecast the future behavior of volcanoes? These questions comprise some of the most fundamental, recurring themes of modern research in volcanology.

The field of volcano geodesy is uniquely situated to provide critical observational constraints on these problems. For the past decade, armed with a new array of technological innovations, equipped with powerful computers, and prepared with new analytical tools, volcano geodesists have been poised to make significant advances in our fundamental understanding of the behavior of active volcanic systems.

The purpose of this volume is to highlight some of these recent advances, particularly in the collection and interpretation of geodetic data from actively deforming volcanoes. The 18 papers that follow report on new geodetic data that offer valuable insights into eruptive activity and magma transport; they present new models and modeling strategies that have the potential to greatly increase understanding of magmatic, hydrothermal, and volcano-tectonic processes; and they describe innovative techniques for collecting geodetic measurements from remote, poorly accessible, or hazardous volcanoes. To provide a proper context for these studies, we offer a short review of the evolution of volcano geodesy, as well as a case study that highlights recent advances in the field by comparing the geodetic response to recent eruptive episodes at Mount St. Helens. Finally, we point out a few areas that continue to challenge the volcano geodesy community, some of which are addressed by the papers that follow and which undoubtedly will be the focus of future research for years to come.

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* Corresponding author. Tel.: +1 808 967 8891; fax: +1 808 967 8890.

E-mail addresses: mpoland@usgs.gov (M. Poland), hamburg@indiana.edu (M. Hamburger), andrew.newman@eas.gatech.edu (A. Newman).

[1] Tel.: +1 812 855 2934; fax: +1 812 855 7899.

[2] Tel.: +1 404 894 3976; fax: +1 404 894 5638.

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2. Volcano geodesy: a historical context

Among the most prominent – and often most threatening – signs of volcanic unrest are the major changes in Earth's surface that commonly precede or accompany volcanic eruptions. Because of their scale, such changes have been recognized by people living near volcanoes, even without the benefit of sophisticated instrumentation, for hundreds, if not thousands, of years. But it is only within the past century that measurements of ground deformation have been used as a tool to infer subsurface processes and forecast eruptions. Now, measurements of surface displacements can be made by continuously recording telemetered instruments and by space-based observing platforms. These measurements are routinely used as input to numerical models that evaluate complex rheologic and geometric conditions in three, and even four, dimensions. Monitoring of Earth deformation, together with a variety of geophysical and geochemical methods, provides the basis for modern eruption forecasting (e.g., Swanson et al., 1983; Banks et al., 1989; Scarpa and Tilling, 1996).

Among the earliest and best documented examples of volcanogenic ground deformation is the ruin of the Roman Temple of Serapis (or Serapeo) in Pozzuoli, Italy, at the center of Campi Flegri caldera. The structure has two generations of floors, with the newer floor built after the first had subsided below sea level (Lyell, 1889, v. 2, p. 171; Newhall and Dzurisin, 1988). Three marble columns from the marketplace were excavated, well above sea level, in 1750 (Fig. 1A). Mollusk shells were discovered in the columns embedded 7 m above the floor of the ruin, suggesting that the monument had subsided at least that far below sea level and had been uplifted a similar amount (Babbage, 1847; Lyell, 1889; Dvorak and Berrino, 1991). Some of this uplift was precursory to the 1538 eruption of Monte Nuovo (Lyell, 1889; Dvorak and Mastrolorenzo, 1991). By the 1820s, seawater was reported on the floor of Serapis, and water-depth measurements indicated steady subsidence at a rate of 15 mm/a through 1968 (Berrino et al., 1984). Babbage (1847) wrote that the uplift and subsidence recorded at the temple (Fig. 1B) clearly indicated "continual but usually slow change in the relative levels of the land and the water," and even suggested that heat played a role in the deformation. In his *Principles of Geology*, Lyell (1889) went further, pointing out "a connection between each era of upheaval and a local development of volcanic heat, and again between each era of depression and the local quiescence or dormant condition of the subterranean igneous causes." In fact, Lyell suggested that uplift occurred when magma accumulated before eruptions, and subsidence accompanied cooling and contraction of "subterranean lava."

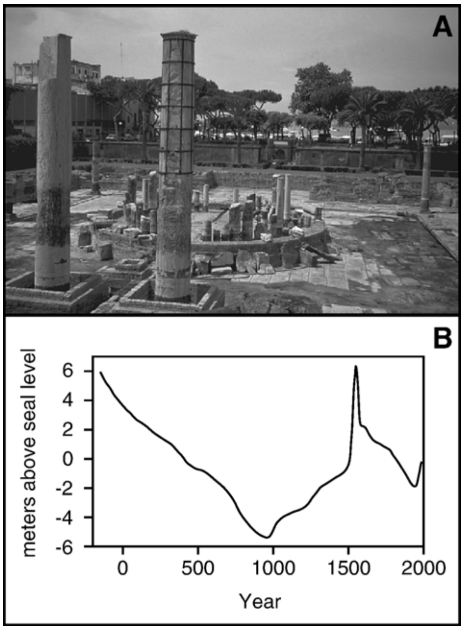

Fig. 1. (A) The ruin of the Temple of Serapis in Pozzuoli, Italy, includes three marble columns, two of which are seen here. The darkened patches on the lower third of each column (especially apparent on the left column) are due to mollusk borings, suggesting that the columns were submerged to at least this height since construction more than 2000 years ago. (B) Elevation of the floor of Serapis above sea-level, inferred from water damage to the ruin and water level measurements at the site (after Berrino et al., 1984).

The first modern scientific efforts at volcano geodesy were initiated by Fusakichi Omori and Thomas A. Jaggar in the early 20th century in Japan and Hawaii, respectively, using methods not originally intended for deformation monitoring. Omori (1913) may have been the first scientist to specifically attempt to quantify displacements associated with a volcanic eruption. He conducted a leveling survey at Usu volcano following its 1910 eruption and noted changes in the elevations of benchmarks, relative to those measured during a topographic survey conducted prior to the activity. He inferred that the vertical changes were caused by the intrusion of a cryptodome coincident with the eruption. A few years later, Omori (1918) again recognized deformation related to volcanic activity, this time at Sakurajima, which erupted in 1914. By comparing leveling surveys conducted prior to and shortly after the eruption, he was able to document a broad pattern of subsidence extending tens of kilometers from the volcano.

Work at the Hawaiian Volcano Observatory starting in 1912 may constitute the first continuous deformation monitoring at a volcano. Thomas A. Jaggar, founder and director of the Hawaiian Volcano Observatory, noted deviations in the pendulum, relative to its median position, of a two-component horizontal pendulum seismometer and recognized that these deviations indicated tilting of the ground surface (Kinoshita et al., 1974). Jaggar and Finch (1929) ascribed these wanderings to ground tilt associated with rainfall, temperature variations, and volcanic and seismic activity (especially the explosive eruption of Kīlauea volcano in 1924).

Later volcano geodesy studies followed the pioneering examples of Omori and Jaggar, often using classical surveying methods, such as precise leveling and triangulation, to quantify ground deformation related to volcanism. Wilson (1935) conducted leveling surveys at Kīlauea volcano in the 1920s and compared results to earlier topographic surveys. The results indicated a pattern of uplift between 1912 and 1921, followed by several meters of subsidence centered on Halema'uma'u crater between 1921 and 1926, probably associated with the 1924 explosive eruption there. Wilson corroborated the leveling results with triangulation measurements that showed radially symmetric motion toward Halema'uma'u between 1922 and 1926 at points within a few kilometers of the crater. Similarly, leveling measurements begun in 1905 through Campi Flegri caldera in Italy confirmed subsidence centered on Pozzuoli during the first 69 years of the 20th century, supporting inferences from water level measurements and other investigations at Serapis (Dvorak and Berrino, 1991; Dvorak and Gasparini, 1991; Dvorak and Mastrolorenzo, 1991).

As it became increasingly apparent that volcano deformation was a valuable tool for monitoring activity and forecasting eruptions, the challenge evolved from the detection of such ground motions to their interpretation. A critical breakthrough was Kiyoo Mogi's (1958) publication of "Relations between the eruptions of various volcanoes and the deformations of the ground surfaces around them." Mogi used a previously derived analytical solution for pressure change of a point source in an elastic half-space to approximate deformation patterns measured at Sakurajima, Kīlauea, and other volcanoes. The "Mogi model", as it has become widely known, was the first of many analytical solutions for surface deformation that followed, including dislocations (Okada, 1985), ellipsoids (Yang et al., 1988), disk-shaped cracks (Fialko et al., 2001), and other source geometries (De Natale and Pingue, 1996). Further advances were introduced as computational power allowed for more complex modeling, including numerical solutions using the finite- and boundary-element methods, an excellent example of which is the pioneering work of Dieterich and Decker (1975).

Geodetic networks are now commonly established on volcanoes for the specific goal of monitoring, forecasting, and predicting eruptive activity, as well as to gain insights into subsurface magmatic processes. These efforts have been enhanced by recent advances in technology that have enabled continuous, three-dimensional displacement data to be telemetered to scientists in near-real time. In addition, satellite data are now being used to map surface displacements without relying on ground-based observations. As a result, it is now possible to infer magma accumulation at depth, even at inaccessible or otherwise unmonitored sites — an especially important tool for hazard-mitigation efforts.

Geologic studies can recognize volcanic centers that hold the potential for future activity within a few centuries (e.g., Scott, 1989), and geophysical monitoring has become relatively reliable at predicting eruptive activity within time scales of weeks to hours (e.g., Banks et al., 1989; Punongbayan and Tilling, 1989; Tilling, 1995). Identifying volcanoes that may become active on intermediate time scales (years to decades), however, continues to pose a formidable challenge. Advances in the technology and strategy of geodetic monitoring have begun to address even this forecasting gap (Dzurisin, 2003), and they promise additional insights into magmatic processes in the years to come.

3. Case study: recent eruptive episodes of Mount St. Helens

A comparison of the scientific responses to the latest eruptive episodes of Mount St. Helens in Washington, USA, provides an excellent illustration of the recent advances made in the field of volcano geodesy. The catastrophic eruption of Mount St. Helens on 18 May, 1980 is one of the best-studied events in volcanologic history (see papers in Lipman and Mullineaux, 1981). It was followed by sporadic episodes of lava dome growth that continued through October 1986 (Swanson and Holcomb, 1990). The volcano was subsequently quiescent for nearly two decades until its latest eruptive sequence began in September 2004, with a new period of dome extrusion that has continued into 2005 (Gardner, 2005). The approaches used to study surface deformation during the two eruptive periods, summarized in Table 1, highlight an extraordinary evolution that has taken place in the past 25 years, both in technology and strategy of geodesy applied to active volcanoes.

When Mount St. Helens displayed signs of renewed activity in March 1980, the only geodetic measurement

Table 1
Summary of methods used to measure deformation during the 1980–1986 and 2004–2005 eruptions of Mount St. Helens, Washington, USA

Scientific target	1980–1986 methods	2004–2005 methods
Far-field displacements	EDM, leveling	Dual-frequency continuous GPS, InSAR
Ground tilt	"Dry" tilt, lake-level, platform tiltmeters	Borehole tiltmeters
Volume measurements	Photogrammetry	Photogrammetry, LIDAR
Near-field deformation	Steel tape, displacement meters, EDM	Single-frequency continuous GPS
Visual	Film cameras	Remote telemetered digital cameras
Telemetry	Analog	Digital, satellite uplinks

available was a 1972 Electronic Distance Measurement (EDM) line length between two points east of the volcano's summit (Lipman et al., 1981; D. Swanson, pers. comm., 2005). Regional deformation was constrained only by large-scale tilt measurements from analysis of the surface of Spirit Lake (Lipman et al., 1981). As seismic activity and phreatic explosions continued through April and into May 1980, monitoring strategies evolved to meet the challenges posed by the awakening stratovolcano, which included the adaptation of techniques used to monitor deformation in Hawai'i (D. Swanson, pers. comm., 2005). Following the climactic eruption of May 18, a variety of geodetic methods were used to detect deformation of the crater floor, growing lava dome, and flanks of the volcano. These observations were major contributors to numerous successful predictions of dome-building eruptions (Swanson et al., 1983).

Clearly, the most important geodetic monitoring tool at Mount St. Helens during the 1980s was EDM. Prior to the 18 May, 1980 eruption, EDM measurements of the north flank revealed displacement rates as high as 2.5 m/day and were instrumental, along with analysis of Digital Elevation Models (DEMs) derived from aerial photogrammetry, in identifying that sector of the volcano as the major area of deformation (Lipman et al., 1981; Moore and Albee, 1981). After 18 May, 1980, measurement of thrust faults on the crater floor using steel tapes and, eventually, telemetered displacement meters, provided surface displacements in the near-field (Iwatsubo and Swanson, 1992; Iwatsubo et al., 1992a). As the lava dome covered the crater floor, EDM measurements replaced thrust fault measurements (Swanson et al., 1981). EDM was also used to measure edifice-wide displacements by using reflectors mounted on steel towers (Fig. 2A) on the flanks of the volcano (Iwatsubo et al., 1992b). The rate of surface deformation increased systematically before each dome-building eruption, aiding in the successful prediction of such activity (Swanson et al., 1983; Chadwick et al., 1988;

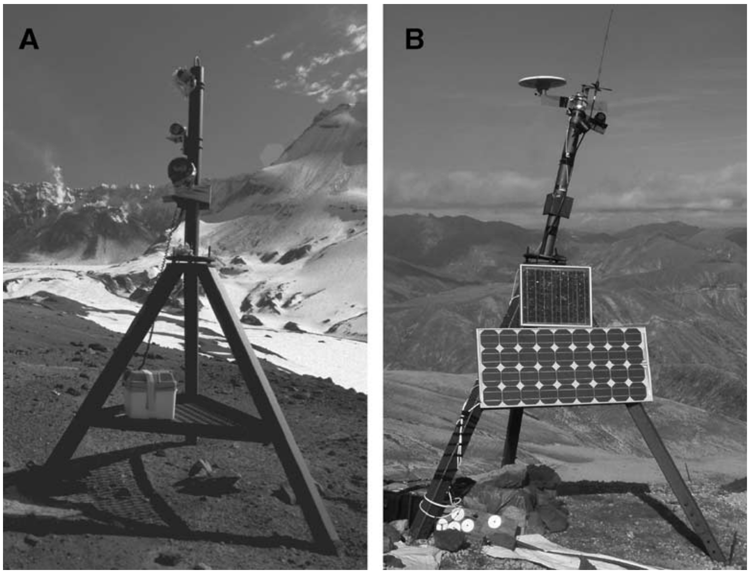

Fig. 2. EDM reflector towers at Mount St. Helens, Washington. (A) In 1980, several reflectors were positioned on the vertical part of the tower to allow EDM line lengths to be taken from several different instrument locations. (B) In 2004, the EDM towers provided locations for continuous GPS installations. Note that reflectors are still attached to the vertical mast and a bank of highway reflectors, used in 1980 before the towers were constructed, lies on the ground near the left leg of the tower.

Chadwick and Swanson, 1989). The sporadic steel tape crack measurements were eventually replaced by continuously recording and telemetered displacement meters, which provided better constraints on the dome-building activity (Iwatsubo et al., 1992a). Telemetered, electronic platform tiltmeters further aided eruption prediction (Dzurisin et al., 1983; Dzurisin, 1992). Automated, film-based photo stations were also deployed to provide a visual record of geomorphic changes at Mount St. Helens during the 1980s (Topinka, 1992).

The most recent eruptive period at Mount St. Helens began in late September 2004 with a swarm of earthquakes accompanied by intense, localized deformation within the volcano's crater. Deformation included uplift of the south margin of the 1980–1986 lava dome and fresh cracks in the glacial ice that had accumulated since 1986 (Dzurisin et al., 2005). The first new lava was observed at the surface in mid-October, which marked the initiation of a period of continuous dome extrusion (Dzurisin et al., 2005; Gardner, 2005). In contrast to the situation in 1980, a vast amount of baseline geodetic data had been acquired prior to the 2004–2005 activity, and the advent of newer recording systems has permitted continuous monitoring of deformation.

The greatest leap in geodetic methodology since the 1980–1986 eruptions of Mount St. Helens is the development of space-based technology, in particular the Global Positioning System (GPS). A 40-station campaign GPS network was established in 2000, replacing the previous wide-aperture array of EDM sites. This new geodetic approach is particularly important for volcanology, because it permits not only high-resolution determination of 3-D site positions but also observation without inter-site visibility and under a variety of weather and volcanic conditions. Reoccupation of the GPS network in 2003 showed no displacements associated with repressurization or depressurization of the magmatic system (Lisowski et al., 2003). This result suggests that the most recent eruptive episode was not characterized by long-term precursory deformation and that magma was already near the surface, which is supported by the shallow depths of seismicity associated with the eruption (Dzurisin et al., 2005). A single, continuously operating GPS instrument was installed at the Johnston Ridge Observatory, located 8 km north of Mount St. Helens crater, in 1997. Data from this instrument indicate motion toward the volcano by at least 2 cm between late September 2004 and mid-2005, consistent with a deflating magma source beneath the volcano (Poland et al., 2005; M. Lisowski, pers. comm.., 2005). By mid-October 2004, over a dozen continuous telemetered GPS instruments, established by the U.S. Geological Survey (USGS) and the EarthScope Plate Boundary Observatory (Borenstein et al., 2004), had been installed to further investigate centimeter-scale surface displacements on the flanks of the volcano and the surrounding area (Fig. 2B) (Dzurisin et al., 2005; Gardner, 2005).

Despite the importance of GPS to the geodetic monitoring strategy at Mount St. Helens, traditional dual-frequency GPS stations were not established in the crater due to the danger posed by unpredictable phreatic explosions, rockfalls, and other hazards. To retrieve quantitative deformation data from the crater, the USGS Cascades Volcano Observatory (CVO) adapted an existing single-frequency GPS landslide- and volcano-monitoring system (LaHusen and Reid, 2000) for helicopter sling-deployment at Mount St. Helens (Fig. 3). These relatively inexpensive "spiders" could be deployed rapidly without relying on ground-based personnel, minimizing the exposure of the flight crew to hazardous activity. During the first six months of the eruption over a dozen spiders were deployed, including several on the surface of the growing lava dome (Gardner, 2005). Although some of these stations were destroyed by rockfalls and explosive activity, they provided valuable measurements of near-field deformation and extrusion velocity that would otherwise have been unavailable.

Another significant advancement in geodetic technology since the 1980–1986 eruption of Mount St. Helens is the development of inteferometric synthetic aperture radar (InSAR), which has been used with great success to determine the deformation style of numerous

Fig. 3. Telemetered, single-frequency GPS unit used during the 2004–2005 eruption of Mount St. Helens. Each unit was slung by helicopter to its site. Over a dozen of these instruments were deployed in the crater of the volcano in 2004 and early 2005, providing valuable near-field displacement data while minimizing the hazard to field personnel.

stratovolcanoes (e.g., Lu et al., 2002a,b; Wicks et al., 2002). Pre- and co-eruptive imagery confirmed that little, if any, volcano-wide deformation preceded and accompanied the onset of eruptive activity at Mount St. Helens in 2004, supporting the dual-frequency GPS results (Poland et al., 2005).

One technique from the 1980s that was used extensively during the 2004–2005 activity is aerial photogrammetry for mapping changes in the morphology of the crater. DEMs constructed from these photos, in addition to infrequently collected LIDAR data (Haugerud et al., 2004), have provided the only quantitative estimates of volume change in the crater during the most recent eruptive episode.

The use of telemetered visual imagery to monitor temporal variations in extrusion rate and the level of activity of the volcano is another improvement over 1980s monitoring techniques. A digital camera located just north of Mount St. Helens crater transmits a high-resolution (2 megapixel) image to a receiving station every 2.5 minutes, which can be accessed almost immediately via the Internet (Fig. 4).

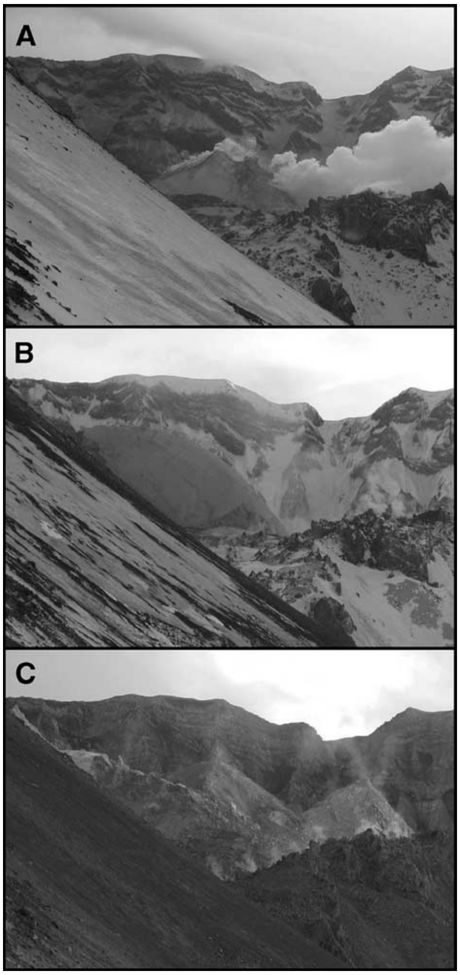

Fig. 4. Digital photos of the growing lava dome at Mount St. Helens on (A) 10 November, 2004, (B) 18 February, 2005, and (C) 1 September, 2005. The photos were taken by a fixed telemetered digital camera and sent to the Cascade Volcano Observatory via a satellite link to the Internet in near real time.

The collection of this vast amount of geophysical and visual data is made possible by improvements in telemetry systems, and in particular satellite communications, since the 1980s. This development has allowed greater flexibility in the types and locations of instrument deployments, and made it possible to make timely interpretations of data and public notifications of activity levels. As of mid-2005, the geodetic response at Mount St. Helens continues with new equipment and techniques planned for use during the upcoming field season. Deployments will include supplemental GPS instruments as well as borehole tiltmeters and strainmeters.

In spite of the great technological developments over the 18-year interval between eruptive episodes at Mount St. Helens, significant challenges remain. Because of the strong localization of 2004–2005 activity within the volcano's crater, the resolution of magmatic processes in this case was limited by the initial lack of geodetic observations near the growing dome. However, one of the strengths of the current methodology is that it permits rapid response to evolving volcanic crises. With the recognition of activity concentrated within the Mount St. Helens crater, CVO scientists were able to deploy telemetered equipment in time to capture deformation events as they were unfolding. Application of this strategy to other erupting volcanoes is certain to improve understanding of volcanic processes and aid with forecasting activity.

4. New advances and recent results in volcano geodesy

The papers that make up this special issue offer an excellent snapshot of the state of the art in geodetic monitoring of active volcanoes. These articles demonstrate the growing capabilities of high-resolution, space- and land-based observational systems that provide the basis for three- and four-dimensional imaging, in unprecedented detail, of the sources of volcanic deformation. These results in turn can provide critical input for volcanic hazard mitigation and eruption prediction.

We have grouped this collection of papers based on what we see as the three leading areas for future development in volcano geodetic research: (1) insights into eruptive activity and magma transport based on results from specific volcanic systems; 2) advanced modeling of volcano geodetic data (moving beyond elastic half-space models and addressing the temporal evolution of deformation fields), and 3) new applications of volcano geodetic measurements. Each of the papers in this volume addresses these topics in some way, and we are optimistic that continued work in the field of volcano geodesy will advance our understanding of volcano dynamics at an ever-increasing pace.

4.1. Insights into eruptive activity and magma transport

As demonstrated by the example of Mount St. Helens, the past two decades have seen major improvements in the strategies and techniques associated with volcano geodesy research. This can be attributed, at least partially, to the development of new methods for detecting deformation of the Earth's surface using space-based geodetic techniques, primarily GPS and InSAR. When combined with other measurement types, including leveling, EDM, and tilt, the deformation pattern of any given volcano can be rigorously constrained.

This combined approach to volcano geodesy research is demonstrated by Sturkell et al. (2006-this issue), who use a variety of techniques over the past 15 years to characterize the behavior of nine volcanoes in Iceland. Dzurisin et al. (2006-this issue) focus a similarly diverse suite of geodetic techniques to South Sister volcano in Oregon, which is inflating due to inferred magma accumulation at depth. Only minor seismicity is present, and the deformation probably would not have been detected without the aid of InSAR data over the region. By contrast, Medicine Lake volcano, in northern California, has been experiencing steady-state subsidence over the past several decades. Poland et al. (2006-this issue) point out that while the use of one data set alone might lead to a conclusion of magma withdrawal or contraction due to cooling, combined results from leveling, GPS, and InSAR suggest a more complicated, and ambiguous, source mechanism.

Campaign geodetic results have also been used to identify changes in the deformation style of a given volcano. GPS surveys conducted by Geist et al. (2006-this issue) at Sierra Negra volcano, in the Galapagos archipelago, captured a change from uplift to subsidence which was not associated with an eruption. Similar patterns of uplift and subsidence are apparent over a longer time period at Iwo–Jima volcano in Japan, though Ukawa et al. (2006-this issue) show that the source is masked by a broader, superimposed pattern of deformation. Conversely, no deformation is apparent at Shishaldin volcano, Alaska, in radar interferograms that span several eruptions. This result leads Moran et al. (2006-this issue) to speculate that magma must have accumulated at deep levels before ascending quickly to the surface (in the intervals between SAR data acquisitions).

While much of the attention in geodetic monitoring is justifiably directed at understanding the dynamics of magmatic systems beneath active volcanoes (e.g., Dvorak and Dzurisin, 1997), attention should also be focused on the coupled hydrothermal systems that overlie magma chambers. These systems are of intrinsic interest because of their role in convective heat transfer from magma reservoirs, chemical exchange of materials between magmatic and groundwater systems, and release of volatiles from magma bodies. Further, hydrothermal systems can produce significant secondary volcanic hazards in their own right, may be associated with the triggering of volcanic eruptions (e.g., Reid, 2004), and are of important economic value because of their central role in geothermal energy systems (e.g., Duffield and Sass, 2003).

Of primary concern to the geodesist is the possibility that changes in hydrothermal systems can obscure signals from subsurface magma bodies, potentially resulting in flawed interpretations that may give rise to spurious volcanic warnings. Distinguishing the signals from these two interacting systems will require a combination of high-resolution geodetic monitoring linked with water-well, geochemical, and potential-field measurements that are sensitive to differing physical properties of magmatic and hydrothermal systems (e.g., Battaglia et al., 2003). Gottsmann et al. (2006-this issue) performed such a study at Campi Flegri caldera, Italy. By reanalyzing geodetic data and incorporating additional geophysical and geochemical measurements, they propose a new quantitative source model for recent unrest and speculate, based on gravity data, that the source volume contains a combination of magmatic and hydrothermal fluids.

There is growing interest in the broad set of interactions between tectonic and magmatic systems (e.g., Hill et al., 2002). These range from regional tectonic processes that allow for magma formation and provide conduits for magma ascent (e.g., Bursik and Sieh, 1989) to the relation between local structural processes and dike propagation (Cervelli et al., 2001, 2002) and the triggering of volcanic seismicity by local and remote seismic events (e.g., Hill et al., 2002; West et al., 2005). Investigation into these processes will have important implications for the fundamental geologic processes controlling magmatism as well as understanding the triggering mechanisms of volcanic eruptions.

Components of volcanic and tectonic activity are evident at the rift-related volcano of Pantelleria, in southern Italy. Behncke et al. (2006-this issue) use EDM and GPS, combined with microgravity results, to recognize distinct blocks characterized by different volcano-tectonic styles. The interrelation between magmatic and tectonic activity is also readily apparent at Kīlauea Volcano, Hawai‘i. Owen and Bürgmann (2006-this issue) find that a large earthquake on the south flank of the volcano in 1975 was accompanied by rift opening and summit deflation, and that the geodetic slip and earthquake distribution are apparently not coincident. This use of both seismic and geodetic evidence to characterize volcanoes will become increasingly important in the future. GPS receivers that record at high sampling rates (1 Hz or more) have the ability to record over a large dynamic range, yielding data similar to low-frequency displacement seismometers (e.g., Larson et al., 2003). Continued observations of this type will help break down the ‘instrumentation barrier’ that separates the disciplines of geodesy and seismology.

4.2. Advanced modeling of volcano geodetic data

Great advances have taken place in our technical capabilities to monitor active volcanoes, but we are only beginning to explore models of deformation sources that reflect an equivalent degree of sophistication. Replacing elastic half-space models with more realistic approximations of the Earth that include heterogeneous elastic constants, structural discontinuities, and plastic or viscoelastic rheologies will aid understanding and interpretation of volcanic deformation sources. Finite element models (FEMs) will play an important role in this line of study. For example, Masterlark et al. (2006-this issue) use a thermoelastic FEM to approximate InSAR-derived displacements of a cooling pyroclastic flow at Augustine volcano, Alaska. Their model attempts to determine the thickness distribution of the deposit, a measurement that would not be achievable from traditional field- or map-based analyses.

Continuous geodetic data are becoming increasingly available at volcanoes around the world and provide input to models of the temporal evolution of deformation sources. The 2000 eruption of Miyakejima volcano, Japan, provided an excellent opportunity for such explorations, as deformation associated with the activity was recorded at a large number of nearby continuous GPS stations. Irwan et al. (2006-this issue) take advantage of this dataset to model the time-dependent evolution of the early stages of the eruption, focusing on the migration of magma from a deeper source toward the surface. The same data set is exploited by Murase et al. (2006-this issue) to infer magma migration patterns and variations in the source of magma supply over the ~2 month duration of the activity.

A third important area for modeling volcano geodetic data is the use of realistic source geometries. This includes a variety of more complex, non-spherical sources (e.g., Yang et al., 1988; Fialko et al., 2001) and distributed sources (e.g., Cervelli et al., 2001; Mann and Segall, 2004), in order to distinguish the relative contributions from regional tectonic deformation, local structural deformation, magmatic intrusion, and superficial hydrothermal or mass-wasting phenomena. Yun et al. (2006-this issue) model InSAR-derived displacements at Sierra Negra volcano, in the Galapagos, using a sill-like source with distributed opening. However, they also show that models of deformation data are only sensitive to the tops of sources, and that any flat-topped source geometry (e.g., sill, diapir, etc.) fits the InSAR data equally well. Deformation data alone cannot constrain the geometry of the sides and base of a subsurface magma chamber. Newman et al. (2006-this issue) build on an earlier study of time-dependent deformation at Long Valley caldera, California (Newman et al., 2001), by incorporating a more realistic source geometry in their model. With a varying pressure history and incorporating viscoelastic rheology, they find that the observed deformation data recorded by EDM, GPS, and InSAR can be explained by much lower pressures than those predicted by simpler elastic half-space models.

4.3. New applications of volcano geodetic measurements

With ever-improving geodetic measurement technologies, new applications to volcanoes are sure to develop. A poorly exploited form of volcano geodesy is microgravity, which can be combined with deformation results to become a powerful tool for assessing the causes of volcanic unrest. For example, campaign gravity and deformation measurements have been used to infer convection between shallow and deeper magma sources beneath several volcanoes (Rymer et al., 2000; Williams-Jones et al., 2003). Recent application of gravity to caldera systems has been especially successful in determining mechanisms of unrest. Battaglia et al.

(2003) demonstrated that inflation at Long Valley caldera is probably driven by magma, and not water or gas, based on deformation and gravity results. At Askja caldera, Iceland, De Zeeuw-van Dalfsen et al. (2004) showed that magma withdrawal from a shallow chamber is the likely cause of subsidence, a conclusion that could only be reached with coincident gravity and deformation measurements.

Berrino et al. (2006-this issue) go beyond campaign gravity measurements and report on the results of a continuous gravity experiment at Vesuvius volcano, Italy, over a 15-year time period. The authors propose new methods for modeling the instrumental response of a gravity meter, allowing for the detection of both far-field effects and local volcano dynamics. Gravity can also be used as an exploratory tool for characterizing subsurface structure. Montesinos et al. (2006-this issue) perform an investigation at El Hierro volcano, in the Canary Islands, using terrestrial and submarine 3D gravity surveys to identify features at various depths that are associated with both the early and recent volcanic history of the island. As suggested by the results of Yun et al. (2006-this issue), such geophysical explorations provide critical independent constraints on the geometry of deformation sources.

Geodetic measurements are also beginning to be used in non-traditional environments. Recent application of helicopter-deployable continuous single-frequency GPS to the growing lava dome at Mount St. Helens (Gardner, 2005) is but one example. Beauducel et al. (2006-this issue) also apply GPS to an active silicic lava dome, in this case using kinematic GPS to track centimeter-scale changes on and around the dome of Merapi volcano in Indonesia. These measurements indicated varying behavior of different parts of the dome and surrounding area, including significant changes in the displacement field interpreted as a precursor to a dome collapse event. A still more exotic location is explored by Chadwick et al. (2006-this issue) — Axial Seamount, on the Juan de Fuca Ridge in the northeast Pacific Ocean. Campaign and continuous pressure measurements indicate significant vertical deformation of the volcano. The change in inflation rate over time suggests fascinating parallels in the behavior of this submarine volcanic center and comparable subaerial sites, including volcanoes in Iceland that are detailed by Sturkell et al. (2006-this issue).

5. The future of volcano geodesy

Without question, future studies in the field of volcano geodesy will expand upon the themes that are explored in this collection of papers. These studies will be aided by the development of a number of high spatial and temporal resolution observation systems. The extraordinarily dense, nationwide, GEONET GPS network in Japan made possible the detailed exploration of deformation associated with the 2000 eruption of Miyakejima volcano (including Irwan et al., 2006-this issue and Murase et al., 2006-this issue). As similar systems come on line, we can expect an explosion in our ability to detect and model volcano deformation. These systems may include dense networks of more expensive, but higher sensitivity, instruments, such as borehole strainmeters and long-baseline tiltmeters, broadband, three-component surface and borehole seismometers, dense networks of continuous GPS systems, and gas monitoring systems. Examples of this sort of intensive observation include USGS arrays at Kīlauea volcano, Hawai‘i (see papers in Heliker et al., 2003), and Long Valley caldera, California (e.g., Roeloffs et al., 2003), the CALIPSO system deployed at Montserrat Volcano (Mattioli et al., 2004), and a number of volcanoes targeted for intensive study as part of EarthScope's Plate Boundary Observatory program (Hamburger et al., 2003; http://volcanoes.usgs.gov/pbo/). Such dense observation systems promise to provide extremely high spatial and temporal resolution imaging of subsurface magmatic processes, ranging from the low-signal periods of gradual magma accumulation or magma chamber pressurization to the rapidly evolving seismic, strain, and surface deformation signals associated with eruptive events.

Continued development of radar interferometry will also play an important role in the future detection and interpretation of volcanic deformation. The initial applications of InSAR to volcanoes were hampered by problems that included lack of coherence on heavily vegetated, ice-covered, and/or steep-sided volcanoes, and the fact that only one component of deformation is available from InSAR, though deformation signals were identified at several volcanoes (e.g., Zebker et al., 2000). More recently, the use of persistent scatterers (Ferretti et al., 2001; Hooper et al., 2004) is making it possible to retrieve useful displacement data from poorly coherent areas, which will allow archive SAR data to be reexamined for deformation signals at volcanoes where traditional InSAR studies were not successful. Further, the use of longer wavelengths on future satellite missions promises better coherence on vegetated volcanoes, as demonstrated by successes using L-band data from the now-defunct JERS satellite (Massonnet and Sigmundsson, 2000; Lu et al., 2005). Even the single deformation component problem is being addressed. With the use of multiple look angles and directions, it is possible to extract at least two, and perhaps three, components of deformation from InSAR data alone (Wright et al., 2004). Continued development and use of new techniques in this field will certainly result in the wider application of InSAR to volcanoes and should result in important insights into the dynamics of active volcanism.

This volume is jointly dedicated to the memories of Bob Decker, who pioneered the application of EDM to volcanoes, and Dan Johnson, who made great strides in the use of gravity as a tool for understanding magmatic processes. Both scientists fought numerous logistical and technological barriers to retrieve geodetic measurements from a number of active volcanoes. In the decades since they began their work, the challenge has evolved from the collection of volcano geodetic data to its interpretation. The quiet revolution that has taken place in volcano geodesy over the past several decades has opened doors to numerous realms of scientific inquiry that would otherwise have remained closed to volcanology. We hope that this collection of papers – which we feel exemplify the state of the art in volcano geodesy – will help to stimulate the next generation of scientific research on active volcanic systems.

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