A Volcano Rekindled: The First Year of Renewed Eruption at Mount St. Helens, 2004-2006. Edited by David R. Sherrod, William E. Scott, and Peter H. Stauffer
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Chapter 1. Overview of 2004 to 2005, and Continuing, Eruption of Mount St. Helens, Washington

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Abstract

Rapid onset of unrest at Mount St. Helens on September 23, 2004, initiated an uninterrupted lava-dome-building eruption that continues to the time of writing of this overview (spring 2006) for a volume of papers focused on the eruption. Three distinct phases compose the eruption. About two weeks of intense seismic unrest and localized surface uplift punctuated by five short-lived explosions constituted a vent-clearing phase, during which there was considerable uncertainty regarding the course of the eruption and a frenzy of media attention. About one week of lessened seismicity, minor venting of steam and ash, and continued rapid growth of the uplift, or welt, south of the 1980–1986 lava dome followed as magma continued to punch upward. Crystal-rich dacite lava first appeared on October 11, 2004, beginning growth of a complex lava dome accompanied by persistent low levels of seismicity, rare explosions, low gas emissions, and frequent rockfalls. Largely episodic extrusion between 1980 and 1986 produced a relatively symmetrical lava dome composed of stubby lobes. In contrast, continuous extrusion at mean rates of about 5 m^3/s in autumn 2004 to <1 m^3/s in early 2006 has produced an east-west ridge of three mounds that about equals the volume of the old dome. Much of late 2004 to summer 2005 witnessed growth and disintegration of a succession of three smoothly gouge-covered recumbent spines that grew to nearly 500 m in length in the southeastern sector of the 1980 crater and later disintegrated into two mounds. Since then, growth has been concentrated in the southwestern sector, producing a relatively symmetrical mound with steep gouge-covered slabs on its east flank. Throughout the eruption the extrusive vent has remained relatively fixed. Development of the welt and new dome severed horseshoe-shaped Crater Glacier, which formerly wrapped around three sides of the 1980s dome, and compressed and thickened the severed arms. Doubling of ice thickness resulted in intense crevassing, increased flow rate, and advance of termini, although infiltration of water into the highly porous glacier bed prevented substantial basal sliding. Overall, dome growth and disintegration has produced surprisingly little ice loss. The outcome of the ongoing eruption remains uncertain and Mount St. Helens' eruptive history suggests multiple possibilities. But one dynamical model and some petrologic investigations suggest that the current eruption is an extension of 1980s dome building that may persist continuously or episodically for years to come.

Introduction

A commonly asked question in the Pacific Northwest during the past 20 yr, "When will Mount St. Helens erupt again?," was answered in late September to early October 2004, when a typical days-long swarm of small earthquakes escalated into intense unrest and eruption. Many of the widely acknowledged lessons of successful volcano-risk mitigation were reinforced:

- Understand a volcano's eruptive history and have an up-to-date hazard assessment.
- Have adequate monitoring systems installed and a good record of background behavior.
- Have a strong team of scientists and technicians on site, be able to draw on other experienced personnel, and have replacement equipment available.
- Have an interagency coordination or response plan in place and a working relationship with local emergency-response and land-management agencies.
- Have a well-coordinated joint information center to deliver updates to the media, public officials, and the public.

Fortunately, these conditions were largely met owing to the volcano's memorable eruption in 1980 (Lipman and Mullineaux, 1981), to long-established monitoring systems operated by the U.S. Geological Survey (USGS) and the Pacific Northwest Seismograph Network (PNSN) at the University of Washington, and to long-term cooperation in volcano-hazard and risk-mitigation issues by the Gifford Pinchot National Forest, in which Mount St. Helens is located, Washington State Military Department–Emergency Management Division, and U.S. Geological Survey–Cascades Volcano Observatory (USGS–CVO). Nonetheless, scientific uncertainty, strong media interest and scrutiny, and excitement of a volcanic crisis created an intense and, at times, chaotic scene.

As described in the contributions to this volume, more than 18 months of continuous activity has given scientists from the USGS and numerous academic institutions an opportunity to closely study an eruption that has progressed much differently than that of 1980 to 1986. Rapid onset of unrest and eruption, apparently continuous extrusion of gas-poor mostly crystallized lava into a glacier-filled crater, and month after month of monotonous seismicity, among numerous other observations and surprises, have led to new insights and models of eruptive processes. The duration and outcome of the current eruption remain unknown, but we look forward to exploiting the rich research environment that Mount St. Helens continues to provide. Furthermore, the eruption has stimulated the seemingly insatiable interest of the public and media in volcanoes, and reinvigorated visitation at the Forest Service's Mount St. Helens National Volcanic Monument (hereafter, the Monument). The result is a more volcano-savvy citizenry in the Pacific Northwest, which is essential for maintaining awareness of potential volcano hazards posed by the other 12 Cascade Range volcanic centers in the U.S.

This overview briefly summarizes the recent eruptive history of Mount St. Helens, including the 1980–1986 eruption, the1986–2004 period of quiet punctuated by several notable periods of unrest and minor explosions, and the current eruption.

Eruptive History

Mount St. Helens has been by far the most frequently active volcano in the Cascade Range during the past few thousand years, producing a wide variety of eruption types and scales (Hoblitt and others, 1980; Crandell, 1987; Scott, 1989; Mullineaux, 1996; Clynne and others, this volume, chap. 28). Recent work shows that an eruptive center has existed in the Mount St. Helens area for at least 300,000 years. Early dacitic lava domes created a broad volcano surrounded by aprons of pyroclastic and volcaniclastic deposits. Only during the past few thousand years did the volcano grow into the high graceful cone of early 1980. Late Holocene cone building followed an apparent dormant period that lasted about 7,000 yr and began with several periods of lava-dome and plinian eruptions of dacite, not unlike earlier events in the volcano's history. But starting about 2,500 yr ago, substantial amounts of basalt and andesite began to erupt between dacitic eruptions. Such lava flows buried large parts of a central cluster of dacite domes and flanking fans and started cone building in earnest. Eruptions during the 17th and early 18th centuries raised the cone about 300 m with emplacement of the summit dacitic lava dome and added fans of debris on all flanks of the volcano. Eruptions during the early to middle 19th century did not alter the shape of the volcano greatly but provided an opportunity for early settlers to witness several small eruptions and to realize that Mount St. Helens is an active volcano.

1980–1986 Eruption

Although a detailed understanding of Mount St. Helens' eruptive history and a hazard-zonation map were available in spring 1980 (Crandell and Mullineaux, 1978), volcano monitoring was minimal (one telemetered seismometer on the west flank and one surveyed electronic-distance-meter line on the east flank). With no recent eruptions, local officials and land managers had no experience with volcanic crises. Onset of seismicity in mid-March 1980, accelerating greatly on March 25, steam explosions starting on March 27, and intense interest by public officials and the media required rapid creation of an emergency coordination center to bring together representatives of key agencies. Gifford Pinchot National Forest's experience in fire operations helped greatly in organizing a response. Scientists learned numerous lessons, especially the need to speak with one voice and to quickly address rumors and conflicts (Miller and others, 1981). During April and early May, a decrease in seismicity and frequency of steam explosions reduced public concern and intensified calls to open closed areas. But the rapidly growing north-flank bulge, driven by intrusion of a cryptodome into the volcano, kept scientists wary.

Hopes that seismic precursors or rapid acceleration of ground deformation would permit a short-term hazard forecast were dashed in a minutes-long span on May 18 when the north flank failed in a great debris avalanche (Glicken, 1998). The avalanche was the largest subaerial landslide on Earth in historical time. Resulting rapid decompression of the cryptodome generated explosions that produced a lateral blast, a rapidly moving pyroclastic density current that leveled ~600 km^2 of forest (Hoblitt, 2000) and killed most of the 57 victims of the eruption. The debris avalanche and blast were of a scale unknown in Mount St. Helens' history and proved milestones in recognition of such events as an important hazard at composite volcanoes worldwide (Siebert, 1984). The hours-long eruption of pumice and ash that followed the blast was of expectable scale, although many affected communities in eastern Washington, northern Idaho, and western Montana were unaware of potential hazards from tephra fall and poorly prepared to respond to fallout on the order of millimeters to as much as 8 cm thick (Warrick and others, 1981).

Five smaller subplinian eruptions during summer 1980 were preceded by recognizable precursors, as were the 20 lava dome-building eruptions that ended in October 1986 (Malone and others, 1981; Swanson and others, 1983). Dome-building eruptions were chiefly several-day episodes of extrusion of 1 to 6×10^6 m^3 of lava at average rates as high as 25 m^3/s. Three episodes lasted longer, including one of largely endogenous growth in 1982–1983 that lasted 368 days and had an average eruption rate of 0.7 m^3/s. By October 1986, the lava dome stood about 270 m above the 1980 crater floor and had a total volume in the range of 77 to 91 $\times10^6$ m^3 (Swanson and others, 1990; Mills, 1992, respectively).

1986 to 2004

During 1980–1986 dome building, seismicity was largely confined to shallow depth (<3 km) and related temporally to periods of extrusion, but, starting in 1987, deeper earthquakes became more frequent. Stress-field modeling using focal mechanisms of deep earthquakes supported a hypothesis of pressurization of the magmatic system, which was thought to result from sealing of the shallow conduit (Moran, 1994). By late 1989, deep (3–10 km) seismicity was dominant and, over the next 22 months, 28 shallow, explosion-like seismic signals were recorded, at least 6 of which had confirmed explosions that ejected blocks and produced ash clouds. Gas to drive these events was inferred to come from a deep magmatic source, likely from crystallization of magma in the conduit (Mastin, 1994).

Several other months-long periods of increased deep seismicity occurred after 1992; the most persistent and energetic was in summer 1998. A detectable efflux of CO_2 during the 1998 seismicity suggested that magmatic intrusion was involved. Although scientists infer that some intrusion happened between 1987 and 2004 (Moran and others, this volume, chap. 2), geodetic surveys offer no support for a substantial increase in volume or pressure in the magmatic system (Dzurisin and others, this volume, chap. 14).

Throughout 1986–2004, winter snowfall and avalanche snow alternating with summer rock-fall debris from the crater walls was accumulating in the moat between the 1980–1986 lava dome and crater wall. By 1996 the mass was thick enough to initiate glacier flow and to form steep advancing snouts at a time when most of Earth's glaciers were shrinking (Schilling and others, 2004). As the volcano reawakened in 2004, the glacier, formally named Crater Glacier in 2006, formed a collar around three sides of the dome and was gaining mass yearly. South of the dome, the glacier's surface stood as much as 150 m above the 1986 crater floor.

Media attention to periods of increased seismicity and to anniversaries of the 1980 eruption, as well as other Mount St. Helens' issues, kept the volcano in the news and maintained awareness among the public that the volcano was active and could erupt again. Policy discussions related to continuing high sediment production in the Toutle River basin (Major and others, 2000), to longevity and effectiveness of the sediment retention structure built on the North Fork Toutle River, to the environmental impact of a proposed extension of State Route 504 across the Pumice Plain north of the 1980 Crater, and to concerns regarding long-term funding issues at the Monument also helped to periodically focus attention on the volcano. Educational programs at the Monument and in local school districts also helped to maintain awareness of potential hazards.

Chronology of Events: 2004 to Early 2006

The current eruptive episode comprises three distinct phases. Beginning September 23, 2004, two weeks of intense seismicity punctuated by five short-lived explosions along with localized intense ground deformation constituted a vent-clearing phase. During this phase there was great uncertainty as to how the unrest would progress and what style of eruption would likely result. After October 5, 2004, one week of lessened seismicity but continued localized intense ground deformation preceded lava-dome extrusion. A phase of continuous lava-dome building began on October 11, 2004, and continues to the time of this writing (spring 2006). The highlights of each phase are summarized below, taken largely from contributions in this volume.

Vent Clearing—September 23 to October 5, 2004

A two-day swarm of tiny (mostly <M_d 1), shallow volcano-tectonic earthquakes beginning early on September 23, 2004, resembled a swarm in November 2001 (Moran and others, this volume, chap. 2) and prompted release of an Information Statement by USGS–CVO and PNSN at 18:00 PDT on September 23 (table 1, fig. 1). The statement discussed the swarm's similarity to previous ones and surmised that the swarm might reflect heavier-than-normal precipitation in the preceding four weeks. A rain gage at the mouth of the crater had recorded an abnormally wet last month of summer—more than 30 cm of rainfall. An update on the morning of September 24 noted the difference between the shallow seismicity of the past day and activity during summer 1998 that consisted of larger and deeper events and was considered evidence of deep magmatic intrusion. Both statements considered eruption unlikely without significant precursors.

Beginning on the afternoon of Saturday, September 25, earthquakes increased in magnitude ($\leq M_d$ 2.8) and by the following morning a total of ten large (> M_d 2.0) earthquakes had been recorded, which is the most in a 24-hr period since lava-dome building ended in 1986. This increase in seismicity, along with the appearance of low-frequency and hybrid earthquakes, prompted reassessment of the probability of hazardous activity (Moran and others, this volume, chap. 2). At 15:00 PDT on Sunday, September 26, after notifying the Washington State Emergency Management Division and Gifford Pinchot National Forest, USGS–CVO and PNSN released a Notice of Volcanic Unrest (table 1; fig. 1), indicating that seismicity had surpassed background level and that the volcano was in a state

Table 1. System used by USGS–CVO for event notification at Mount St. Helens[1]. Dual notification schemes are used—one is directed toward hazards on the ground and the other toward ash hazard to aircraft in flight.

Notification for Ground Hazard		
Information Statement		Describes short-lived events that may or may not be hazardous or gives commentary on status of volcano. May also be issued to provide commentary about notable events occurring within any staged alert level during volcanic unrest.
Staged Alert Levels		
1	Notice of Volcanic Unrest	First recognition of conditions that could lead to a hazardous event
2	Volcano Advisory	Hazardous volcanic event likely but not expected immediately or ongoing eruption with localized hazards[2]
3	Volcano Alert	Hazardous volcanic event underway or expected within a few hours or days
Notification of Ash Hazards to Aircraft		
Aviation Color Code		
Green		Volcano is quiet; no eruption is anticipated
Yellow		Volcano is restless; eruption is possible but not known to be imminent
Orange		Small explosive eruption(s) either imminent or occurring; ash plume(s) not expected to reach 25,000 feet above sea level
Red		Major explosive eruption imminent or occurring; large ash plumes expected to reach at least 25,000 feet above sea level

[1] By October 1, 2006, all USGS volcano observatories will be using a new notification system for volcano hazards that uses some different terms and changes definitions of some levels. See (web address) for details.
[2] The second part of the definition was added during the current eruption.

that could evolve toward eruption. Greatest concern was for explosions such as those between 1989 and 1991 that could shower the crater and upper flanks with ballistic fragments and create ash clouds that could affect aircraft in flight and downwind communities.

The increase in alert level spurred several actions. The Gifford Pinchot National Forest activated their Emergency Coordination Center and closed the south-side climbers trail and other trails near the crater (Frenzen and Matarrese, this volume, chap. 23). The number of daily media inquiries, chiefly to USGS–CVO, PNSN, and the Monument, rose rapidly, requiring a considerable effort be directed toward interviews and briefings (Driedger and others, this volume, chap. 24). Field crews took advantage of uncommonly clear autumn weather to begin installation of additional seismometers and Global Positioning System (GPS) receivers around the volcano. Fortunately, Earthscope's Plate Boundary Observatory had been planning installation of a network of continuous GPS instruments at the volcano, and they were able to accelerate their program. Aerial observations of the crater showed no obvious changes, but, in retrospect, a series of new cracks had appeared in the glacier immediately south of the 1980–1986 lava dome (Dzurisin and others, this volume, chap. 14).

By September 29 seismicity had intensified to about three events per minute with maximum magnitudes of M_d 2.4–2.8, rising RSAM (real-time seismic amplitude measurement) values (Moran and others, this volume, chap 2), and hours-long periods during which repetitive earthquakes of similar waveform dominated records (Thelen and others, this volume, chap. 4). The well-known association of such seismicity with lava-dome-building eruptions of the past few decades at Mount St. Helens and elsewhere raised eruption concerns further and prompted issuance of a Volcano Advisory (table 1, fig. 1) mid-morning on September 29. Aviation color code was raised to Orange over increasing concern that explosions could send ash to altitudes where air traffic would be affected. The Volcano Advisory signified that processes were underway that could lead to hazardous eruptive events, but not imminently. Initial airborne missions to detect volcanic gases (carbon dioxide, sulfur dioxide, and hydrogen sulfide) found little, if any (Gerlach and others, this volume, chap. 26). Interpretation of the apparent lack of volcanic gas was tempered by the possibility of scrubbing of gas at high water-to-gas mass ratios likely present at shallow levels beneath the nearly glacier-covered crater floor.

The alert-level rise to Advisory triggered the Gifford Pinchot National Forest to activate a local Incident Management Team and to begin discussions with other agencies regarding a Joint Operation Center, which would be necessary if unrest continued to escalate or eruptions began (Frenzen and Matarrese, this volume, chap. 23). Intense media interest directed chiefly toward USGS–CVO and the Monument was beginning

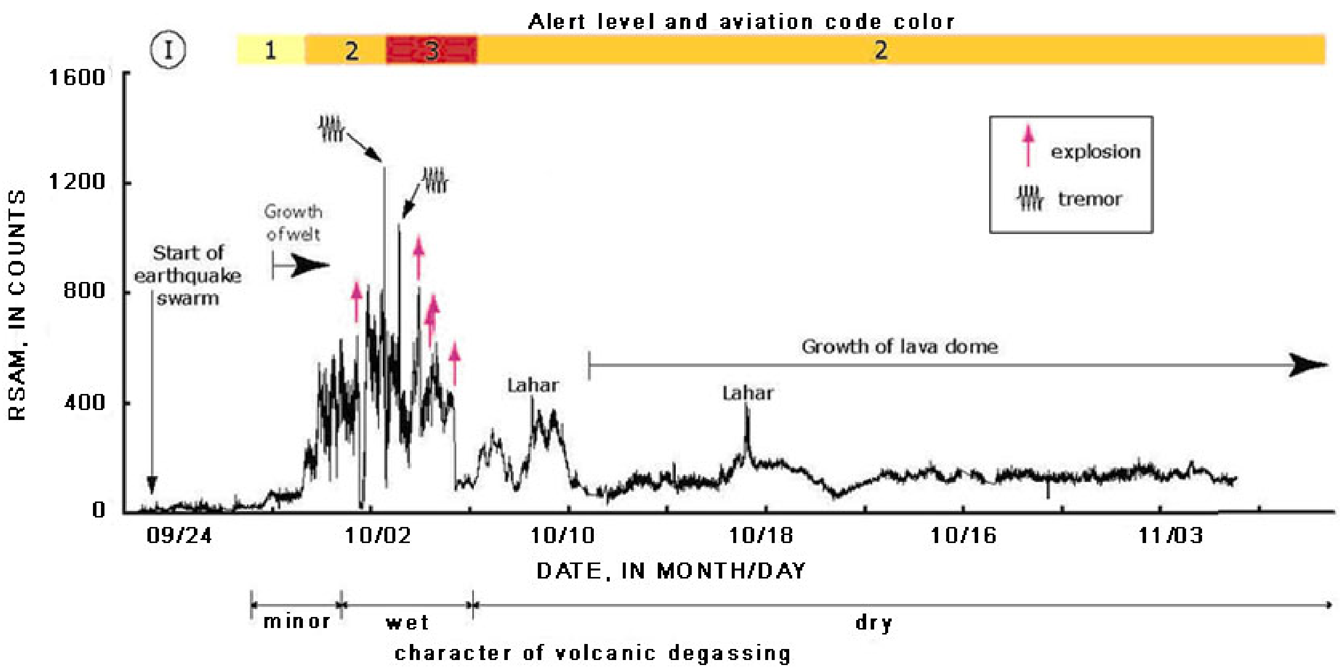


Figure 1. RSAM (Real-time seismic amplitude measurement) during first six weeks of unrest and eruption serves as a proxy for rate of seismicity. Times of explosions and periods of tremor are shown by symbols. Numerals and colored bars indicate alert level and aviation color code (table 1); **I**, release of first information statement.

to adversely affect operations, so local and state emergency management agencies joined with USGS–CVO and the Forest Service to begin organizing a Joint Information Center (Driedger and others, this volume).

RSAM increased again on the evening of September 29, reflecting an increase in maximum earthquake magnitudes (M_d 2.8–3.3) and rate of earthquakes of M_d >2 of about 1 per minute. RSAM values fluctuated over the next 1.5 d. Flights during this time period failed to detect volcanic gas. But an area of glacier south of the 1980–1986 lava dome and a sliver of the dome were fracturing and rising several meters per day, creating what became known as the welt (Dzurisin and others, this volume, chap. 14). Data from a GPS receiver on the west side of the 1980s lava dome showed northward movement of several centimeters per day, consistent with a shove from a rising mass south of the dome.

The inaugural flight at Mount St. Helens of a forward-looking infrared radiometer (FLIR) on October 1 was rewarded with close observation of the first explosion of the current eruption, which bored an ice-walled crater through the western part of the welt shortly before noon (figs. 2*A*, *B*; Schneider and others, this volume, chap. 17). The FLIR recorded a maximum temperature at the base of the explosion column of 140°C, well below magmatic temperature, which suggested that the explosion was driven largely by steam. The explosion was also witnessed by several thousand cheering visitors at the Monument and was clearly visible from the Portland metropolitan area as an ash and vapor cloud rose several hundred meters above the crater rim and drifted southwestward. About 6 min after the explosion started, earthquakes stopped and, when the explosion signal ended abruptly 17 min later, helicorders were quiet for about 3 hr. Rate of earthquakes rapidly increased during the evening and, by late evening, RSAM values exceeded those prior to the explosion, suggesting that the explosion had relieved elevated pressure in the conduit, but that the system was repressurizing quickly (Moran and others, this volume, chap. 2).

For the next two days, seismicity remained at a high level of several thousand events per day, punctuated by earthquakes of M_d 3.5–3.9. Midday on October 2, a 50-minute episode of energetic broadband tremor, coupled with the previous day's confirmation of volcanic gas and continued high rate of ground deformation prompted USGS–CVO and PNSN to issue a Volcano Alert at 14:00 PDT (table 1, fig. 1). With concern over an imminent and potentially hazardous event, the Forest Service evacuated the Johnston Ridge Observatory (JRO), which lay 8 km north of the crater. The Washington State Department of Transportation closed State Route 504 at the Coldwater Ridge Visitor Center, and land and air space was closed within 8 km (5 mi) of the crater (Frenzen and Matarrese, this volume, chap. 23). Fear that an explosive magmatic eruption could produce pyroclastic flows, swiftly melt large amounts of snow and ice surrounding the vent, and generate lahars that could sweep into the upper North Toutle River valley was a key concern. The increased possibility of ash clouds reaching high altitudes where they could affect air traffic warranted raising the aviation color code to Red. Memories of the catastrophic events of May 18, 1980, preoccupied many media and citizens, so a major public-information effort was required to maintain a realistic hazard perspective (Driedger and others, this volume, chap. 24). An explanation that seemed to work well was that the 1980 eruption had so eviscerated the volcano, creating a

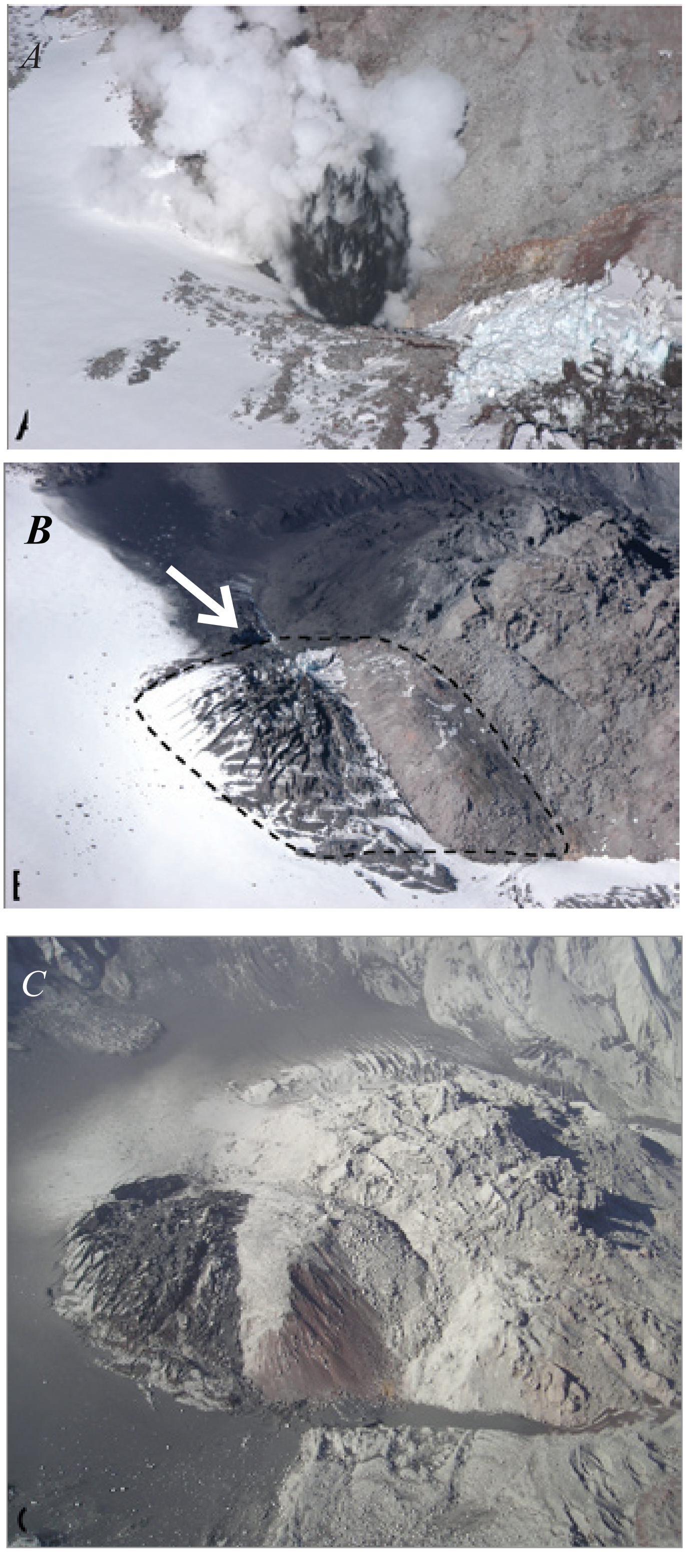


Figure 2. Crater features seen in first two weeks of eruption. A, Start of explosion of October 1, 2004, looking north across glacier toward 1980–1986 lava dome (USGS photograph by J.S. Pallister). B, About 30 min after explosion of October 1, 2004, ended; looking west (USGS photograph by J.S. Pallister). Note tephra-covered snow and crater (white arrow) bored into west end of welt (dashed line), which is formed of uplifted glacier ice and southern part of 1980–1986 lava dome. C, Noticeably larger welt on October 4, 2004, looking west. Some tephra of October 1 and 4 explosions is drying to light color (USGS photograph by ?).

deep crater open to the north, that the volcano could no longer support a scenario of intrusion of a cryptodome, large flank failure, and catastrophic lateral blast. Media and public interest peaked during the first few days of October, resulting in high rates of inquiry and visits to websites (Driedger and others, this volume, chap. 24). A Joint Information Center opened on October 3, and a Joint Operations Center under Unified Command was established the following day with representatives from key land-management and emergency-management agencies.

Additional explosions late on October 3 to midday October 4 were followed by decreases and rebounds in seismicity that were much less dramatic than those on October 1; the last explosion on October 5 initiated a drop in RSAM that never recovered (Moran and others, this volume, chap. 2). The last explosion was the largest, generating an ash plume that reached about 1 km above the crater rim and rated a Volcanic Explosivity Index (VEI) of 2. It drifted to the north-northeast and lightly dusted several communities and the eastern part of Mount Rainier National Park about 100 km away. The relatively low level of seismicity that followed the explosion, including multiplets of hybrid events with similar wave forms (Thelen and others, this volume, chap. 4), combined with low gas emissions (Gerlach and others, this volume, chap. 26) and continued growth of the welt (fig. 2*C*; Dzurisin and others, this volume, chap. 14), suggested that the eruption would probably progress to lava-dome extrusion. Under such conditions, the probability of hazardous events affecting areas beyond closures were small, except for ash clouds that could pose hazards to aircraft, so USGS–CVO and PNSN lowered the alert level to Volcano Advisory at 09:15 PDT on October 6, where it remained throughout late 2004 and into 2006 (table 1, fig. 1). Concurrently the aviation color code was lowered to Orange. The Forest Service reverted to a local Incident Management Team (Frenzen and Matarrese, this volume, chap. 23) and inquiries to the Joint Information Center began to decline, eventually leading to its being disbanded on October 13 (Driedger and others, this volume, chap. 24). USGS–CVO continued to update agencies through daily conference calls.

Waiting for Lava—October 5 to October 11, 2004

Several days of stormy weather beginning on October 6 drove visitors and media from the Monument, increased RSAM with storm noise, and generated a small lahar from the crater—a common occurrence with the onset of autumn rain. Brief views showed that the welt continued to grow upward and outward, reaching more than 100 m above the former glacier surface. On October 10 a fixed camera on Sugar Bowl dome, at the northeast mouth of the crater, began transmitting images that tracked growth of part of the welt (Poland and others, this volume, chap.11). Later analysis of digital elevation models (DEMs) showed that by October 13 the deformed area had a volume of about 12×10^6 m^3 (Schilling and others, this volume, chap. 8). FLIR measurements confirmed that by October 10 an area on the northwest part of the welt had reached about 300°C, suggesting that the crater floor was being heated and punched upward by rising magma. An airborne survey detected gas-emission rates of 2400 metric tons per day (t/d) CO_2, ~100 t/d SO_2, and 10 t/d H_2S, which, although relatively modest for volcanoes such as Mount St. Helens, suggested that a dry pathway had been established and scrubbing reduced (Gerlach and others, this volume, chap. 26). The question on everyone's mind and asked repeatedly by the media, was, "Has new lava appeared on the surface yet?"

Lava-Dome Growth—October 11, 2004, to Spring 2006

On October 11, a FLIR survey showed that a newly extruded fin-shaped rock spine (in retrospect designated spine 1) about 30 m high and 60 m long had a maximum temperature of about 620°C; this spine is considered to be the initial appearance of new lava (fig. 3) and the start of growth of what we call the new lava dome. The spine occupied the approximate location of the vent for early October explosions and stood about 250 m [check] above the subglacial crater floor. In the following days the spine grew, its base and cracks showed temperatures as high as 700°C, and additional areas of hot rock appeared to the south of spine 1 (designated spine 2; Vallance and others, this volume, chap. 9). The first samples of the new lava dome were dredged from spine 1 using a weighted bucket on the end of a 30-m line slung from a helicopter. The samples looked like typical Mount St. Helens dacite (Pallister and others, this volume, chap. 30). During this time period, RSAM fluctuated broadly, multiplets of hybrid earthquakes appeared and faded, and seismicity settled into a pattern of small (M_d <1) earthquakes, dubbed drumbeats, occurring at rate of one to two per minute with larger events at longer intervals (Moran and others, this volume, chap. 2).

The potential for unheralded explosions required minimizing exposure of field crews, so, beginning in early October 2004, new and replacement instruments in the crater were deployed by helicopter sling. Single-frequency GPS receivers and accelerometers (seismometers) mounted alone or together on tripods, dubbed spiders, proved invaluable for maintaining close-in telemetered seismic instruments (McChesney and others, this volume, chap. 7) and allowing real-time geodetic measurements of rates and directions of movement of the welt and new dome, as well as movement of the glacier and deformation of the old lava dome (LaHusen and others, this volume, chap. 16; Dzurisin and others, this volume, chap. 14; Walder and others, this volume, chap. 13).

Growth of the new lava dome has progressed steadily since mid-October 2004, apparently without pause (papers in this volume: Moran and others, chap. 2; Schilling and others, chap. 8; Vallance and others, chap. 9). In contrast, the 1980–1986, or old, lava dome grew in episodic spurts on either side of a one-year period of continuous growth (Swanson and Holcomb, 1990). Rather than building a single dome-shaped structure similar to the old dome, the new dome has grown as a series of recumbent, smoothly surfaced spines or whalebacks that extruded to lengths of almost 500 m (Vallance and others, this volume, chap. 9; Herriott and others, this volume, chap. 10). As is typical for such spines (Williams, 1935), the surface

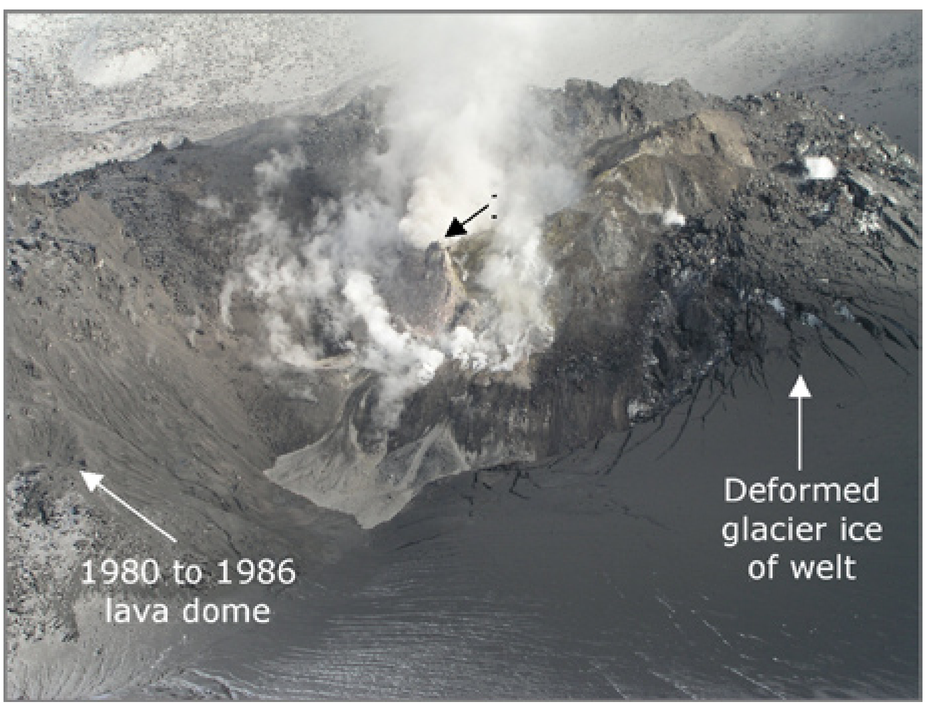


Figure 3. First view (toward southeast) of hot, new lava at surface, October 11, 2004 (USGS photograph by J.J. Major). Spine 1 is composed of pinkish-gray dacite that is disintegrating and forming light-colored debris fans between welt, old dome, and west arm of glacier. Blocky terrain to the right of the numeral 1 is where spine 2 emerged several days later.

is striated and grooved and formed of powdery, crushed rock (gouge) that results from the solid extrusion grinding against the conduit walls during its last few hundred meters of ascent (Cashman and others, this volume, chap. 19; Moore and others, this volume, chap. 20). Early gouge contained both dacite from the extrusion and more mafic constituents from the conduit walls, but during most of the eruption, gouge has been formed of dome dacite (Pallister and others, this volume, chap. 30; Rowe and others, this volume, chap. 29).

The erupting dacite is similar in chemical composition (~65 wt. percent SiO_2) and mineralogy (plagioclase>hornblende>orthopyroxene) to the dacite erupted on May 18, 1980, and is among the most silica-rich and incompatible-element-depleted magmas of the past 500 yr (Pallister and others, this volume, chap. 30). The dome lava contains 40-50 percent phenocrysts and the groundmass is largely crystalline for most of its last 500 m of ascent (Cashman and others, this volume, chap. 19). In several contributions in this volume, petrologists and geochemists explore the origin of the lava and evidence of its recent history. Some is thought to represent residual magma from the 1980s, but several lines of evidence suggest that there is a component of new dacite mixing with the 1980s dacite. Reaction rims on phenocrysts suggest storage for a prolonged period at 4-5 km or deeper (Rutherford and Devine, this volume, chap.31), but other evidence is permissible of long storage at a shallower level (check if this is discussed in some contributions). Similar texture to the 17^{th}–18^{th} century lava dome that formed the pre-1980 summit, which is known to have been emplaced over about 150 yr, suggests the current eruption may last for many more years (Pallister and others, 1992; Pallister and others, this volume, chap. 30).

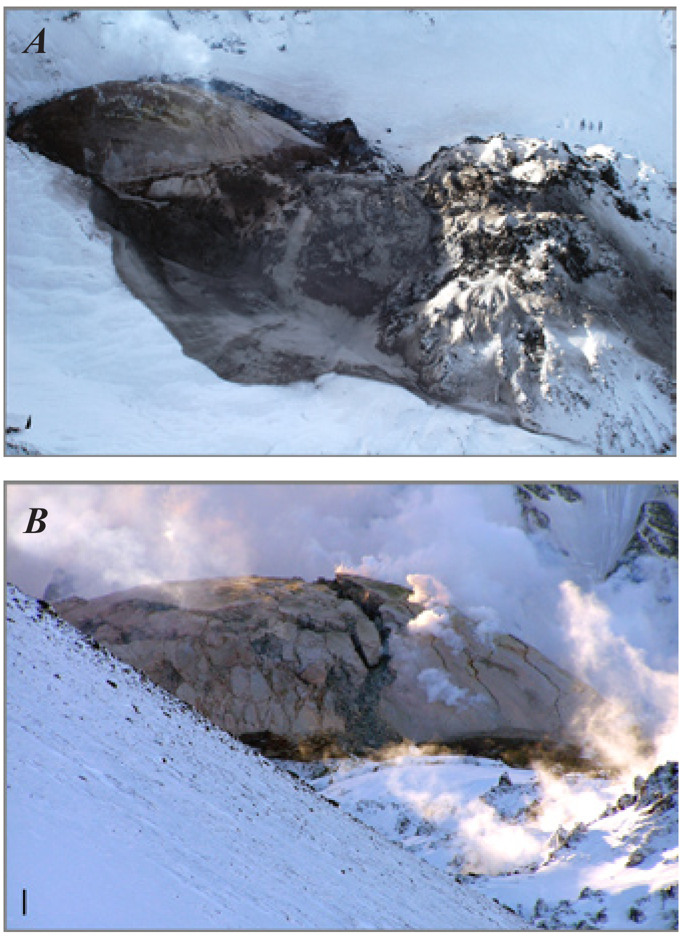


Figure 4. Views of spine 3. *A*, On December 16, 2004, spine was at itmaximum extent just as fractures (right of the white vapor plume) were beginning to develop that would eventually sever the spine from the vent. Note thin deposit of ash formed by density current(s) of ash originating as slough(s) of fine-grained gouge carapace (USGS photograph by W.E. Scott). *B*, One week later, fractures had expanded and severed spine 3 from vent; spine 4 was riding up on and pushing the disintegrating remains of spine 3 chiefly southeastward (USGS photograph by M.P. Poland).

Late Autumn 2004

The first of the whaleback-shaped spines (spine 3) started growing in late October 2004 from southeast of spine 1 and east of spine 2. A GPS instrument riding on the spine moved at an average rate of about 10 m/d for 8 d (LaHusen and others; this volume, chap. 16; Dzurisin and others, this volume, chap. 14). By the end of November 2004, spine 3 was about 475 m long and had reached the base of the southeast crater wall (Schilling and others, this volume, chap. 8). Concurrently a GPS receiver on the outer southeast flank of the volcano showed a small outward movement in response to this loading (Dzurisin and others, this volume, chap. 14). By mid-December 2004, the total volume increase represented by the three spines of the new dome and welt, using the 1986 crater floor as a base datum, was about $30{\times}10^6$ m^3 (Schilling and others, this volume). Whether due to the increasing difficulty of extruding an ever-lengthening mass or stress imposed by impinging on the crater wall, longitudinal fractures appeared and widened and transverse fractures severed the spine from the vent (fig. 4). The breakup of the spine was accompanied by sporadic earthquakes of ~M_d 2.5–3.5, suggesting a causal relation (Moran and others, this volume, chap. 2). The remaining stump of spine 3 grew to form a new spine (spine 4) that pushed most of the old spine aside to the east (Vallance and others, this volume, chap. 9) except for a small amount that was stranded on the west side of spine 4 (Herriott and others, this volume, chap. 10). As spine 3 drifted eastward, it became increasingly fractured, and little of its smooth, gouge-covered surface remained intact.

January to July 2005

Growth and disintegration of spines continued through the first 8 months of 2005. Spines 4 and 5 formed prominent whalebacks whose growth ended similarly to that of spine 3 (Vallance and others, this volume, chap. 9). Growth periods lasted from about 7 weeks (spine 3) to 16 weeks (spine 4). Extrusion rates during growth of spines 4 and 5 were less than that for spine 3 (Schilling and others, this volume, chap. 8), as were linear rates of motion determined by GPS spiders (LaHusen and others, this volume, chap. 16), by analysis of repeat photographs from the crater mouth (Major and others, this volume, chap. 12), and by tracking of points through sequential DEMs (Vallance and others, this volume, chap. 9). By mid-summer 2005, the top of spine 5, which was growing at a steeper angle than had earlier spines, reached the highest altitude attained by the new dome, 2368 m. At that time the top stood only a few meters below the lowest point on the crater rim, Shoestring notch, and about 180 m below the summit; the dome then extended about 450 m above the 1986 crater floor. Spine 5 was a prominent feature in the view of the crater from JRO in mid-summer 2005, with the crumbled remains of spine 4 and its large raft of intact gouge-covered surface lying off to the east (fig. 5*A*).

August 2005 to Spring 2006

A key change in pattern of dome growth began in late July 2005, as towering spine 5 began to crumble. Rather than follow the previous pattern of a new spine bulldozing the remains of older spines eastward, growth of spine 6 progressed westward. The likeliest explanation is that spine 6 faced less resistance by plowing into the west arm of the glacier than by continuing to push the previously extruded rock mass eastward (Vallance and others, this volume, chap. 9). Although spine 6 had some areas displaying the smooth, gouge-covered surface typical of earlier whalebacks, it formed a more domical mass than had previous spines. Photogrammetric techniques estimated a rate of movement of several meters per day westward and slightly upward (this volume: Dzurizin and others, chap. 14; Major and others, chap.12). As spine 6 moved westward, the west side of spine 5, which was by then highly fractured, slumped westward into the widening sag forming between the spines. By mid-October 2005, a new spine was detected in FLIR imagery to be rising between spines 5 and 6 (Vallance and others, this volume, chap. 9). Spine 7 rode up the east side of spine 6 and both continued to move westward (fig. 5*B*). By spring 2006, much of spine 6 had been covered by spine 7 or by an apron of rockfall debris being shed westward from it. The combined mass of spines 6 and 7 continued to move west-northwestward and slightly downward at about 1 m/d during spring 2006 (this volume: Dzurisin and others, chap. 14; Vallance and others, chap. 9). Even though spines have formed and crumbled repeatedly throughout the eruption, the vent area (the area at which the extrusion daylights) has remained in the approximate position of the early October 2004 explosion pit and initial spine (this volume: Schilling and others, chap. 8; Vallance and others, chap. 9 Herriott and others, chap. 10).

The future of dome growth remains uncertain. By the end of 2005, the new dome had a total volume of about 73×10^6 m^3, nearly equaling the volume of the old lava dome in a time span about one-fifth as long (fig. 6). The rate of extrusion had declined from about 5 m^3/s in late 2004 to less than 1 m^3/s. Overall the rate of extrusion appeared to be either slowing exponentially or becoming relatively linear and fluctuating between 1 and 2 m^3/s (Schilling and others, chap. 8; Dzurisin and others, chap. 14). Will the eruption come slowly to a halt over the next several months or year? Alternatively, will the rate of extrusion become variable and episodic—more reminiscent of dome growth during the 1980s? Or, appreciating the varied eruptive history of Mount St. Helens (Hoblitt and others, 1980), does the volcano have something entirely different in store?

Small Explosions Accompany Dome Growth

Early on the stormy morning of January 16, as spine 4 was advancing toward the crater wall, the first of two notable explosions of 2005 occurred. There were no recognizable precursors to the explosion, but any subtle seismic precursors would probably have been lost in storm noise. Transmission from several crater instruments stopped for seconds-long

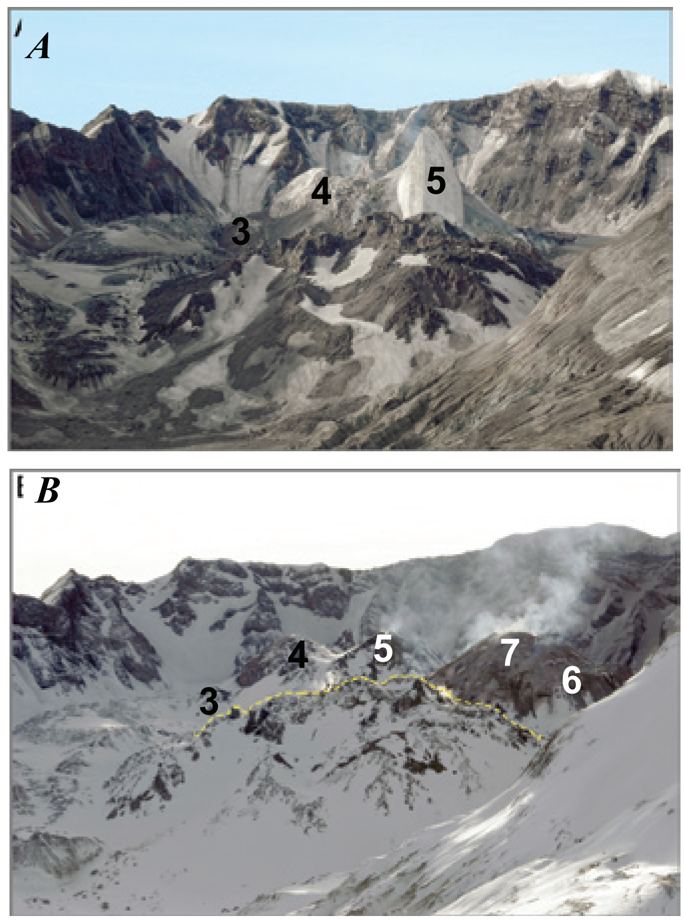


Figure 5. Views south to lava dome from fixed camera point at Johnston Ridge Observatory, 8 km north of crater (USGS photographs by E.T. Endo). Numerals denote spines of new lava dome. *A*, June 24, 2005; actively extruding spine 5 is approaching its highest altitude. Note highly crevassed east arm of crater glacier, which had been compressed by eastwardly migrating lava dome. *B*, December 5, 2005; spine 5 has disintegrated and spines 6 and 7 are migrating westward (to right). Yellow dashed line marks profile of 1980s lava dome.

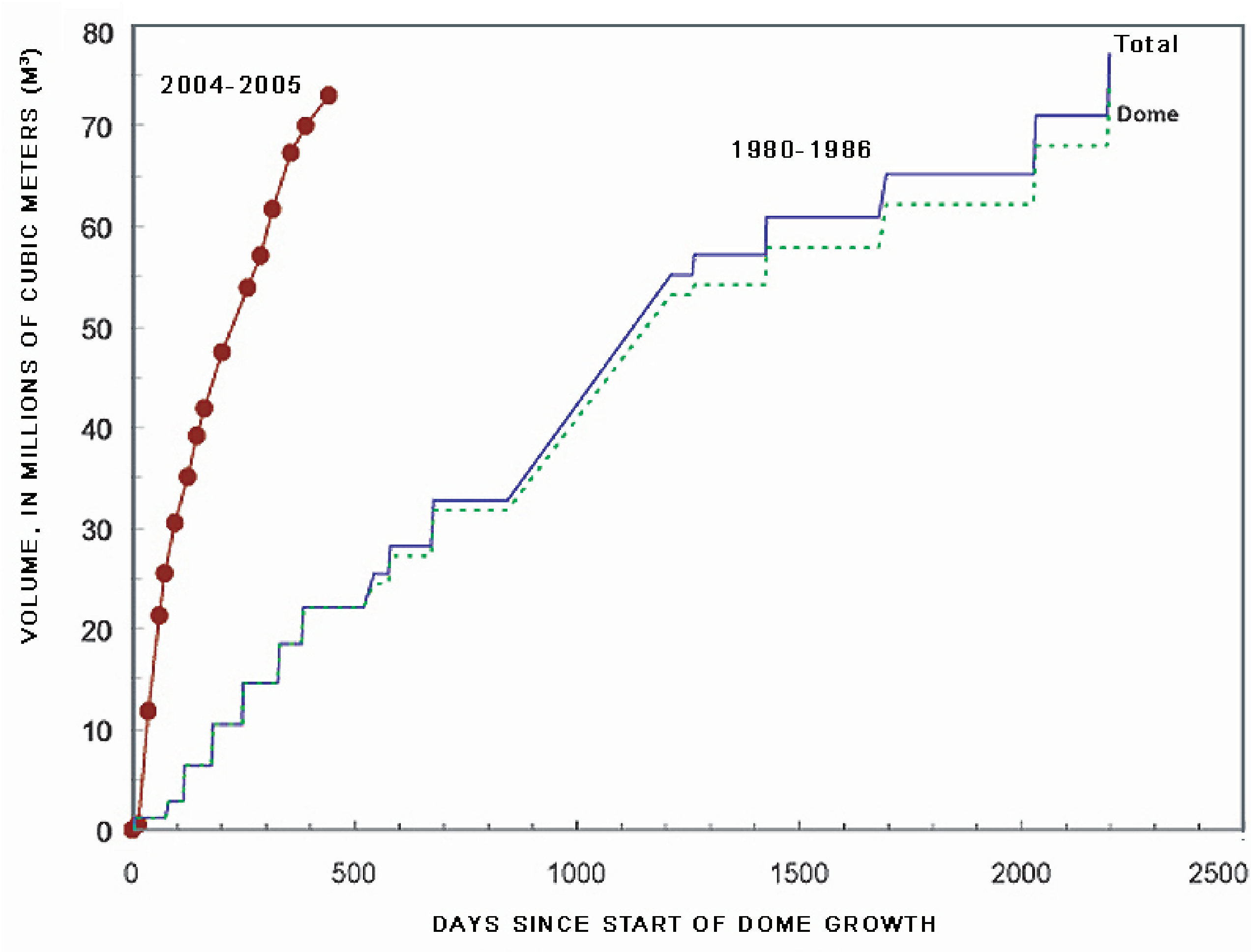


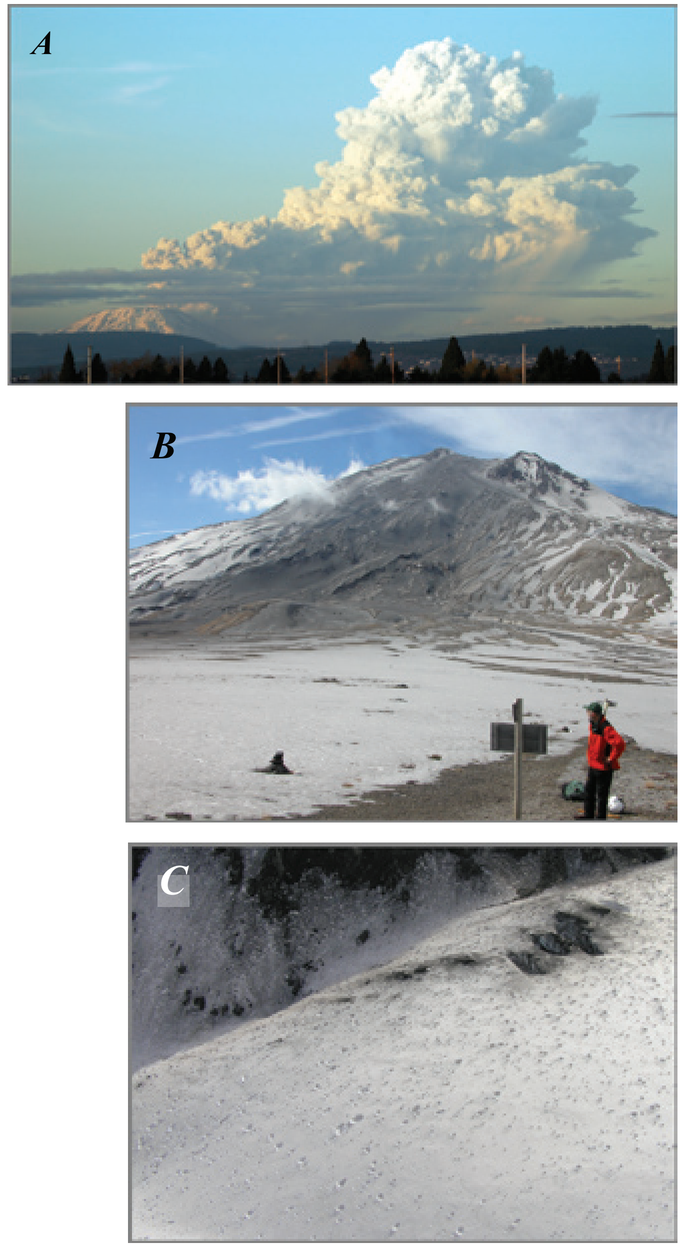
Figure 6. Comparison of lava-extrusion rates for 1980–1986 (Swanson and Holcomb, 1990) and 2004–2005 (Schilling and others, this volume) lava domes at Mount St. Helens. Total for 1980–1986 includes tephra and rockfall debris from growing dome.

intervals during the explosion-like seismic signal, presumably by ash in the air blocking radio signals (Moran and others, this volume, chap. 6). Reception from one near-vent seismometer stopped for several hours. Several other instruments on and close to the actively growing part of the lava dome were destroyed. Poor weather precluded field observations for several days, but a reconnaissance flight eventually revealed evidence of an explosion. Craters from ballistic blocks pock marked the glacier surface chiefly east of the new dome for hundreds of meters. Ash covered the crater east and west of the new dome and formed a narrow deposit on the east flank, consistent with strong westerly winds. About 5 mm of ash fell on the lower east flank; extent of ashfall farther east is unknown owing to lack of snow-covered surface to preserve the ash and to heavy rainfall that accompanied and followed the explosion. Effects of the explosion were similar to those of October 2004 events, but no visible crater formed. A shallow trough along the northeast margin of spine 4 may have marked the vent. The similarity in texture and composition of the ash with previously collected samples of the spine's surficial gouge suggested that the explosion vented along the margin of the spine, entraining powdery gouge and blocks (Rowe and others, this volume, chap. 29).

The second explosion occurred under good viewing conditions late on the afternoon of March 8, 2005 (fig. 7*A*). Seismicity had increased slightly for several hours prior to the explosion and had initiated a close watch in the operations room at USGS–CVO but was not recognized as a precursor to an imminent explosion (Moran and others, this volume, chap. 6). The Sugar Bowl camera at the northeast mouth of the crater captured images of a dense ash cloud rising from near the new dome and ballistic-impact craters snow on the north flank of the old dome. Ballistic fragments destroyed one seismometer located between the old and new lava domes and one seismometer and two microphones located on the old lava dome. A white vapor cloud billowed high above the crater rim and drifted east-northeastward. Pilots reported the top of the cloud reached 11 km; National Weather Service's NEXRAD detected it up to 6 km. The whiteness of the upper parts of the cloud suggested that it contained little ash. The explosion continued vigorously for about 10 min and then waned over tens of minutes. Investigations the following day revealed a field of ballistic craters extending about 1 km north-northwest of a poorly defined and vapor-shrouded possible vent area at the north end of the new lava dome. A narrow deposit of coarse ash and fine lapilli extended east-northeastward, discernible on snow for about 7 km from the vent (fig. 7*B, D*). The fallout deposit was about 20 mm thick on the crater rim and a couple of millimeters thick on the lower east flank. Dustings of ash were reported in Ellensburg, Yakima, and Toppenish, Washington, as far as 150 km from the volcano. Lithic lapilli as large as 4 cm fell near the crater rim and as large as 1 cm fell on the lower east flank.

Rockfalls and Avalanches

Rockfalls and avalanches have generated small pyroclastic density currents with reaches of <1 km and numerous ash clouds that rose above the crater rim. At most, such clouds have only weakly dusted the outer flanks and have extended only a short distance downwind. Signals of rockfalls and small rock avalanches are common on seismic records, and such events have been observed during hours-long occupations of sites on the old lava dome and crater rim, as well as during fortuitously timed flights (fig. 8). Many events have also been recorded by fixed cameras (Poland and others, this volume, chap. 11). The largest-volume avalanches have been on the order of tens of thousands of cubic meters, but most have been much smaller. Periods of rapid disintegration of spines and accompanying large earthquakes favored large avalanches and frequent rockfalls. The high degree of crystallization and low gas content of the lava (this volume: Pallister and others, chap. 30; Gerlach and others, chap. 26) are probably responsible for the relatively small amount of ash generated by avalanches and rockfalls and the restricted distribution of density currents. Sloughing of ashy gouge from the outer parts of whaleback-shaped spines, especially spine 3, have also created weak density currents of ash and accompanying ash clouds (fig. 4*A*).



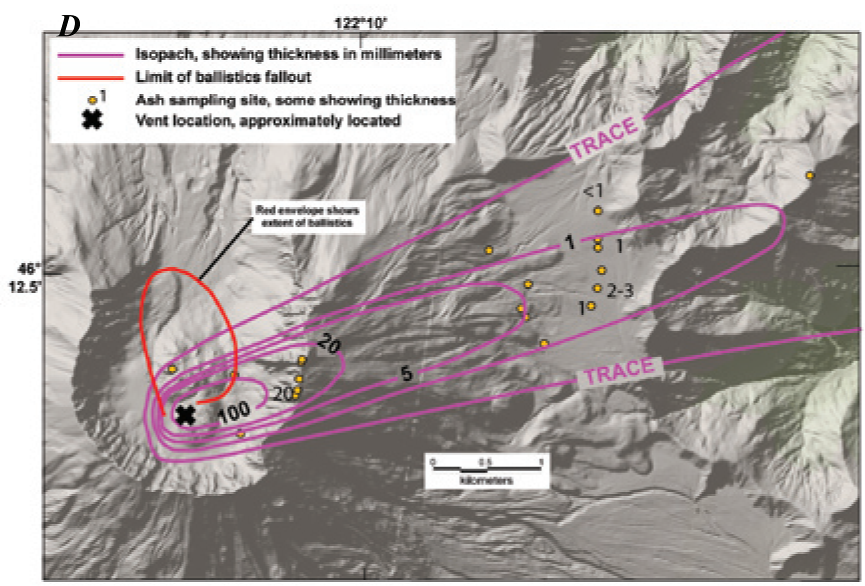


Figure 7. Explosion of March 8, 2005. *A*, Ash and vapor cloud as viewed toward north-northeast from Cascades Volcano Observatory (USGS photograph by Matthew Logan). *B*, Tephra deposit on east-northeast flank as seen from the Plains of Abraham (USGS photograph by D.R. Sherrod). Note meager snowpack of winter of 2004–2005. *C*, Northwest base of old lava dome and west arm of crater glacier pock marked by craters formed by rain of ballistic fragments (USGS photograph by Daniel Dzurisin). *D*, Map showing extent of ballistic fragments and tephra fall.

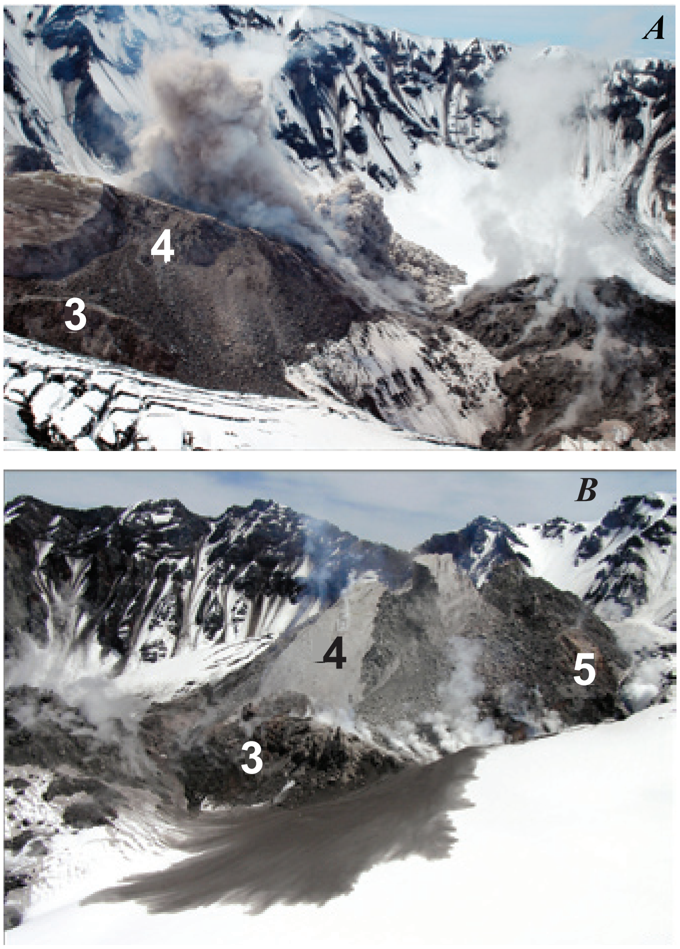


Figure 8. Rockfall from spine 5 and small pyroclastic density current of May 12, 2005; older spines designated by numeral. *A*, View from east crater rim of density current flowing northwestward and ash cloud rising and obscuring spine 5 (USGS photograph by Matthew Logan. *B*, Aerial view from northwest following event showing scar at rockfall source and thin ash deposit on snow (USGS photograph by Daniel Dzurisin).

Dome Growth Perturbs Glacier

Continued eastward movement of spines 3, 4, and 5 through late summer 2005 greatly compressed, thickened, and fractured the east arm of Crater Glacier (fig. 5*A*). Such conditions created an unprecedented glaciological experiment (Walder and others, this volume, chap. 13). The resulting doubling of thickness accelerated surface movement to more than 1 m/d, which, although high for such a small glacier, is less than would be expected from such a dramatic thickening. The explanation for lower-than-expected flow rate is that the bed of the glacier, which comprises talus and coarse pyroclastic debris, is so permeable that water pressure at the bed cannot rise sufficiently to induce rapid basal sliding (Walder and others, 2005). In response to this perturbation, the snout of the east arm thickened noticeably and advanced markedly during winter of 2005–2006. Beginning in late summer 2005, westward movement of spines 6 and 7 started compressing the west arm of Crater Glacier (fig. 9). A similar thickening and accelerated flow rate is underway (Walder and others, this volume, chap. 13).

A remarkable aspect of the interaction of the growing lava dome and glacier is the apparent lack of significant glacier melting (Walder and others, 2005; this volume, chap. 13). As the glacier grew in the crater between 1986 and 2004, USGS–CVO noted the potential for increasingly larger lahars were future explosive eruptions or lava-dome collapses to generate pyroclastic flows. Such concerns dominated the hazard outlook for the first couple of weeks of unrest in 2004. Once lava-dome growth commenced, the lahar hazard focused on explosions from the dome swiftly melting snow in the crater as happened in 1982 and 1984 (Pierson, 1999), as well as on collapses from the new lava dome incorporating and melting snow and ice. Neither scenario has been a factor to date. Explosions in January and March 2005 did not generate pyroclastic flows or surges of note and apparently melted little snow and ice. Rockfalls and avalanches from the dome have been of modest size and neither they nor pyroclastic density currents derived from them have induced much melting.

New Insights from the Ongoing Eruption

Mount St. Helens' ongoing extrusion of gas-poor dacitic lava has presented an opportunity to develop a variety of models to illuminate controls on eruptive behavior.

The persistent "drumbeat" earthquakes, at times amazingly periodic, that have accompanied nearly steady lava extrusion tantalized scientists early in the eruption. Was this behavior an indication of repetitive stick-slip motion along the margins of the extruding plug producing the coating of striated fault gouge? Strength tests of samples support this hypothesis and also show evidence for rate-weakening friction (Moore and others, this volume, chap. 20). A dynamical model demonstrates that repetitive stick-slip events are an almost inevitable consequence of magma influx at a near-equilibrium rate occurring in conjunction with rate-weakening frictional slip along the margins of an extruding solid plug (Iverson, this volume, chap. 21). Because such a condition was attained very early in the eruption, the model implies that the magma-plug system was probably close to equilibrium at the onset and perhaps needed only a small perturbation to be triggered into action. Whether the trigger was related to a small increase in magmatic pressure from below or to a shallow process such as increased ground-water pressure from heavier-than-normal late summer rain is unknown. In either case, from the perspective of the model, the current eruption is a continuation of 1980s dome building wherein conditions of the magma-plug system differ little between eruptive and noneruptive periods.

Geodetic modeling of GPS data, primarily the long-term record from the receiver at Johnston Ridge Observatory, 8 km from the new lava dome, suggests that the responsible deformation source is an ellipsoidal body that extends from about 5

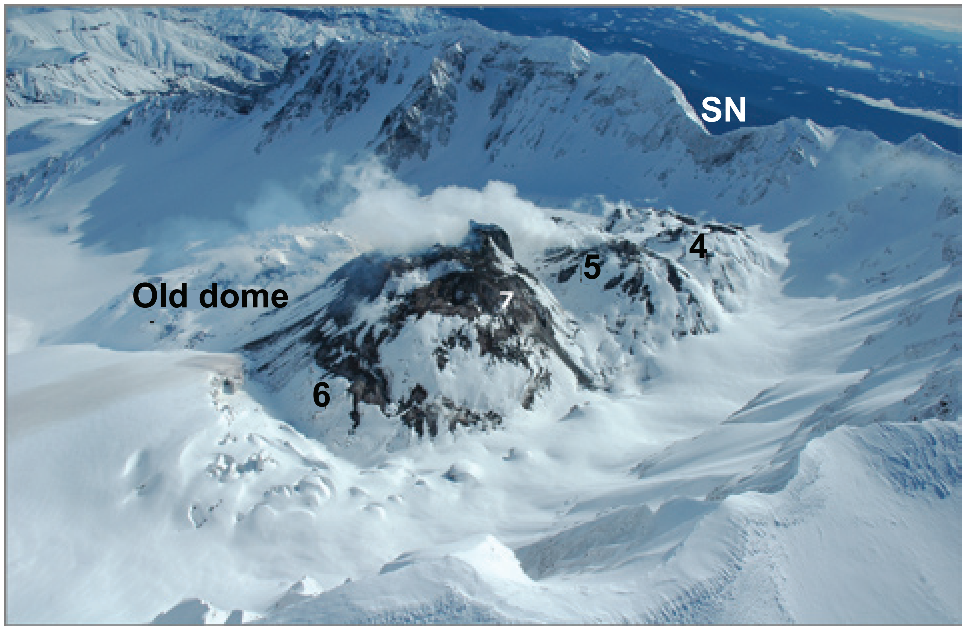


Figure 9. View of crater looking east-northeastward taken April 4, 2006 (USGS photograph by J.W. Vallance); spines 4 to 7 are identified by numerals. Spine 7, including a steeply east-dipping gouge-covered slab (high point) is riding up over spine 6 and has nearly buried it. At the time of the photograph, a GPS spider riding to the left of the numeral 7 was moving about 1 m/d west-northwestward and slightly downward. The movement of spines 6 and 7 westward was compressing and fracturing the west arm of the crater glacier, but greater-than-normal snowfall during winter of 2005–2006 was filling in crevasses and is burying much of the older parts of the new lava dome. Shoestring notch, the lowest point on the crater rim, lies just above spine 4.

km to 10-20 km deep, but that the volume lost from the source is only a few tens of percent of the erupted volume of lava (Lisowski and others, this volume, chap.15). Whether this apparent inconsistency is due to ongoing partial recharge, what role is played by magma compressibility controlled by gas content, and what the size is of the Mount St. Helens magma chamber are explored in a model that incorporates geodetic and dome-growth data (Mastin and others, this volume, chap. 22). Substantial uncertainties in data and parameter values hamper precise assessments of magma-chamber size and conditions but raise several points that are relevant to efforts to better understand and model the magmatic system.

Summary

The contributions that follow in this volume represent the work of more than 100 scientists and emergency managers from numerous academic institutions, the USGS, the Forest Service, and state and local government. Together they provide a broad perspective of the ongoing eruption of Mount St. Helens and highlight the following events, findings, and lessons learned.

- The key requirements for successful volcano crisis response were in place at Mount St. Helens when unrest began on September 23, 2004, including geophysical monitoring systems, detailed knowledge of the volcano's eruptive history, a well-trained and highly experienced scientific staff, many public officials and citizens knowledgeable about volcano hazards, and years of close coordination among scientists, land managers, and emergency managers in planning for future eruptions.
- Intense media and public interest in volcanic unrest and eruption required rapid establishment of a joint information center staffed by scientists and representatives of land-management, emergency-management, and other relevant state and local agencies. The center expanded and shrank as demand dictated and coordinated dissemination of clear, consistent messages.
- Three distinct phases compose the 2004 to present eruption: (1) Between September 23 and October 5, intense seismic unrest and localized surface deformation punctuated by five short-lived explosions constituted a vent-clearing phase, (2) between October 5 and October 11, lessened seismicity, minor venting of steam and ash, and continued rapid localized surface deformation during which magma continued to punch upward through crater floor debris and glacier ice, and (3) between October 11, 2004, and the present (spring 2006), persistent low levels of small drumbeat earthquakes and sporadic larger events, rare explosions, low gas emissions, and frequent rockfalls accompanying continuous lava-dome extrusion.
- Ongoing continuous lava-dome growth has contrasted markedly with the largely episodic growth of the 1980s

dome and has resulted in a strikingly different-looking dome. A succession of spines, some recumbent, smoothly gouge-coated, and nearly 500-m long, has built a dome about equal to the volume of the 1980s dome in about one-quarter of the time. Rather than a single mound, the new dome currently comprises three main rock masses arrayed east-west across the 1980 crater between the 1980s dome and south crater wall. The vent for extruding lava has remained relatively fixed, but successive spines have been able to push older masses aside across the glacier-covered crater floor.

- A dynamical model demonstrates that repetitive stick-slip events, such as drumbeat earthquakes might represent, are an almost inevitable consequence of magma influx at a near-equilibrium rate occurring in conjunction with rate weakening frictional slip along the margins of an extruding solid plug. Because such a condition was attained very early in the eruption, the model implies that the magma-plug system was close to equilibrium at the onset and perhaps needed only a small perturbation to be triggered into action. From this perspective, the current eruption is a continuation of 1980s dome building wherein conditions of the magma-plug system differ little between eruptive and noneruptive periods.
- Crystal-rich dacite with a bulk chemical composition similar to that erupted explosively on May 18, 1980, is building the lava dome. Some is thought to be residual dacite from the 1980s, but a new component is likely admixed. Similar texture to the pre-1980 summit dome, which was emplaced over about 150 yr, suggests that the current eruption may last for many more years.
- The outcome of the ongoing eruption is uncertain. During its recent history, Mount St. Helens has sustained dome growth for more than a century, as during construction of the pre-1980 summit dome, has alternated between explosive and effusive eruptions of dacite, and has quickly switched from eruptions of dacite to eruptions of lava flows of more mafic composition.
- Lava-dome extrusion in a glacier-covered crater has created an unprecedented glaciological experiment. The lava dome severed the formerly horseshoe-shaped Crater Glacier into two arms that have been successively squeezed against the crater wall and thickened as lava spines bulldozed them outward. The arms were about doubled in thickness over a period of months. Flow rates increased and both termini are advancing vigorously. But rapid dewatering of glacier beds owing to highly permeable crater floor material has discouraged basal sliding and most glacier movement consists of internal flow. The intrusion of the lava dome through the glacier has resulted in amazingly little melting.
- Localized surface deformation and dome growth, potential hazards in proximal areas to scientists and instruments, and a relatively slow but persistent pace of lava extrusion required development and adaptation of monitoring systems in order to study the eruption. Low-cost, portable alternatives to traditional GPS and seismic installations, dubbed spiders, allowed helicopter deployment and retrieval of telemetered instruments to areas on and near the growing lava dome and highly crevassed glacier. Ingenuity combined with skillful pilots ensured collection of a suite of lava samples from helicopter-borne dredges. Fixed cameras that telemetered images permitted visual observations and repeat images from which rates of movement could be estimated. DEMs made from a succession of vertical-aerial photographs tracked volumetric rates of lava-dome growth and provided detailed bases for a variety of investigations. Throughout the eruption, helicopter-mounted FLIR surveys, a relatively new technique for USGS scientists, provided key information regarding extrusion temperature, vent location, and dome structure.

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