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Mount St. Helens Reawakens

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Following 18 years of relative quiescence, Mount St. Helens volcano (MSH) became restless and began erupting again during September-December 2004.

On 23 September, the U.S. Geological Survey's (USGS) David A. Johnston Cascades Volcano Observatory (CVO) and the Pacific Northwest Seismograph Network (PNSN) at the University of Washington detected the onset of a shallow earthquake swarm beneath the 1980–1986 lava dome. The Mount St. Helens Emergency Response Plan defines three alert levels that differ from normal background activity: Level 1, Notice of Volcanic Unrest (unusual activity detected); Level 2, Volcano Advisory (eruption likely but not imminent); and Level 3, Volcano Alert (eruption imminent or in progress).

On 26 September, CVO issued a Notice of Volcanic Unrest. This was followed on 29 September by a Volcano Advisory.

During the next several days, earthquakes increased in rate of occurrence and magnitude, and were accompanied by dramatic uplift and fracturing of glacier ice on the south crater floor. On 2 October, a 50-min. episode of strong tremor prompted CVO to issue a Volcano Alert (level 3) warning of the possibility of an imminent eruption.

Anomalous concentrations of CO_2, H_2S, and SO_2, three common magmatic gases, were initially detected during the first week of October. Small steam and ash eruptions (VEI ~1) (Volcanic Explosivity Index, VEI; a measure of the size of volcanic eruptions akin to the Richter magnitude scale for earthquakes. VEI 1 corresponds to the smallest class of explosive eruptions, with plume heights 100–1000 m above the vent) occurred on 1, 4, and 5 October. The rate of seismic energy release declined markedly after the most vigorous eruption on 5 October, and on 6 October the alert level was lowered to a Volcano Advisory.

Lava Dome Growth

An initial lava spine was seen emerging from the deforming area ("welt") on 11 October. During the next 2 weeks, the spine grew upward and several smaller spines appeared to the south. In late October, a whaleback-shaped extrusion emerged immediately southeast of the initial spine. The early spines plus the whaleback extrusion are referred to as the 2004 lava dome. By early December, the welt and 2004 lava dome grew to a combined volume of ~30 x 10^6 m^3 while the level of seismicity remained remarkably steady (Figure 1).

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Steam and Ash Eruptions

Of five phreatic eruptions that occurred from 1 to 5 October, three produced fine-ash fallout downwind, and at least one (1 October and possibly 5 October) threw ballistic blocks as far as 1 km across the western half of the 1980–1986 dome. Several smaller events produced condensed steam plumes containing little or no discernible ash, or were unobserved but left thin ash deposits on the crater floor.

The three largest eruptions of 1, 4, and 5 October lofted ash from hundreds of meters to ~1 km above the vent. Only the ashfall of 5 October affected populated areas: A light dusting of ash extended downwind (NNE) as much as 100 km to the northeast part of Mount Rainier National Park.

Seismicity

Seismic unrest began at about 0200 LT (0900 UTC) on 23 September with a swarm of small (most Richter magnitude $M < 0.0$), shallow (0–2 km below the surface) volcano-tectonic (VT) earthquakes that occurred more frequently throughout the day. VT earthquakes are seismic events with clear p-waves and s-waves that occur beneath volcanoes. They are otherwise indistinguishable from normal shallow tectonic earthquakes. Other common forms of volcanic sesimicity include long-period or low-frequency earthquakes and tremor. Earthquake rates peaked on 24 September with a few larger events, and gradually declined throughout the evening. At this point, the swarm bore a striking resemblance to a previous MSH swarm on 3–4 November 2001.

However, on 25 September, shallow seismicity began to increase again as event sizes increased to M_{max} ~2.0, and event rates also increased. These increases coincided with a decrease in high-frequency energy, but the events remained predominantly impulsive and VT in character.

Seismic energy increased in spurts through 1 October, with peak magnitudes reaching M_{max} 3.5 and earthquakes of $M > 2.5$ occurring approximately one per minute. Three hours of seismic quiescence followed the 1 October steam and ash eruption, but seismicity returned to preeruption levels overnight. A very energetic 50-min-long harmonic-tremor episode began at 1212 LT on 2 October (Figure 1).

Seismicity decreased following this and another shorter, less energetic episode on 3 October, but in both cases it soon built back to pretremor levels. A similar pattern followed a steam emission during the night of 3 October and two steam and ash eruptions on 4 October.

Seismicity dropped a final time following the largest steam and ash eruption on 5 October. Thereafter, seismicity levels waxed and waned but never reached the peak levels of 29 September through 5 October.

Through late November, the total seismic energy released was roughly equivalent to a M 5.5 earthquake.

Events were shallow throughout the sequence but changed progressively from predominantly high frequency VT types at the start, to "hybrid" types containing both high-frequency onsets and low-frequency codas, and finally to purely low frequency (1–2 Hz) events beginning shortly before dome extrusion. "Clones" (events with nearly identical waveforms) occurred repetitively at regular intervals during several hours-to-days-long periods.

The transition from VT to hybrid to low-frequency events and the repeating sequences of identical events are typical of seismicity prior to dome-building episodes at MSH in the 1980s.

Ground Deformation

While repeated photography, photogrammetry, and lidar surveys tracked remarkable growth of the 2004 welt and dome, a network of 10 campaign and 10 continuous Global Positioning System (GPS) stations on or near the volcano measured little or no deformation beyond the immediate vicinity of the vent.

Campaign GPS observations were made at 10 pre-existing benchmarks starting on 27 September. By mid-October, four continuous GPS stations had been installed on the volcano by USGS, and five others by UNAVCO, Inc., as part of the Plate Boundary Observatory (PBO), a geodetic observatory funded by the U.S. National Science Foundation to study the three-dimensional strain field resulting from deformation across the active boundary zone between the Pacific and North American Plates in the western United States (http://pbo.unavco.org/). Another USGS continuous GPS station, JRO1, had been operating at the U.S. Forest

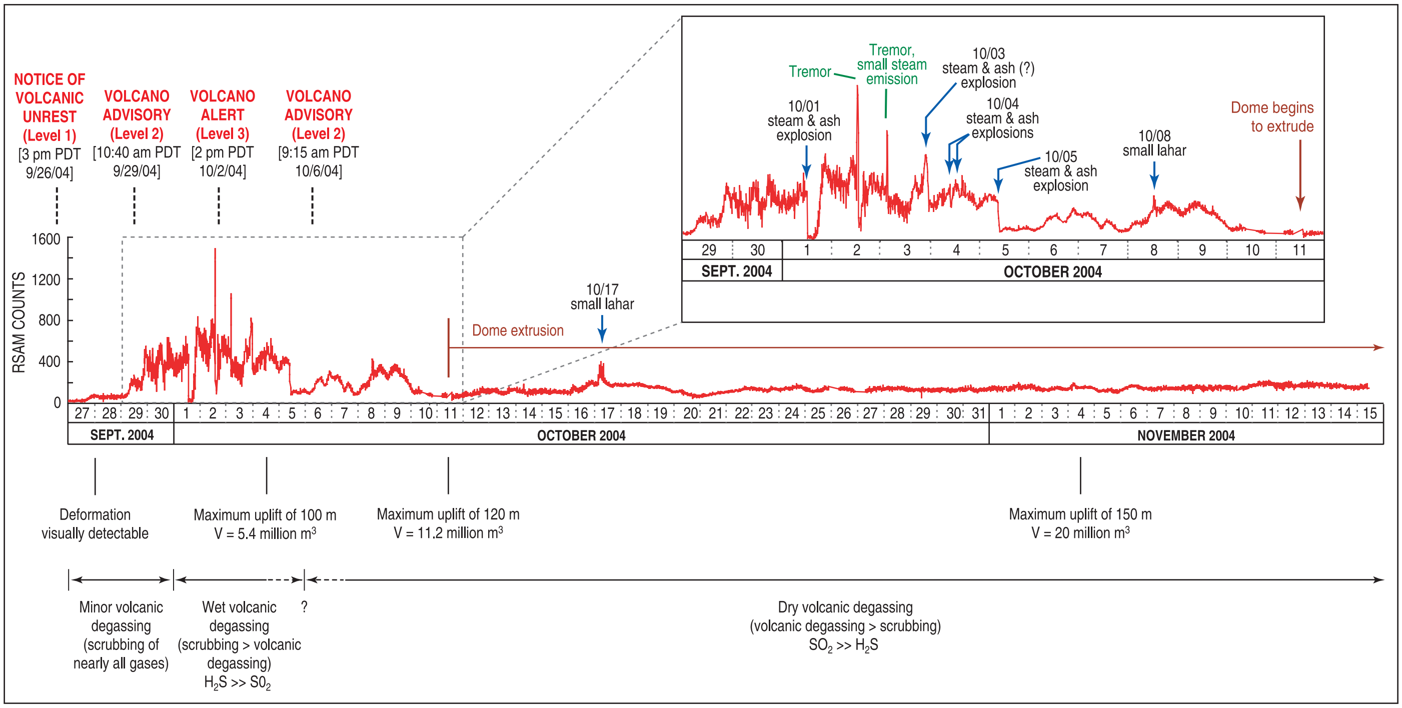

Fig. 1. Chronology of events at Mount St. Helens from 27 September to 15 November 2004, including (1) RSAM (real-time seismic amplitude measurement, an automated proxy for seismic energy) at station SHW on the volcano's west flank, (2) notable occurrences of tremor, explosions, and rainfall-induced lahars, (3) growth of the welt and lava dome on the south crater floor, and (4) volcanic gas observations.

Service's Johnston Ridge Observatory, 8.5 km NNW of MSH, since 2000.

No significant displacements occurred from summer 2003 to September 2004, based on the campaign observations. Small displacements (up to a few cm) occurred at a few of the continous stations during October-November 2004, but there was no pattern to indicate inflation or deflation of a shallow (few km deep) magma reservoir. A ~1 cm SSE displacement of JRO1 during the first few weeks of unrest is consistent with deflation of a deeper reservoir.

Several single-frequency GPS stations were installed near the vent during October-November 2004. (Most were slung into place by helicopter to minimize risk to field crews.) Of these, stations on the 1980–1986 dome moved northward away from the vent at rates of several centimeters per day, while stations on the 2004 welt and dome moved at rates of up to 10 m per day.

Volcanic Gases

Measurements of CO_2, SO_2, and H_2S by Li-Cor (CO_2) and Interscan (SO_2 and H_2S) analyzers and by COSPEC (SO_2) define three periods of volcanic degassing (Figure 1): (1) an initial period of "negligible" degassing characterized by scrubbing or sealing-in of gases; (2) an intermediate period of "wet" degassing, when gas scrubbing dominated degassing; and (3) a period of "dry" degassing when degassing exceeded gas scrubbing.

Measurements made during the 27–30 September period of almost no degassing showed little or no CO_2 above atmospheric levels, and no SO_2 or H_2S. The absence of these gases implies fairly complete scrubbing at high water-to-gas mass ratios (>100), or confinement of the gases by post-1986 sealing of previous gas channels. Scrubbing seems likely to have dominated sealing as a deterrent to gas emission.

Increases in the number of fumaroles and CO_2 emission and increasingly common detection of H_2S characterized the period of wet degassing that began on 1 October. Wet degassing of CO_2 and H_2S included their emission via large bubbles ejected through pools of water near the western margin of the welt. Field crews reported intermittent H_2S odor over the crater, especially after steam and ash events.

However, persistent light and variable winds commonly prevented determination of emission rates. The few available emission rates for CO_2 during this period are < 150 t d^{-1}, but these may not be representative.

As temperatures rose and steaming increased, rock adjacent to the invading magma dried out progressively, and the period of dry degassing commenced on 5 or 6 October. As of early January 2005, measured emission rates ranged from 800 to 2400 t d^{-1} CO_2, 40 to 250 t d^{-1} SO_2, and 0 to 10 t d^{-1} H_2S.

Thermal Monitoring

Thermal features on the 2004 welt and dome and on the 1980–1986 dome are monitored with a forward looking infrared radiometer (FLIR) paired with an optical camera, which are mounted beneath a helicopter in a gyrostabilized gimble and controlled by a crew member using a joystick. The FLIR is calibrated so temperatures can be measured to within 0.1°C up to 1500°C. Beginning 1 October, the FLIR tracked low-temperature thermal features including fumaroles, fractures, ground warming, and phreatic eruptions.

Three phreatic eruptions captured by the system exhibited temperatures of no more than 140°C. Most of the surface of the welt remained within a few degrees of ambient temperature, but daily thermal images showed progressive warming at the eventual extrusion site. The day prior to extrusion, temperatures on the northwest part of the welt were as high as 300°C.

On 11 October, when the new dome emerged, the maximum temperature had increased to 620°C. The hottest areas were near the base of the dome and in fresh cracks, where temperatures exceeded 700°C within the next few days. Thereafter, the FLIR system revealed the thermal evolution of the growing dome, which generally was hottest near the vent and in areas of recent collapse or fracturing.

Hazards

During the past few thousand years, Mount St. Helens has produced a wide variety of eruptive products, including basalt and andesite lava flows, dacite lava domes, plinian air-fall ash deposits, and pyroclastic flows. The volcano is notorious for its avalanche and laterally directed blast on 18 May 1980, which claimed 57 lives, including that of U.S. Geological Survey scientist David A. Johnston.

Potential hazards from future eruptions include ash from vertically directed plinian eruption columns, pyroclastic flows, and lahars (volcanic mudflows). At present, land-use closures have been imposed by federal (U.S. Forest Service), state, and local agencies to prohibit access to threatened areas by all but essential personnel.

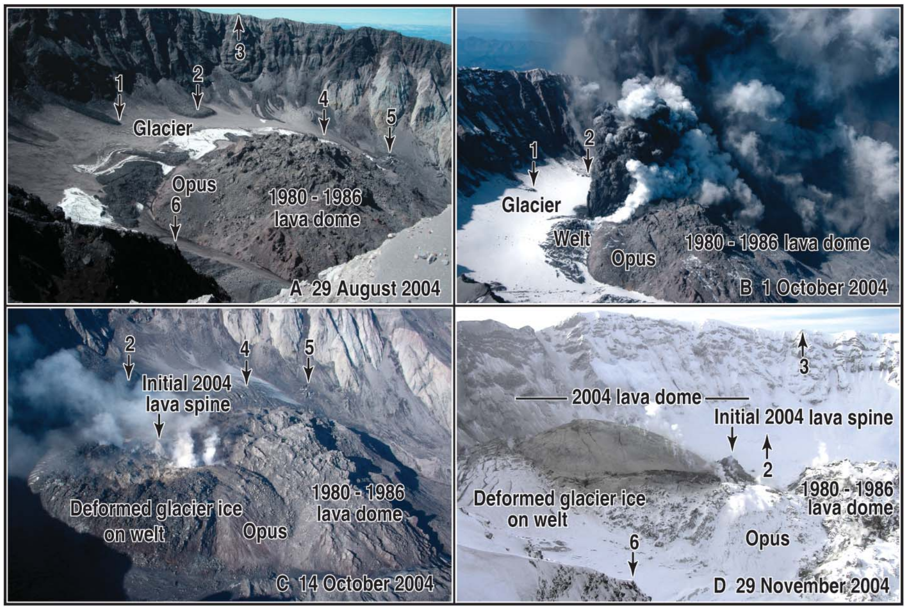

Fig. 2. Oblique aerial photographs from near the northeast crater rim looking southwestward. Numbers 1–6 mark the same features in each image. (a) The 1980–1986 lava dome, with a volume of approximately 75 x 10^6 m^3, is surrounded on all but its north side (beyond the field of view to the right) by intercalated glacier ice and rockfall talus with a maximum vertical thickness of ~240 m above the 1980 crater floor. The area known as Opus formed during a dome-building episode in May 1985. The dark gray feature left of Opus is superglacial rockfall debris from the south crater wall. (b) This steam and ash eruption at 1213 LT on 1 October was the first of several that occurred in early October. A welt began to form on the crater floor south of Opus several days earlier, as evidenced by fractured glacier ice and rockfall debris. (c) The welt had grown considerably to the south and west by 14 October, and a lava spine began to emerge. (d) By late November, the 2004 welt and dome had encroached on the crater wall to the east, south, and west, and the feature continued to grow at an average rate of several cubic meters per second. USGS photos by S. Schilling (Figure 1a), J. Pallister (Figure 1b), W. E. Scott (Figure 1c), and D. Dzurisin (Figure 1d).

Remaining hazards are those posed by volcanic ashfall in populated areas and by suspended ash to aircraft flying downwind from the eruption site. CVO immediately notifies the U.S. Federal Aviation Administration, the U.S. National Oceanic and Atmospheric Administration, and the Washington State Emergency Management Division of any event at the volcano that could pose such threats, and appropriate warnings are issued through a global network of Volcanic Ash Advisory Centers.

Current Status

The level of seismicity decreased markedly in late December but dome growth has continued through early January 2005. In comparison to lavas of the 1980–1986 dome, 2004 dome samples are relatively low-temperature (850°C), high-silica (65% SiO_2), volatile-poor, and crystal-rich dacite with textures indicative of a multistage ascent history that culminated with extrusion of a highly viscous and gas-poor magma. The volcano appears to be in a steady state condition in which magma reaches the surface through an open conduit. Previous dome growth episodes at MSH have persisted for decades, punctuated by small-to-moderate explosive activity. CVO and PNSN continue to monitor the situation and to disseminate information about the eruption and associated hazards.

Details of the eruption can be found at http://www.usgs.gov and http://www.pnsn.org.

Acknowledgments

Eruption responses are team efforts by their very nature. The authors call attention to the hard work and dedication of dozens of colleagues whose names do not appear with ours. Staff authorship would be preferable but is contrary to editorial policy. A few of us wrote the words, but all of us did the work together. This research was supported by the USGS Volcano Hazards Program at the David A. Johnston Cascades Volcano Observatory in Vancouver, Washington, and the Pacific Northwest Seismograph Network at the University of Washington in Seattle, Washington.

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Where Rivers and Oceans Collide

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Fluvial sediment fills the coastal ocean, and sea level rise floods river valleys. This epic battle of terrestrial and marine processes occurs along all shorelines, and the complexities are especially well revealed in the Gulf of Papua, a foreland basin on the southern coast of New Guinea. Two hundred to four hundred million tons of sediment are supplied each year by the Fly and other rivers to a continental shelf that has been dissected by ancestors of these same rivers. The new sediment builds a large depositional feature known as a clinoform, which grows seaward and buries the record of earlier environments.

Research in the Gulf of Papua is documenting the temporal and spatial variability of this sedimentation, done in part through the delineation of old river valleys and smaller channels in various stages of burial. A significant discovery has been valleys with only minor fill (Figure 1), which reveal much of their terrestrial geometry and provide evidence regarding the history of their formation. This, in turn, holds the potential to tell us about late Pleistocene and Holocene rivers, sea level rise, tectonic deformation, and the transformation of a land surface into a seafloor.

The Source-to-Sink segment of the U.S. National Science Foundation's MARGINS program investigates sediment dispersal systems extending from mountain tops to deep seafloors. New Guinea was chosen as a study site because the mechanisms of sedimentation (e.g., erosion, transport, and accumulation) occur intensely and create strong signals that are easily identified. Collaborative studies extend from the terrestrial drainage basin of the Fly River to the continental rise in the Coral Sea, located between Australia and the island of New Guinea.

This article describes recent observations made on the continental shelf where the Fly and other rivers meet the ocean today. Two years of intense fieldwork ended in 2004, and although complete analysis of samples and data will require several years, the initial results reveal the great potential of the source-to-sink approach, for example, for investigating the complexities associated with marine sedimentation burying old land surfaces. Here we focus on river valleys and channels.

The Gulf of Papua and Heterogeneous Sedimentation

Previous studies have described sedimentation in the Gulf [*Harris et al.*, 1996; *Walsh et al.*, 2004], and recognized the presence of antecedent topography being buried by

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