A Volcano Rekindled: The Renewed Eruption of Mount St. Helens, 2004–2006
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Chapter 11

Remote Camera Observations of Lava Dome Growth at Mount St. Helens, Washington, October 2004 to February 2006

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Abstract

Images from a Web-based camera (Webcam) located 8 km north of Mount St. Helens and a network of remote, telemetered digital cameras were used to observe eruptive activity at the volcano between October 2004 and February 2006. The cameras offered the advantages of low cost, low power, flexibility in deployment, and high spatial and temporal resolution. Images obtained from the cameras provided important insights into several aspects of dome extrusion, including rockfalls, lava extrusion rates, and explosive activity. Images from the remote, telemetered digital cameras were assembled into time-lapse animations of dome extrusion that supported monitoring, research, and outreach efforts. The wide-ranging utility of remote camera imagery should motivate additional work, especially to develop the three-dimensional quantitative capabilities of terrestrial camera networks.

Introduction

During the 20th century, advances in technology have added an array of geophysical and geochemical instrumentation to the modern volcanologist's toolkit. The study of active volcanoes has relied increasingly upon datasets derived from such technology to infer the mechanics of volcanic processes, which often occur at depth. As detailed in this volume, many geophysical and geochemical techniques have been applied to improve understanding of eruptive activity at Mount St. Helens in 2004–6. Visual surveillance in volcanology, however, remains critical for providing "ground truth" necessary to confirm inferences drawn from geophysical and geochemical data.

Visual observations can be recorded by imaging systems on the ground or in an aircraft or spacecraft. For example, photogrammetric applications of aerial photography to volcanoes include quantification of large-scale deformation before the 1980 eruption of Mount St. Helens (Moore and Albee, 1981) and calculations of erupted volumes at Stromboli, Italy, in 2002–3 (Baldi and others, 2005) and at Mount St. Helens in 2004–6 (Schilling and others, this volume, chap. 8). Ground-based visual imagery is equally important for observing volcanic activity, having the advantages of low cost, frequent image acquisition, and flexibility in deployment. Starting in September 2004, we made extensive use of terrestrial cameras to investigate activity at Mount St. Helens using a continuously operating Webcam located 8 km north of the volcano and repeat photographs from a network of remote, telemetered digital cameras. The imagery was used to evaluate broad-scale eruptive activity in near real time, correlate geophysical signals with changes in eruptive activity, investigate dome extrusion processes, track the evolution of the eruption (including deformation of glacial ice) over time, and assess weather conditions for planning fieldwork.

We describe here the remote camera deployments and the activity recorded at Mount St. Helens during the period October 2004 to February 2006. Other types of camera deployments and applications at Mount St. Helens are described elsewhere in this volume. Results from high-rate, small field-of-view photography experiments designed to measure small-scale changes in dome extrusion are described by Dzurisin and others (this volume, chap. 14). Major and others (this volume, chap. 12) discuss quantitative dome-growth measurements

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using images from a single remote camera in combination with a digital elevation model.

Previous Uses of Visual Observation Systems to Monitor Active Volcanoes

Volcanology is fundamentally an observational science, and repeat observations from fixed locations have proven critical to the documentation and interpretation of many volcanic processes. During dome extrusion in 1902–5 at La Montagne Pelée, Martinique, Lacroix (1908) collected photographs from fixed vantage points to record the development of the dome over the course of the extrusive phase of the eruption. In 1944–45, Mimatsu Masao, the postmaster of the Sobetsu Post Office in Japan, lacked camera equipment but documented the growth of the Showa-Shinzan dome at the base of Mount Usu in a detailed diary and with careful sketches. His unique surveying methods included a fixed observation point behind the post office, from where he viewed the growing dome by resting his chin on a level and by using a series of horizontally stretched cords as reference lines. His drawings of the uplift and dome growth from this vantage point were presented at the 1948 International Association of Volcanology conference in Oslo, Norway, and what came to be known as “Mimatsu diagrams” were praised as “the only existing records of the entire birth of a volcano” (Mimatsu, 1995).

One of the best known volcano photographic sequences was taken by Gary Rosenquist at Mount St. Helens during the landslide and lateral blast of May 18, 1980. The Rosenquist photos, and similar sequences taken from other locations around the volcano at the start of the eruption, were critical to understanding the development of the landslide and lateral blast (Voight, 1981; Voight and others, 1981; Moore and Rice, 1984), lahar initiation (Pierson, 1985), pyroclastic stratigraphy (Criswell, 1987), and the question of whether or not the blast was a product of one or two explosions (Hoblitt, 2000). Fixed-vantage-point cameras from more than 100 repeat terrestrial photography and time-lapse film stations were also a key tool for studying dome building at Mount St. Helens during 1980–86 (Topinka, 1992).

The development of digital cameras has facilitated the use of visual observation systems at volcanoes. At Kīlauea Volcano, Hawai‘i, time-lapse digital cameras powered by solar panels and encased in weatherproof boxes now record details of volcanic events, including ground deformation, vent collapses, and surface breakouts of lava (Orr and Hoblitt, 2006). Repeat views from remote digital cameras have also been employed at Soufrière Hills volcano[4], Montserrat, where they provided important visual documentation of dome growth (Watts and others, 2002) and of the 2003 catastrophic dome collapse (Herd and others, 2005).

[4] Capitalization of “Volcano” indicates adoption of the word as part of the formal geographic name by the host country, as listed in the Geographic Names Information System, a database maintained by the U.S. Board on Geographic Names. Noncapitalized “volcano” is applied informally—eds.

Remote Camera Systems Used at Mount St. Helens

During October 2004 to February 2006, two types of remote camera systems were used for visually monitoring eruptive activity at Mount St. Helens—a Webcam and a network of remote, telemetered digital cameras. These systems are described below.

Webcam

A Webcam, herein referred to as the “VolcanoCam,” was installed in 1996 at the U.S. Department of Agriculture–Forest Service’s Johnston Ridge Observatory (JRO; fig. 1), 8 km north of Mount St. Helens (fig. 2*A*). At that time, the installation of the camera was more of an Internet novelty for the Gifford Pinchot National Forest (GPNF) and the Mount St. Helens National Volcanic Monument. The GPNF had just established one of the first Web sites within the Forest Service, and the addition of the VolcanoCam, they hoped, would provide a boost to forest recreation use by stimulating general interest in the area.

The VolcanoCam operated with minimal problems for 7 years until it suffered a mechanical failure in June 2003. Funding problems delayed replacement of the camera for more than a year. New equipment was finally procured and installed on September 23, 2004—coincidentally the day that seismic unrest began at Mount St. Helens. The new VolcanoCam was a color charge-coupled camera that provided a signal of 525 TV lines at 30 frames per second (terminology from the National Television System Committee standards). Still images were uploaded every five minutes to the Forest Service’s national Web server. The clock on the camera was not synchronized to Internet time and was probably only accurate to within about 1 minute.

Access to the camera was initially limited to Forest Service and USGS staff, but the VolcanoCam was opened for public access on September 27, 2004, and immediately became a major attraction (http://www.fs.fed.us/gpnf/volcanocams/msh/, last accessed January 28, 2008). The number of hits on the VolcanoCam Web site became so large that the main Forest Service Web server crashed several times, and excessive bandwidth use threatened the main U.S. Department of Agriculture Web servers. A Web caching system alleviated the most serious bandwidth concerns. Fourth-quarter 2004 statistics for all Federal government Web sites later revealed that the Forest Service enjoyed the largest quarterly increase in customer satisfaction ever recorded for a Federal government Web site, due mainly to the worldwide popularity of the VolcanoCam.

Despite its relative simplicity, the VolcanoCam was a remarkably useful educational resource and volcano-monitoring tool. Many of the thousands of emails received by the Forest Service in late 2004 regarding the VolcanoCam were from teachers across the United States, offering their thanks for the opportunity to view volcanic activity in their classrooms. In addition, the VolcanoCam proved to be a valuable tool for volcanologists, enabling rapid assessment of volcanic activity and weather conditions from any location having Internet access. The camera also demonstrated limited infrared capabilities. Nighttime observations were important for detecting magma extrusion and rockfall events, and they garnered substantial interest from the general public. An independent Web site managed by Mr. Darryl Luscombe even made available daily movies from sequential “glow” images collected during the previous night (http://www.luscombe-carter.com/index.html, last accessed January 28, 2008).

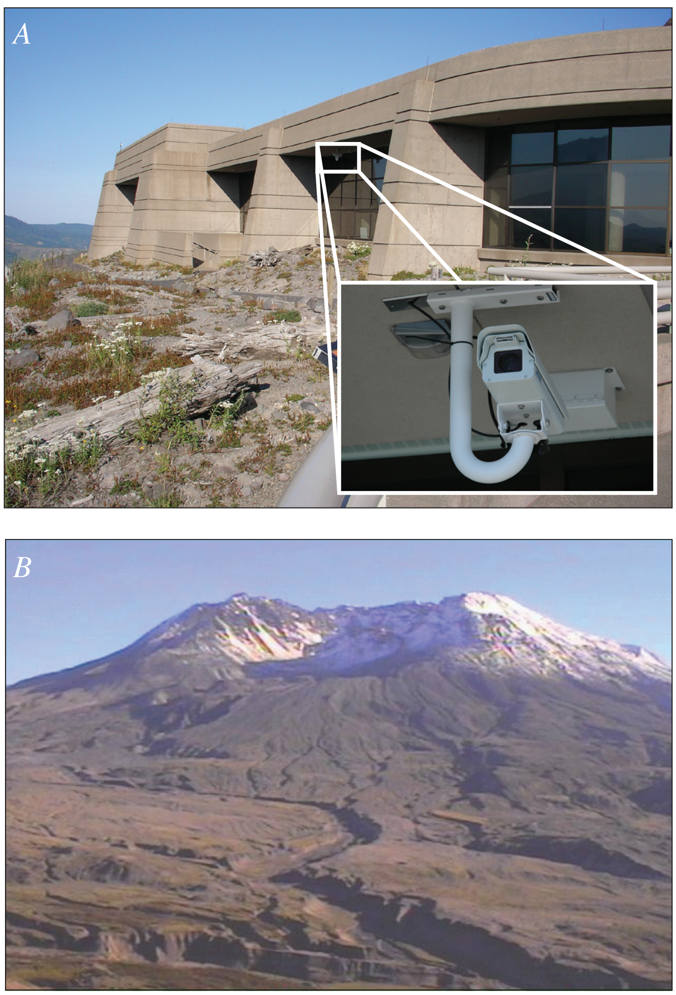

Figure 1. Field setting for U.S. Department of Agriculture Forest Service VolcanoCam at Mount St. Helens, Washington. *A*, Camera position beneath eave of Johnston Ridge Observatory. USGS photo by J.P. Griswold, August 25, 2006. Inset shows camera. USGS photo by S.P. Schilling. *B*, Example of VolcanoCam view of the volcano acquired on September 24, 2004.

Remote, Telemetered Digital Cameras

In early October 2004, the value of having a visual monitoring station close to the volcano became obvious because the VolcanoCam’s view of the locus of renewed activity was blocked by the 1980–86 lava dome. To meet this need, staff at the USGS Hawaiian Volcano Observatory constructed a remote, telemetered digital camera, based on models used at Soufrière Hills volcano, Montserrat (Herd and others, 2005), and sent it to the Cascades Volcano Observatory (CVO) for deployment at Mount St. Helens. The system included an Olympus C–3030 3.3-megapixel camera with a × 3 optical zoom lens. The camera was connected through a serial port to a 900-MHz radio mounted in a weatherproof box (fig. 3). The

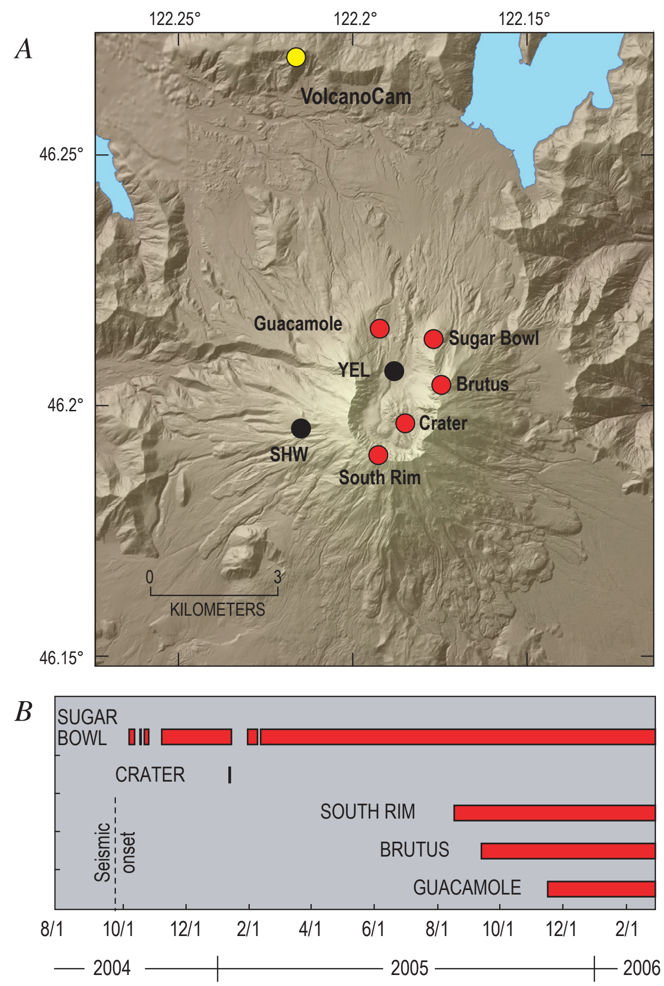

Figure 2. Remote, telemetered digital cameras used during monitoring of Mount St. Helens, Washington, 2004–6. *A*, Map showing locations of U.S. Geological Survey remote cameras (red dots) and U.S. Department of Agriculture Forest Service VolcanoCam (yellow dot). Black dots show locations of seismic stations that are referred to in figures 10 and 11. Hillshade-relief base map is from digital elevation model (DEM) of October 2005. *B*, Timeline with dates of operation (red bars) for remote, telemetered digital cameras through February 2006. Usable images were lacking on about half of all operating days, owing to inclement weather.

box was fastened to a tripod and pointed towards the deforming area in the southeast part of the crater (fig. 4). Power was supplied by a solar panel and batteries with enough capacity to ensure that the camera and radio would operate even during long periods of cloudy weather. Image resolution, zoom, and timing of acquisition were controlled from a computer located at the Forest Service's Coldwater Ridge Visitor Center, about 13 km northwest of the crater, using PhotoPC public domain software (http://www.lightner.net/lightner/bruce/photopc/ppc_use.html, last accessed January 28, 2008). Images were time stamped according to the camera time. The controlling computer could be reached via ftp from CVO through a satellite link, thereby providing access to imagery in near real time.

The remote camera was installed on October 10, 2004, on Sugar Bowl dome, immediately northeast of the breach in the 1980 crater wall and 2.3 km from the intensely deforming area, or welt (Dzurisin and others, this volume, chap. 14), in the southeast part of Mount St. Helens crater (fig. 2). The goals for the Sugar Bowl camera deployment were to (1) establish a visual record of volcanic activity, which could be used to test inferences drawn from geophysical, geological, and geochemical measurements, (2) monitor volcanic activity in near real time, and (3) provide a means of assessing general conditions in the volcano's crater to support field operations. Sugar Bowl offered a good view of the welt and subsequent dome growth (fig. 4*B*) from a point relatively safe from the mild explosive activity that characterized the early stages of the eruption.

A few problems resulted in a loss of imagery from the digital camera. Although high winds minimized snow accumulation, rime ice built up when temperatures were below freezing, obscuring the camera's view (fig. 5). The ice was removed manually during site visits, but it often persisted for weeks at a time when no field work was conducted. The system functioned well during the period October 2004 to February 2006, with only a few lapses in image acquisition (fig. 2*B*) caused by mechanical breakdowns and abrasion of the viewing window by blowing volcanic ash. When the camera was operating, cloudy or icy weather resulted in no usable imagery for approximately half of the total deployment time.

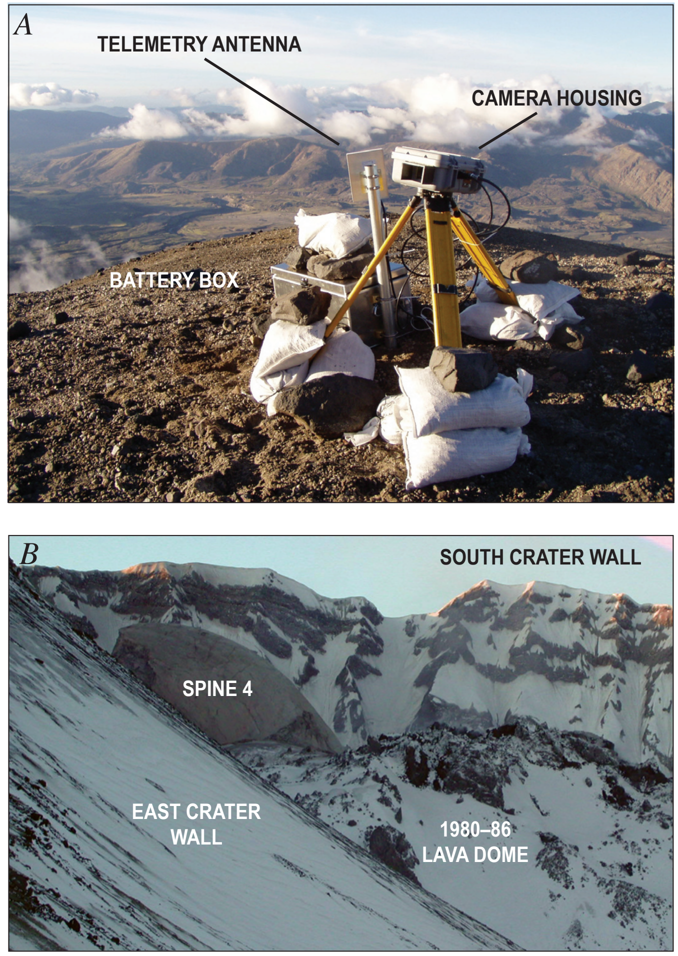

Figure 4. Setting and view for Sugar Bowl remote telemetered camera at Mount St. Helens, Washington. *A*, Field site atop Sugar Bowl dome, 2 km from active vent. Solar panel is out of view to the right. USGS photo by M.P. Poland, October 10, 2004. *B*, Example of camera view, acquired on February 10, 2005, showing spine 4.

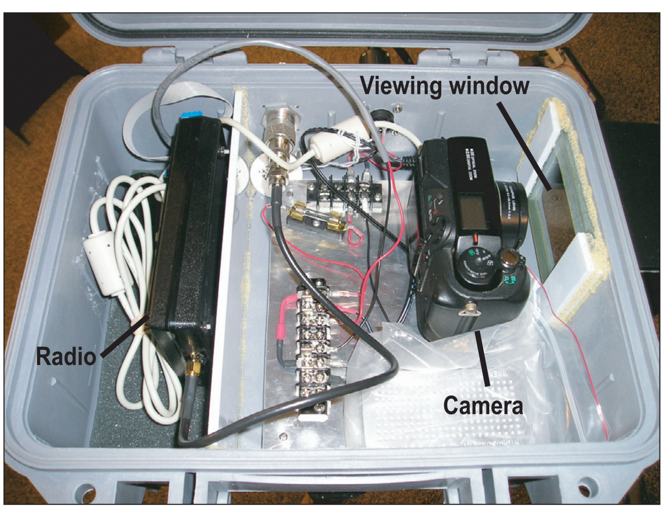

Figure 3. Interior of weatherproof box that contains camera and radio telemetry for Sugar Bowl remote, telemetered digital camera system. USGS photo by M.P. Poland, October 10, 2004.

The Sugar Bowl camera became an important tool in monitoring, research, and public outreach efforts, and it motivated the deployment of four additional instruments (Crater, Brutus, South Rim, and Guacamole; fig. 2) by the end of 2005. These new systems used similar equipment and software as the Sugar Bowl camera (fig. 6*A*). The Crater camera was installed by a helicopter sling operation within a few hundred meters of the growing dome on January 14, 2005. A location close to the dome was selected to provide close-up images that might be used to test dome-growth models (fig 6*B*). This camera suffered a mechanical failure several hours after it was put into place and was subsequently destroyed by a small explosion during the early morning of January 16, 2005. During the summer and fall of 2005, additional cameras were installed on the crater rim: Brutus (fig. 6*C*), 1.1 km east-northeast of the vent, and South Rim (fig. *6A, D*), 0.7 km southwest of the vent. As dome building focused in the southwestern part of the crater during late 2005, a camera was established on the floor of the breach in the 1980 crater: Guacamole (fig. 6*E*), 2.6 km north of the vent. Taken together, these camera systems provided a variety of different views of the growing lava dome.

Insights from Remote Camera Imagery

The remote cameras provided important, and sometimes unexpected, insights into volcanic activity at Mount St. Helens during 2004–2006. For example, the VolcanoCam confirmed that the extrusion of lava had begun in October 2004. Visual and infrared observations from a helicopter on October 11, 2004, noted a craggy, hot (maximum temperature of 580°C), rocky "fin," indicating that lava had reached the surface (Scott and others, this volume, chap. 1; Vallance and others, this volume, chap. 9). During the night of October 11 and the morning of October 12, the VolcanoCam showed signs of glow reflected off steam in the vicinity of the new spine, providing a valuable supplement to the earlier visual and infrared data and accessible to anyone with Internet access.

Both the VolcanoCam and the Sugar Bowl remote camera also had excellent views of explosive activity at Mount St. Helens. VolcanoCam photos posted to the Internet every five minutes provided useful, though approximate, constraints on the duration, magnitude, and timing of the early October 2004 explosions. Following that period, only two additional significant explosions occurred, on January 16 and March 8, 2005 (Scott and others, this volume, chap. 1; Moran and others, this volume, chap. 6). The January 16 explosion occurred shortly after 0300 Pacific standard time (PST, Greenwich mean time minus 8 hours) during a period of poor weather in the middle of the night and was not visible to either the VolcanoCam or Sugar Bowl systems. In contrast, the March 8 event took place at approximately 1725 PST during a time of clear weather (Scott and others, this volume, chap. 1; Moran and others, this volume, chap. 6). Analysis of Sugar Bowl imagery proved useful for the interpretation of seismic and acoustic data recorded during the event (Moran and others, this volume, chap. 6).

Figure 5. Rime-ice accumulation on Sugar Bowl telemetered digital camera at Mount St. Helens, Washington. Ice buildup was a common problem on camera systems during fall and winter months. USGS photo by S.P. Schilling, October 24, 2004.

Visual imagery from remote cameras was useful in the recognition and analysis of rockfall from the lava spines. Although background glow from the growing dome had been observed in VolcanoCam imagery starting on the night of October 11, 2004, brief, brighter flashes were noticed by Internet observers beginning on January 13, 2005 (such flashes probably occurred earlier than this date but were not observed because of either their low intensity or poor weather). These images prompted seismologists to review the overnight seismic records and led to the recognition that the flashes were associated with rockfall signals. A major VolcanoCam flash occurred at about 0303 PST on February 22, 2005, and was accompanied by a large seismic signal (fig. 7). Visual inspection by field crews on the following day recognized a new scar on the growing lava dome, confirming the occurrence of a large rockfall during the previous night.

Significant rockfall events during daylight hours were accompanied by bursts of ash that often drifted above the crater rim (Moran and others, this volume, chaps. 2 and 6). Combining imagery from the remote, telemetered digital cameras, which was available within minutes of acquisition, with real-time seismic data allowed for rapid recognition of the rockfall source. An example occurred on April 26, 2005, at approximately 1126 Pacific daylight time (PDT, Greenwich mean time minus 7 hours), when a part of spine 4 disintegrated, sending a small ash plume above the crater rim (fig. 8).

The volume of extruded lava at Mount St. Helens during 2004–2006 was calculated every 1–2 months by differencing digital elevation models (DEMs) derived from aerial photography or lidar data (Schilling and others, this volume, chap. 8). More frequent, but necessarily qualitative, estimates of the relative rate of lava extrusion could be made by examining time-lapse sequences acquired by the remote, telemetered digital cameras. For example, in December 2004, a marked decline in the release of seismic energy (Moran and others, this volume, chap. 2) suggested that the eruption was slowing. When a sequence of daily images from the Sugar Bowl remote camera was reviewed, however, it became clear that the overall rate of lava extrusion had not changed significantly across the lull in seismicity. The measurement of extrusion rates can be quantified by combining a DEM with the remote camera imagery, as demonstrated using data from the Sugar Bowl camera by Major and others (this volume, chap.

12). In an attempt to assess whether dome extrusion occurred smoothly or by a series of irregular surges correlative with seismicity, high-rate photography of a small field of view of patches on the growing lava dome was performed, but several factors limited the success of this experiment (Dzurisin and others, this volume, chap. 14).

Evolution of the Dome Complex Shown by Animations of Camera Imagery

Perhaps the most useful aspect of remote camera observations during 2004–6 at Mount St. Helens was the

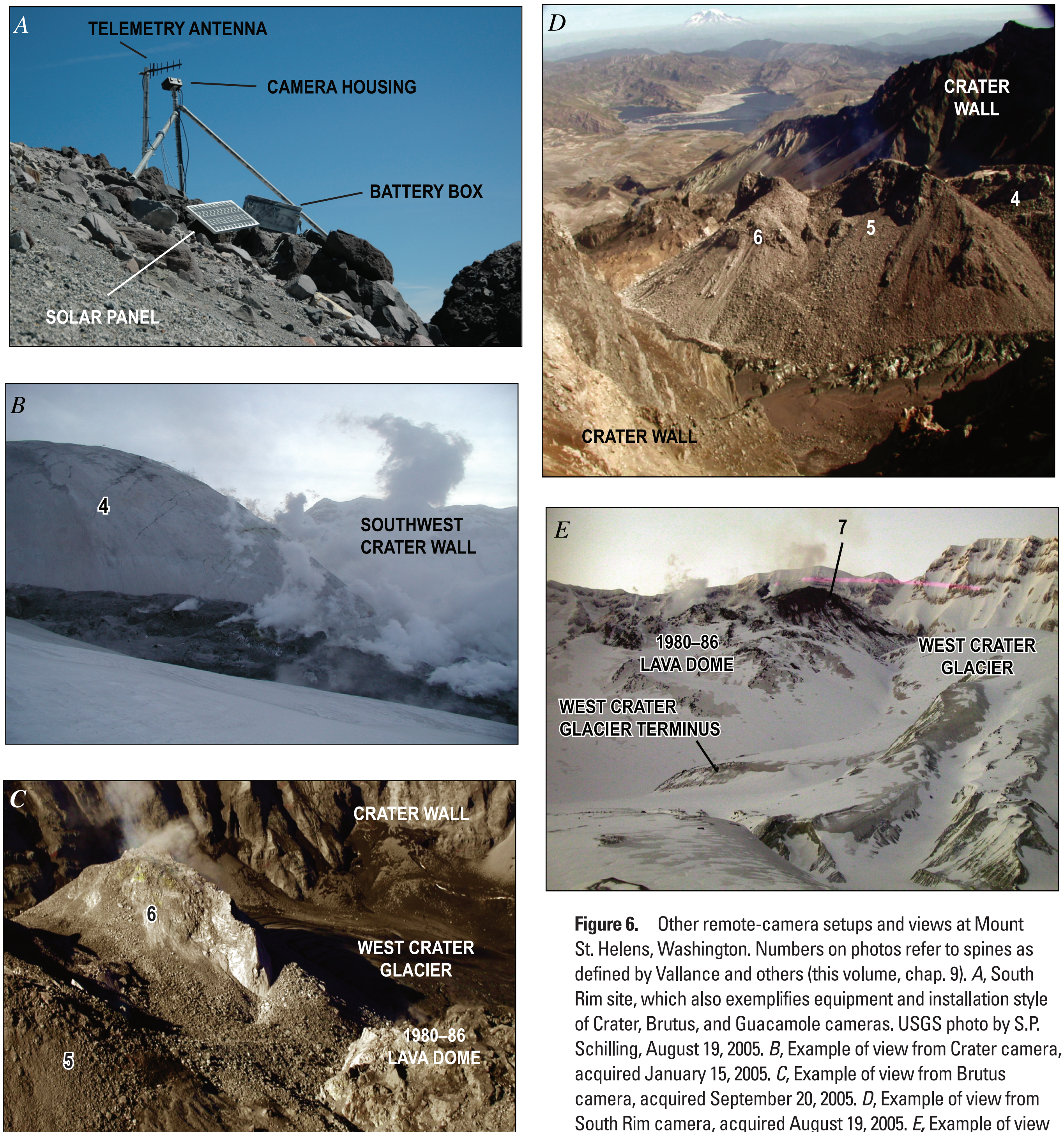

Figure 6. Other remote-camera setups and views at Mount St. Helens, Washington. Numbers on photos refer to spines as defined by Vallance and others (this volume, chap. 9). *A*, South Rim site, which also exemplifies equipment and installation style of Crater, Brutus, and Guacamole cameras. USGS photo by S.P. Schilling, August 19, 2005. *B*, Example of view from Crater camera, acquired January 15, 2005. *C*, Example of view from Brutus camera, acquired September 20, 2005. *D*, Example of view from South Rim camera, acquired August 19, 2005. *E*, Example of view from Guacamole camera, acquired February 24, 2006. Pink streak in middle of image is caused by sun damage to camera.

documentation of the lava dome complex's morphological evolution over time. During clear weather and rime ice-free conditions, and regardless of the presence of field personnel, the remote, telemetered cameras provided high-quality views of the volcano from common vantage points. Imagery was therefore directly comparable over time, and visualizing the changing morphology of the lava dome complex by animating images into time-lapse movies proved to be an important tool for monitoring and interpreting volcanic activity.

Time-lapse animations of images from the Sugar Bowl, Brutus, South Rim, and Guacamole remote camera are provided as supplementary digital data to this report (Major and others, this volume, chap. 12, appendix 1, found on the DVD accompanying the volume and on the Web version of the work). Below, we describe and interpret the time-lapse animations of dome growth at Mount St. Helens obtained from the remote, telemetered digital cameras during the period October 2004 to February 2006. This account relies heavily on the Sugar Bowl camera for observations during the first year of the eruption, when that was the only remote camera that had been deployed. The observations that follow are drawn solely from remote camera imagery and do not rely on other data. The account is not meant to supplant but rather to complement descriptions of dome growth derived from other types of observations and data that are contained elsewhere in this volume. The chronology of 2004–6 activity is reported in this volume by Scott and others (chap. 1), Schilling and others (chap. 8), Vallance and others (chap. 9), and Herriott and others (chap. 10). In addition, geophysical and geochemical time series from the eruption are summarized by Moran and others (chaps. 2 and 6), Lisowski and others, (chap. 15), LaHusen and others (chap. 16), Gerlach and others (chap. 26), and Pallister and others (chap. 30).

Between October 2004 and February 2006, dome growth at Mount St. Helens occurred through the extrusion of seven distinct spines (Scott and others, this volume, chap. 1; Vallance and others, this volume, chap. 9). Spines 1 and 2, formed in mid-October 2004, were the smallest of the extrusions, and they were active for the shortest periods of time. Owing to their location along the south margin of the 1980–86 lava dome, they were not visible to the Sugar Bowl camera or the VolcanoCam and were documented only by observations (including thermal imagery) from helicopter overflights. The growth of spines 3–7, however, was visible

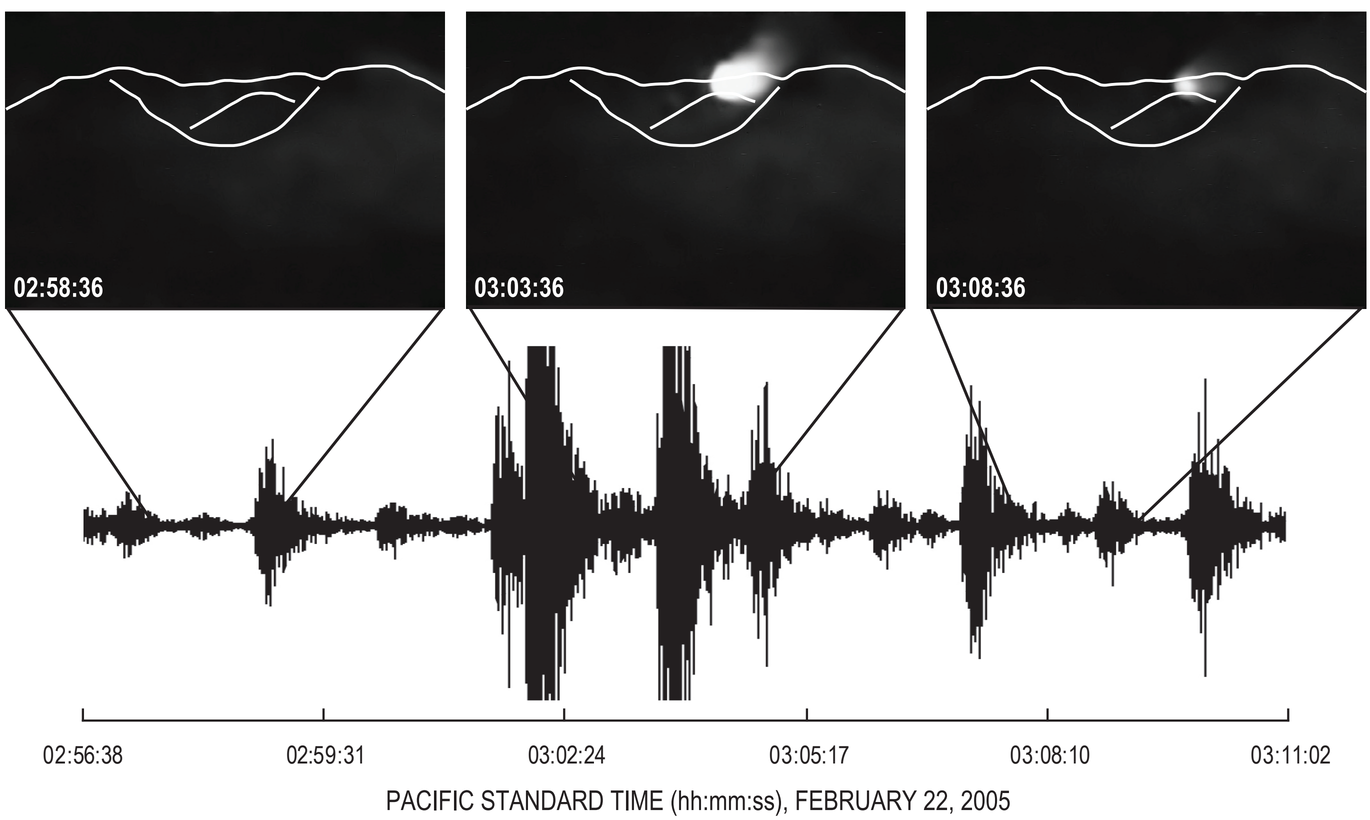

Figure 7. Use of nighttime images from the U.S. Department of Agriculture Forest Service VolcanoCam to track rockfalls at Mount St. Helens, Washington. Top, consecutive images from February 22, 2005 (PST), showing one of the largest rockfalls of that year. Bright patch is a reflection in steam clouds of incandescence created by the sudden exposure of hot material. Outline of Mount St. Helens and 1980–86 lava dome provided for context. VolcanoCam clock was not synchronized to Internet time, so it is probably only accurate to plus or minus 1 minute. Bottom, seismic record from station SHW (see fig. 2*A* for station location).

from the Sugar Bowl camera except for a brief interval during the growth of spine 6.

The Sugar Bowl camera was deployed after the welt had largely formed in the southeastern part of the crater. During the first week of image acquisition, the camera recorded growth of a small knob that protruded from the welt along the southeast margin of the 1980–86 lava dome. The knob disappeared during October 20–27, 2004, a period of inclement weather when no visual observations (either by remote camera or field personnel) were possible. Judging from oblique aerial photos, the bulge appeared to be crater-floor debris and ice that was pushed up and later collapsed during the initial stages of dome extrusion (J. Major, written commun., 2006).

Spine 3 first became apparent in Sugar Bowl camera imagery on October 29, 2004, when uplift of the welt accelerated rapidly. The spine continued to grow steadily towards the southeast until mid-December, when imagery from December 17 showed that cracks had formed along the north side of the extrusion. These cracks continued to develop throughout the remainder of the month, eventually leading to the formation of an independent spine of lava (spine 4). The breakup of spine 3 may have been caused when it impinged upon the

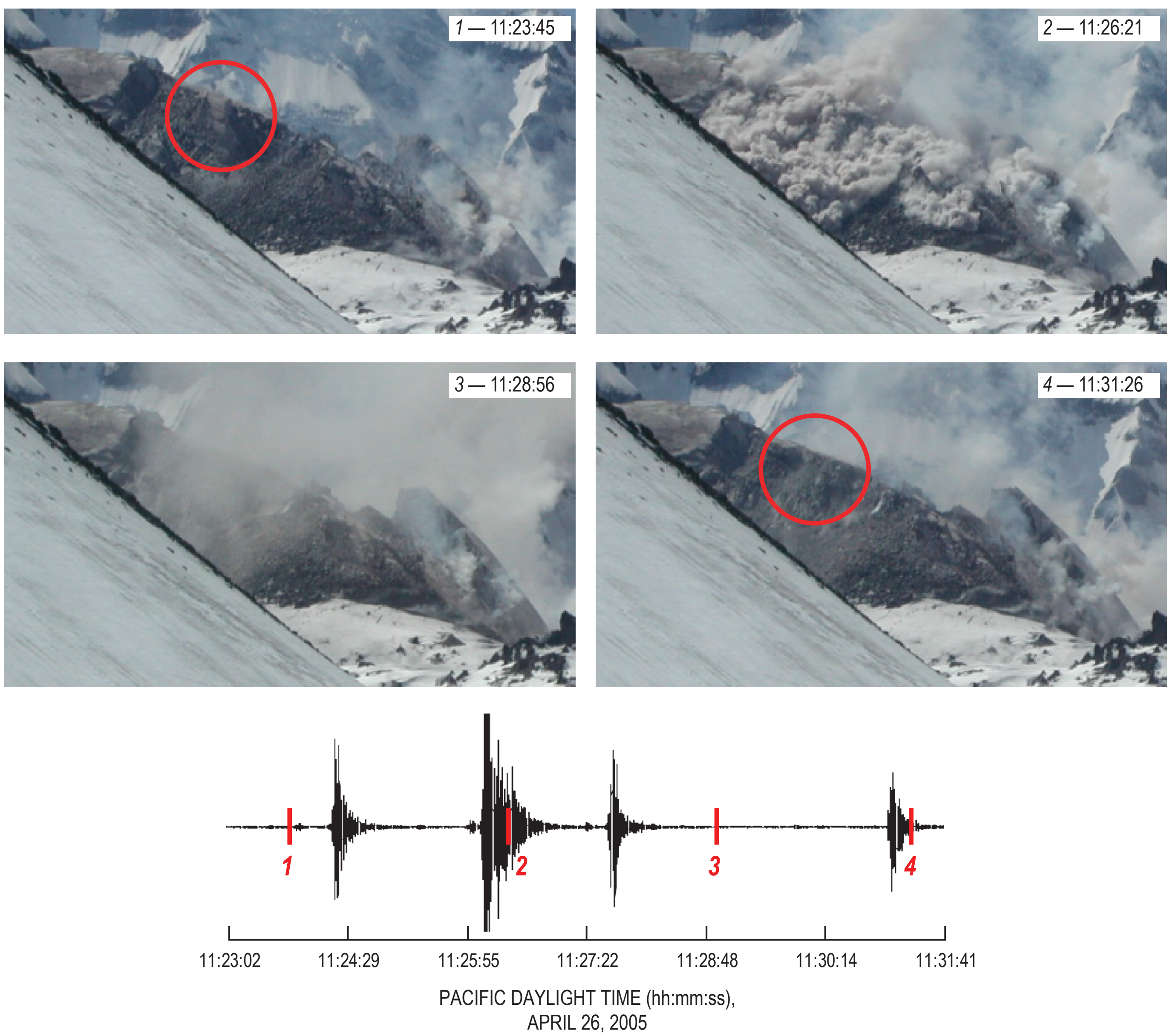

Figure 8. Seismic record from station YEL (bottom) and consecutive images from Sugar Bowl remote camera (top) for April 26, 2005 (PDT), showing major rockfall (source identified by red circle). See figure 2*A* for location of YEL.

southeastern crater wall (Vallance and others, this volume, chap. 9). The apparent extrusion velocity at the vent did not seem to change over this time period, judging from the photographic sequence from the Sugar Bowl camera and calculations of lineal extrusion rates (Major and others, this volume, chap. 12). If extrusion was constant, spine 3 was undergoing horizontal compression as lava continued to extrude from the vent, which probably caused it to fracture (Moran and others, this volume, chap. 2).

Spine 4, which was also characterized by dominantly southeastward motion, first rose to a higher altitude than spine 3, then began to override the latter in early January 2005. Sugar Bowl imagery suggests that the smooth surface of spine 4 began to fracture and disintegrate sometime between March 15 and April 13, 2005. A more definitive date is difficult to assign, because the view from Sugar Bowl was obscured by ice and clouds between those two dates, but field observations show that disintegration began about April 10 (Vallance and others, this volume, chap. 9). The increasingly fractured, but still coherent, spine continued to move to the southeast until April 24, 2005, by which time significant motion (that is, motion on the order of meters per day) had ceased and extrusive activity shifted from spine 4 to spine 5. Major and others (this volume, chap. 12) document this transition using quantitative lineal extrusion rates based on Sugar Bowl imagery.

The Sugar Bowl camera observed the initial formation of spine 5 between April 14 and 18, 2005, when upward motion and lineal extrusion rate (Major and others, this volume, chap. 12) of that spine became independent of spine 4. Spine 5 extruded at a steep angle (about 60°–70° from horizontal) from the vent and was subject to two cycles of construction and destruction during its life. Construction dominated until May 13, 2005, when a large part of the spine collapsed. Spine disintegration competed with extrusion to keep the spine at a relatively constant height from that time through June 4, 2005, when a second period dominated by construction began. By July 1, 2005, spine 5 had reached its highest altitude, although a period of more frequent collapses began around June 30, 2005. A few tens of meters of dome elevation were lost between July 1 and 3, 2005. Upward motion of spine 5 continued, but the highest altitude of the extrusion remained nearly constant between July 3 and 14, 2005, as collapses from the upper part of the spine compensated for the addition of new lava at its base. By July 15, 2005, destructive processes began to outpace spine construction, and the height of the spine decreased daily. Sugar Bowl imagery suggests that the second cycle of growth and destructive phases of spine 5 had mostly ceased by August 2, 2005.

The distinction between spines 5 and 6 is difficult to constrain, but Sugar Bowl images indicate that spine 6 was moving independently of spine 5 by August 1, 2005. Growth of spine 6 was mostly vertical until August 10, 2005, when it began to move to the west without increasing in height. Sugar Bowl imagery and lineal extrusion rates (Major and others, this volume, chap. 12) suggest an apparent acceleration in westward motion starting on about August 16, 2005, and the spine height began to decrease as large collapses destroyed its upper reaches. A consequence of the motion of spine 6 towards the west was the development of a depression between spine 6 and the mostly inactive spine 5. Continued extrusion to the west occurred throughout the remainder of August and September, with the spine's motion becoming almost completely horizontal. During this time period, the westernmost part of spine 5 gradually slumped into the growing depression, probably because it was left unsupported as spine 6 moved to the west (Vallance and others, this volume, chap. 9). Interestingly, unlike other spines, spine 6 apparently did not experience an extended period of collapse and destruction towards the end of its activity. This may have been a result of its relatively low height, compared to spines 3, 4, and 5.

Growth of spines 6 and 7 was well documented by the Brutus, South Rim, and Guacamole remote cameras, which were installed during late summer 2005. Sometime between September 28 and October 17, 2005 (a period of poor weather when few observations were possible), spine 6 gave way to spine 7, which grew out of the western side of the depression between spines 5 and 6. The direction of spine 7's motion was also toward the west but included a significant component of upward motion. As a result, spine 7 pushed and overrode spine 6, obscuring the distinction between the two extrusions. Although poor weather characterized much of late 2005 and early 2006, limited imagery indicates that spine 7 continued to grow into February 2006 with two cycles of alternating height increase (when the spine was gravitationally stable) and decrease (when the spine disintegrated gradually).

Time-lapse animation sequences from the remote, telemetered cameras reveal that spines 3 to 7 each experienced cycles of growth and destruction that lasted several months. The growth stages generally involved the extrusion of smooth-sided spines (with the exception of spine 6, which was mostly covered by rubble) with little accompanying large disintegration events. During destructive phases, spine extrusion continued, but abundant rockfall destroyed the smooth carapaces and resulted in highly fractured and blocky formations surrounded by talus. The onset of the destructive phase preceded the transition to a new spine in the cases of spines 3, 4, and 5. Spines 5 and 7 both experienced multiple constructive and destructive phases, perhaps related to their steeper extrusion angles. The "great spine" at La Montagne Pelée, Martinique, which was similar in appearance to the Mount St. Helens spines, also experienced multiple construction and destruction cycles during 1902–3, although the cycles appear to have been related to an unsteady, pulsing eruption rate (Jaupart and Allègre, 1991; Tanguy, 2004). At Mount St. Helens, lineal extrusion rates derived from Sugar Bowl imagery suggest that the eruption rate during the extrusion of spine 5 was nearly constant (Major and others, this volume, chap. 12); thus, alternating cycles of spine-height increase and erosion must have been controlled by other factors, for example, the strength of the dome carapace, thermal cooling, propagation of fractures, or gravitational stresses. Vallance and others (this volume, chap. 9) discuss the history and driving mechanisms of spine construction and destruction and the transitions between spines.

In addition to lava-dome processes and morphology, deformation of the Crater Glacier—which surrounded the 1980–86 lava dome on the east, west, and south before the onset of eruptive activity in 2004 (Schilling and others, 2004)—was recorded by several of the remote cameras. The Brutus camera's field of view included the contact between the western part of the dome complex and the west arm of the glacier. By the time the camera was installed in mid-September 2005, the west arm of Crater Glacier had already been extensively compressed, thickened, and fractured. The Brutus sequence of images showed continued thickening and cracking of glacial ice as spines 6 and 7 grew toward the west. A complementary perspective was provided by the Guacamole camera, which had a view of much of the glacier's west arm (including its terminus) and recorded glacier deformation from the time of its installation in mid-November 2005. Motion of the glacier's terminus occurred at an accelerated rate between January 23 and February 16, 2006, perhaps because of a downstream-moving bulge caused by compression of the glacier by spines 6 and 7 (Walder and others, this volume, chap. 13).

Strategies for Future Deployments of Remote Camera Systems

The bulk of the contributions from visual observation systems to monitoring efforts at Mount St. Helens in 2004–2006 are necessarily qualitative because of limitations in camera views and weather conditions. Images were generally used to support inferences drawn from geophysical and geological observations or to characterize transient events and long-term processes. As demonstrated by Major and others (this volume, chap. 12), however, quantitative measurements of surface change from single camera deployments are possible.

Future camera deployments at active volcanoes should take advantage of photogrammetric principles, which will allow for more detailed analyses of surface change. For example, oblique aerial photographs that include ground control points with known positions can be used to construct DEMs of the ground surface. The technique has been demonstrated in laboratory conditions (Cecchi and others, 2003), at small scales on active lava flows at Mount Etna (James and others, 2006), and at larger scales on an entire lava dome at Soufrière Hills volcano, Montserrat (Herd and others, 2005). Expanding the use of photogrammetry to terrestrial cameras can be accomplished by deploying a pair (or more) of remote, telemetered digital cameras with views that are separated by 30°–60° in azimuth from the target area and include several ground control points. A DEM of the areas viewed in common by a pair of cameras can then be constructed, and displacements, perhaps on the order of centimeters, may be calculated by differencing DEMs from different time periods. Although the principles involved in deriving such DEMs are not new, they have yet to be applied extensively using ground-based cameras. Terrestrial systems, although limited by weather conditions, offer the benefits of low cost, low power, flexibility, and high temporal and spatial measurement density. Dome-building eruptions characterized by steady topographic change over time, like the 2004–6 activity at Mount St. Helens, offer an excellent opportunity for developing terrestrial photogrammetric systems.

Conclusions

Remote camera systems have provided important information regarding volcanic activity at Mount St. Helens during 2004–6. A Webcam and a network of remote, telemetered digital cameras observed rockfalls, explosive activity, and the steady extrusion of lava on a nearly continuous basis, interrupted only by periods of inclement weather and infrequent mechanical failures. Time-lapse animations from the remote, telemetered digital cameras are outstanding records of lava dome emplacement that can be used to aid interpretations of volcanic activity and support education and outreach efforts.

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References Cited

Baldi, P., Fabris, M., Marsella, M., and Monticelli, R., 2005, Monitoring the morphological evolution of the Sciara del Fuoco during the 2002–2003 Stromboli eruption using multi-temporal photogrammetry: ISPRS Journal of Photogrammetry and Remote Sensing, v. 59, no. 4, p. 199–211.

Cecchi, E., van Wyk de Vries, B., Lavest, J.M., Harris, A., and Davies, M., 2003, N-view reconstruction; a new method for morphological modeling and deformation measurement in volcanology: Journal of Volcanology and Geothermal Research, v. 123, nos. 1–2, p. 181–201.

Criswell, C.W., 1987, Chronology and pyroclastic stratigraphy of the May 18, 1980, eruption of Mount St. Helens, Washington: Journal of Geophysical Research, v. 92, no. B10, p. 10237–10266.

Dzurisin, D., Lisowski, M., Poland, M.P., Sherrod, D.R., and LaHusen, R.G., 2008, Constraints and conundrums resulting from ground-deformation measurements made during the 2004–2005 dome-building eruption of Mount St. Helens, Washington, chap. 14 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Gerlach, T.M., McGee, K.A., and Doukas, M.P., 2008, Emission rates of CO_2, SO_2, and H_2S, scrubbing, and preeruption excess volatiles at Mount St. Helens, 2004–2005, chap. 26 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Herd, R.A., Edmonds, M., and Bass, V.A., 2005, Catastrophic lava dome failure at Soufrière Hills Volcano, Montserrat, 12–13 July 2003: Journal of Volcanology and Geothermal Research, v. 148, nos. 3–4, p. 234–252, doi:10.1016/j.jvolgeores.2005.05.003.

Herriott, T.M., Sherrod, D.R., Pallister, J.S., and Vallance, J.W., 2008, Photogeologic maps of the 2004–2005 Mount St. Helens eruption, chap. 10 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Hoblitt, R.P., 2000, Was the 18 May 1980 lateral blast at Mt. St. Helens the product of two explosions?: Philosophical Transactions of the Royal Society of London, Series A, v. 358, no. 1770, p. 1639–1661.

James, M.R., Robson, S., Pinkerton, H., and Ball, M., 2006, Oblique photogrammetry with visible and thermal images of active lava flows: Bulletin of Volcanology, v. 69, no. 1, p. 105–108.

Jaupart, C., and Allègre, C.J., 1991, Gas content, eruption rate, and instabilities of eruption regime in silicic volcanoes: Earth and Planetary Science Letters, v. 102, nos. 3–4, p. 413–429.

Lacroix, A., 1908, La Montagne Pelée apres ses eruptions: Paris, Académie des Sciences, 136 p.

LaHusen, R.G., Swinford, K.J., Logan, M., and Lisowski, M., 2008, Instrumentation in remote and dangerous settings; examples using data from GPS “spider” deployments during the 2004–2005 eruption of Mount St. Helens, Washington, chap. 16 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Lisowski, M., Dzurisin, D., Denlinger, R.P., and Iwatsubo, E.Y., 2008, Analysis of GPS-measured deformation associated with the 2004–2006 dome-building eruption of Mount St. Helens, Washington, chap. 15 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Major, J.J., Kingsbury, C.G., Poland, M.P., and LaHusen, R.G., 2008, Extrusion rate of the Mount St. Helens lava dome estimated from terrestrial imagery, November 2004–December 2005, chap. 12 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Mimatsu, M., 1995, Showa-Shinzan diary; complete records of observation of the process of the birth of Showa-Shinzan, expanded reprint [Oshima, M., translator]: Sapporo, Suda Seihan Co., 179 p.

Moore, J.G., and Albee, W.C., 1981, Topographic and structural changes, March–July 1980—photogrammetric data, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 123–141.

Moore, J.G., and Rice, C.R., 1984, Chronology and character of the May 18, 1980, explosive eruptions of Mount St. Helens, *in* Explosive volcanism; inception, evolution, and hazards: Washington D.C., National Academies Press, p. 133–142.

Moran, S.C., Malone, S.D., Qamar, A.I., Thelen, W.A., Wright, A.K., and Caplan-Auerbach, J., 2008a, Seismicity associated with renewed dome building at Mount St. Helens, 2004–2005, chap. 2 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Moran, S.C., McChesney, P.J., and Lockhart, A.B., 2008b, Seismicity and infrasound associated with explosions at Mount St. Helens, 2004–2005, chap. 6 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Orr, T., and Hoblitt, R.P., 2006, Monitoring Kilauea Volcano using non-telemetered time-lapse camera systems [abs.]: Eos (American Geophysical Union Transactions), v. 87, no. 52, Fall Meeting Supplement, Abstract G53A-0875.

Pallister, J.S., Thornber, C.R., Cashman, K.V., Clynne, M.A., Lowers, H.A., Mandeville, C.W., Brownfield, I.K., and Meeker, G.P., 2008, Petrology of the 2004–2006 Mount St. Helens lava dome—implications for magmatic plumbing and eruption triggering, chap. 30 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Pierson, T.C., 1985, Initiation and flow behavior of the 1980 Pine Creek and Muddy River lahars, Mount St. Helens, Washington: Geological Society of America Bulletin, v. 96, no. 8, p. 1056–1069.

Schilling, S.P., Carrara, P.E., Thompson, R.A., and Iwatsubo, E.Y., 2004, Posteruption glacier development within the crater of Mount St. Helens, Washington, USA: Quaternary Research, v. 61, no. 3, p. 325–329.

Schilling, S.P., Thompson, R.A., Messerich, J.A., and Iwatsubo, E.Y., 2008, Use of digital aerophotogrammetry to determine rates of lava dome growth, Mount St. Helens, Washington, 2004–2005, chap. 8 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Scott, W.E., Sherrod, D.R., and Gardner, C.A., 2008, Overview of the 2004 to 2006, and continuing, eruption of Mount St. Helens, Washington, chap. 1 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Tanguy, J.-C., 2004, Rapid dome growth at Montagne Pelée during the early stages of the 1902–1905 eruption; a reconstruction from Lacroix's data: Bulletin of Volcanology, v. 66, no. 7, p. 615–621, doi:10.1007/s00445-004-0344-z.

Topinka, L., 1992, Basic photography at Mount St. Helens and other Cascade volcanoes, *in* Ewert, J. and Swanson, D., eds., Monitoring volcanoes; techniques and strategies used by the staff of the Cascades Volcano Observatory, 1980–90: U.S. Geological Survey Bulletin 1966, p. 195–217.

Vallance, J.W., Schneider, D.J., and Schilling, S.P., 2008, Growth of the 2004–2006 lava-dome complex at Mount St. Helens, Washington, chap. 9 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Voight, B., 1981, Time scale for the first moments of the May 18 eruption, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 69–86.

Voight, B., Glicken, H., Janda, R.J., and Douglass, P.M., 1981, Catastrophic rockslide avalanche of May 18, *in* Lipman, P.W., and Mullineaux, D.R., eds., The 1980 eruptions of Mount St. Helens, Washington: U.S. Geological Survey Professional Paper 1250, p. 347–377.

Walder, J.S., Schilling, S.P., Vallance, J.W., and LaHusen, R.G., 2008, Effects of lava-dome growth on the Crater Glacier of Mount St. Helens, Washington, chap. 13 *of* Sherrod, D.R., Scott, W.E., and Stauffer, P.H., eds., A volcano rekindled; the renewed eruption of Mount St. Helens, 2004–2006: U.S. Geological Survey Professional Paper 1750 (this volume).

Watts, R.B., Herd, R.A., Sparks, R.S.J., and Young, S.R., 2002, Growth patterns and emplacement of the andesitic lava dome at Soufrière Hills Volcano, Montserrat, *in* Druitt, T.H., and Kokelaar, B.P., eds., The eruption of Soufrière Hills Volcano, Montserrat, from 1995–1999: Geological Society of London Memoir 21, p. 115–152.