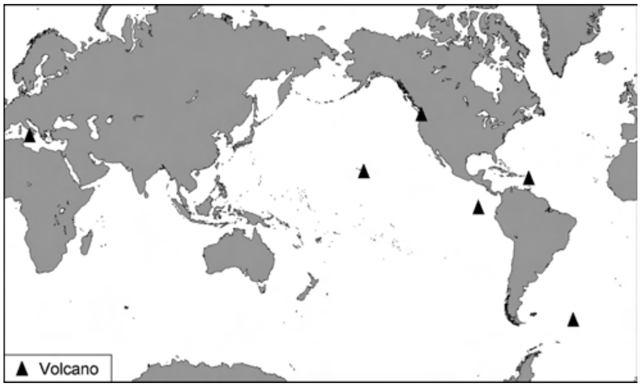
Bulletin of the Global Volcanism Network



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Editors: Rick Wunderman, Edward Venzke, and Gari Mayberry

Volunteer Staff: Robert Andrews, Jacquelyn Gluck, Susan Nasr, and William Henoch

Global Volcanism Program · National Museum of Natural History, Room E-421, PO Box 37012 · Washington, DC 20013-7012 · USA
Telephone: (202) 633-1800 · Fax: (202) 357-2476 · Email: gvn@volcano.si.edu · URL: http://www.volcano.si.edu/

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St. Helens

Washington, USA
46.20°N, 122.18°W; summit elev. 2,549 m
All time are local (= UTC - 8 hours)

After a hiatus of over 13 years, following phreatic eruptions during November 1990 to February 1991, a new eruption began in the crater at Mount St. Helens. Some shallow seismicity preceded the eruption, but this came only 9 days prior to the first ash emission. There was no progression of deep earthquakes propagating upward with time during the preceding months. Also apparently absent were other classical monitored parameters (deformation, gas emissions, geochemical or thermal anomalies) that could help foretell of an eruption several weeks or months ahead.

The eruption extruded a two-pyroxene, hornblende dacite of low vesicularity. The initial extrusions and uplift affected the S dome area and adjacent crater floor to the S. The intrusion included uplift and deformation of glacial ice, as well as some melting of ice, forming a small, short-lived bubbling lake (nicknamed 'the Jacuzzi') and a minor lahar out of the crater.

This report discusses the first 16 days of the eruption, from the first sign, shallow earthquakes, which began on 23 September 2004. This report was chiefly put together from reports posted by the Cascades Volcano Observatory (CVO), but also benefitted from personal communications with James Quick, Marianne Guffanti (both at USGS, Reston, Virginia), and James Vallance (USGS-CVO).

Synopsis. A photograph of the scene several weeks before the eruption came from climbers on the S rim. They visited during the last week of August 2004, a time when all still seemed quiet (figure 1). A chronology of events in the first 16 days (table 1) includes the dates and times of the events, the hazard status to people on the ground and to aviation traffic, and some brief comments on the seismicity and volcanism taking place.

The CVO website contains a complete discussion of the 3-level hazard-status scheme used there during this reporting interval. In brief form, the status rises from *1 – Notice*, to *2 – Advisory*, to *3 – Alert*. (These are short-hand for *Notice of Volcanic Unrest: Alert Level One*, *Volcano Advisory: Alert Level Two*, and *Volcano Alert: Alert Level Three*.) These respective levels of hazard status correspond to an informal color code, rising from green, to yellow, to red (shown in parentheses on table 1). A type of announcement, the *Information Statement*, discusses events that are unusual or short-lived, or both. On days 1-3, at the start of this crisis, a specific volcanic hazard was not specified.

Description of activity. At about 0200 on the morning of 23 September 2004, an earthquake swarm began at Mount St. Helens. Through 1700 hours on that date about 200 small (less than M 1) earthquakes had been located at the volcano, and many smaller events were recorded throughout the morning. The earthquakes occurred at shallow depths (less than 1 km) mostly under the lava dome that formed between 1980 and 1986.

Such earthquakes are common for the volcano. But a swarm with this many earthquakes has not been recorded for several years. The most recently case was on 3-4 November 2001.

By 25 September 2004 seismicity had declined significantly. However it remained elevated above background.

On 26 September the character of the swarm changed to include more than ten larger earthquakes (M 2-2.8), the most in a 24-hr period since the eruption of October 1986. Some of the earthquake types suggested pressurized fluids (water and steam) or perhaps magma. As a consequence, CVO and the University of Washington's Pacific Northwest Seismograph Network released the first *Notice of Volcanic Unrest* at this site in 18 years. The earthquakes occurred at shallow depths (less than 2 km) below the 1980-1986 lava dome.

On 27 September seismicity increased very slowly throughout the day. All earthquake locations were still shallow and beneath the dome. The largest earthquake recorded in the prior 24 hours was about M 1.5. Preliminary results from a gas flight late in the afternoon of 27 September did not indicate any magmatic gas.

Throughout the day of 28 September seismic activity remained at a fairly constant, but high rate of about two small (less than M 2) earthquakes per minute. All earthquake lo-

Day	Date	Hazard Status	Comment
DAY 1-3	23-25 Sep 2004	None posted	Swarm of small, shallow earthquakes (< M 1) began on morning of the 23rd, peaked mid-day on the 24th, then declined thru the afternoon of the 25th.
DAY 4	26 Sep 2004	1 – Notice (green)	Seismicity increased; ten M 2-2.8 events; volcanic unrest at 1500 hours. First Yellow alert since Oct. 1986.
DAY 7	29 Sep 2004	2 – Advisory (yellow)	Higher advisory issued at 1040 hours.
DAY 8	30 Sep 2004	2 – Advisory (yellow)	Deformation S of dome; fissures on ~ 200 m of ice.
DAY 9	01 Oct 2004	2 – Advisory (yellow)	Ash emission rose to 3 km altitude.
DAY 10	02 Oct 2004	3 – Alert (red)	Increased fumaroles, CO_2 and H_2S detected.
DAY 11	03 Oct 2004	3 – Alert (red)	Tremor episode; no eruptive plume. Continued detection of CO_2 and H_2S. Small steam and ash emission with plume to the crater rim. Temporary flight restriction within 9 km radius of summit.
DAY 12	04 Oct 2004	3 – Alert (red)	Large-scale glacial uplift. Steam and ash emission with plume to 3 km.
DAY 13	05 Oct 2004	3 – Alert (red)	Most vigorous ash/steam emission from both vent areas. Ash to 5 km.
DAY 14	06 Oct 2004	2 – Advisory (yellow)	Seismicity and tremor low.
DAY 15	07 Oct 2004	2 – Advisory (yellow)	Seismic activity low. Weak puffs of steam and a new vigorously erupting vent were observed.
DAY 16	08 Oct 2004	2 – Advisory (yellow)	Light seismic activity continued (1-2 events/hour; largest ~ M 1.5).

Table 1. A simplified chronology of the events at Mt. St. Helens from 23 September to 8 October 2004. Taken from material posted by the Cascades Volcano Observatory.

cations were still shallow and in or below the lava dome. That night seismic activity increased significantly. Throughout the day the seismicity remained elevated at 3-4 events per minute. A number of these events were between M 2 and 3. All earthquakes remained in or below the dome. By 30 September and 1 October the seismicity level had increased slightly, including events as large as M 3.3.

Around noon on 1 October a small 25-minute-long eruption occurred from a vent just S of the lava dome. The vent opened in a portion of the glacier that had become increasingly crevassed and uplifted over the past few days. The eruption sent a steam and minor ash plume to an altitude of about 3 km that drifted SW, accompanied by minor, local ashfall. Seismicity dropped several hours after the eruption, but gradually increased with earthquakes (maximum M 3) occurring 1- to 2-times per minute.

Figure 1. Photographs looking N from the crater rim at Mount St. Helens during clear, hot weather in the last week of August 2004. Much of the lower half of the top photo shows the S side of the 1980-1986 dome, the flat area arcing around it called the moat, and parts of the engulfing crater walls. In the upper half of the photo lie (from right to left) Spirit Lake, a large open area called the pumice plain, and some ridges, including the one directly across the pumice plain, Johnson Ridge. Glacial ice covers the moat and portions of the lower dome and lower crater walls. Debris from mass wasting covers parts of the glacier.The bottom photo is the same image with shading added by James Vallance to indicate the approximate locations of the extruding dome and the larger region of uplift. Those events took place between 27 September and the present, one to two months after this photograph, dramatically altering the surface morphology between the dome and the southern crater wall. Photo courtesy of Ivan Savov, taken on the S crater rim ~ 200 m W of the upper end of the Monitor Ridge trail.

A 40-minute steam-and-ash emission started on 2 October at 0943. Steam clouds carrying minor ash billowed out of the crater to an altitude of 3 to 4 km. The emission occurred during a time of gradually increasing seismicity, which dropped slightly after the emission, but continued to increase gradually through the afternoon. CVO's preliminary reports indicated that despite this increase, the event did not generate diagnostic earthquakes or explosion signals. Scientists inferred that hot rock was pushed up into the glacier, which then melted ice and generated the steam.

An interval of tremor lasting 50 minutes occurred immediately after a small steam emission at 1215 on 2 October. When the tremor stopped, the seismic character changed back to the earlier mode with shallow earthquakes under about maximum magnitude M 3 occurring 1- to 2-times per minute. Another period of smaller steam and ash bursts occurred between 1410 and 1440. Visual observations showed that the area of uplift, which includes part of the glacier and a nearby segment of the S flank of the lava dome, continued to rise. Part of the vent for the steam and ash emissions of the past few days was discovered to be covered by a boiling lake.

A gas flight on 3 October found slightly lower concentrations of carbon dioxide. On the other hand, for the first time hydrogen sulfide was detected. The 4 October gas flight detected carbon dioxide, often in association with hydrogen sulfide and occasional sulphur dioxide.

On 5 October at 0943 a 30-minute-long steam-and-ash emission started, and at 1410 a 10-minute-long steam-and-ash emission began. Ashfall on roads SE of the volcano achieved a maximum thickness of 0.2 mm at 8 km from the source. Neither emissions generated diagnostic earthquakes or explosion signals. As on 4 October, steam and ash emissions were associated with sightings of a bubbling lake. After the 4 October emissions, earthquake energy slowly increased to previous high values.

On 5 October continued uplift included part of the glacier and a nearby segment of the dome's S flank. Cracks opened in the dome. Portions of the cracks reached temperatures of 40-50°C (above ambient temperatures at the dome and glacier's surface, but far below the minimum magmatic temperature of ~ 800°C). Rocks avalanched off the dome, falling into the lake and onto the S crater floor. The dome's N flank appeared thermally stable.

The most vigorous steam and ash emission of the reporting period began on 5 October amid an interval with high seismicity shortly after 0900. Steam clouds billowed from the crater for over an hour, with variable ash content. For the first time, the ash content was sufficient to be detected by National Weather Service Doppler Radar. Steam and ash clouds reached about 3 km high and drifted NNE. A light dusting of ash fell in Morton, Randle, and Packwood, Washington, towns about 50 km from the volcano. Seismicity dropped during the emission and stayed relatively low the next day.

On 6 October the low-level tremor observed following the eruption gradually declined. Brief crater observations from Coldwater Visitor Center noted weak steam emissions. Small lahars from the crater traveled N onto the pumice plain during a rainstorm in the early morning of 6 October. Lahars flowed a short distance toward both Spirit Lake and the North Fork of the Toutle river.

The GPS station on the dome's N flank showed a trend of northward displacement totaling 2 cm over the last three days. This is the same sense of movement recorded by the nearby station that was destroyed by the first steam-and-ash emission on 1 October. In contrast, GPS instruments on the outer flanks of the volcano showed no movement.

Additional analysis based on lidar (LIght Detection And Ranging) and photographs of the intensely uplifting area suggested that the total volume change represented by the deformation between late September and 6 October was about 16-20 million cubic meters. The average rate of change was about 2 million cubic meters per day. If this value represents the rate of intrusion of magma into shallow levels of the dome and underlying crater floor, or both, it was an intrusion rate about twice that measured during dome-building eruptions at Mount St. Helens in the 1980s.

The 7 October report noted that a new steam vent opened overnight to join the two that had been present for several days. Steaming from the vents generated a cloud that rose above the lava dome's S side and extended toward the crater rim. Seismic activity was low to moderate with earthquakes of M 1 to 2 occurring about once per minute. Seismicity increased slightly during 7 October. Earthquakes up to M 1 occurred at a rate of ~ 1-1.5 per minute.

Reports issued on 8 October noted seismic activity continued to be low to moderate. Earthquakes occurred at a rate of 1 to 2 per minute with the largest magnitudes about M 1.5. That day field crews reported that there had not been noticeable additional uplift of the S part of the dome and adjacent glacier in the past 24 hours. Measurements from the recent photographs and lidar showed that the intensely deformed and uplifted area on the S side of the lava dome was then about 400 m (N-S) x 500 m (E-W) with a maximum uplift of about 100-130 m.

Seismicity rose gradually for most of 8 October and leveled off overnight. Earthquakes of M 2.4 occurred about once every two minutes. During 10 October seismicity decreased slightly, to levels similar to those observed during the evening hours of 7 October. Earthquakes of 1.0 M or less continued to occur at a rate of about 1 per minute, but most had magnitudes of M 1.0 or less.

On 12 October seismicity remained low. Small earthquakes (maximum about M 1) continued to occur every 5-10 minutes. Thermal imaging around 12 October of the W part of the uplifting area revealed temperatures of 500-600°C, by far the highest yet reported. They were greatest on a large pinkish-gray fin of rock and in nearby fumaroles and cracks. These observations were consistent with new lava having reached the ground surface. Later sampling of adjacent fresh talus using a metal trash can on a line below a helicopter confirmed it's dacitic composition.

Aviation advisories. The Washington VAAC issued advisories beginning on 29 October. Between then and through 8 October, they issued 23 Volcanic Ash Advisories. Some of these were also 'volcano watches.' Most of these were cautionary in nature, and actual plumes were generally minor, frequently steam dominated rather than heavily ash laden.

Background. Prior to 1980, Mount St. Helens formed a conical, youthful volcano sometimes known as the Fuji-san of America. During the 1980 eruption the upper 400 m of the summit was removed by slope failure, leaving a 2 x 3.5 km horseshoe-shaped crater now partially filled by a lava dome. Mount St. Helens was formed during nine eruptive periods beginning about 40,000-50,000 years ago, and has been the most active volcano in the Cascade Range during the Holocene. Prior to 2,200 years ago, tephra, lava domes, and pyroclastic flows were erupted, forming the older St. Helens edifice, but few lava flows extended beyond the base of the volcano. The modern edifice was constructed during the last 2,200 years, when the volcano produced basaltic as well as andesitic and dacitic products from summit and flank vents. Historical eruptions in the 19th century witnessed by early settlers, originated from the Goat Rocks area on the N flank.

Information Contacts: *Cascades Volcano Observatory (USGS/CVO)*, U.S. Geological Survey, 1300 SE Cardinal Court, Building 10, Suite 100, Vancouver, WA 98683-9589, USA (URL: http://vulcan.wr.usgs.gov/; Email: GS-CVO-WEB@usgs.gov); *Pacific Northwest Seismograph Network (PNSN)*, Seismology Lab, University of Washington, Department of Earth and Space Sciences, Box 351310, Seattle, WA 98195-1310, USA (URL: http://www.pnsn.org/; Email: seis_info@ess.washington.edu); *Ivan Savov*, Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560-0119, USA; *Washington Volcanic Ash Advisory Center (VAAC)*, Satellite Analysis Branch (SAB), NOAA/NESDIS E/SP23, NOAA Science Center Room 401, 5200 Auth Rd., Camp Springs, MD 20746, USA (URL: http://www.ssd.noaa.gov/).

Kilauea

Hawaii, USA
19.425°N, 155.292°W; summit elev. 1,222 m
All times are local (= UTC - 10 hours)

Scientists at the Hawaiian Volcano Observatory (HVO) noted that throughout June and July 2004, lava from Kilauea continued to enter the ocean at several points, culminating in several new lava deltas. Some small littoral explosions were reported, but otherwise the ocean entry was passive. Many small lava flows were observed in the area of the ocean entries, on the coastal flat, in the Paliuli area, and in the Kuhio area. Incandescence and some minor spattering was observed at Pu`u `O`o throughout the week. On 13 June, two collapses occurred at Kilauea's western lava delta, sending sizable chunks of the delta into the sea.

On 14 June, most lava was being supplied to the ocean through lava tubes, but several surface lava flows were visible on the delta and traveling down the old sea cliff behind the Wilipe`a delta. The larger eastern lava delta had several active lava entries into the ocean, mostly larger than those on the western delta. Seismicity at Pu`u `O`o was moderate to high, but the overall seismicity at Kilauea was low. Several episodes of inflation and deflation were recorded. Relatively large deflation events occurred on 29 June and 11 July, with no obvious accompanying changes in eruptive activity. An episode of deformation consisting of deflation, inflation, then deflation began at Kilauea on the morning of 27 July. It was accompanied by increased surface activity at several places. During inflation, seismicity greatly increased below Kilauea's caldera. Field observers reported that deformation may have occurred at the S flank of Pu`u `O`o. Aside from the deflation-inflation-deflation event, seismicity was weak beneath Kilauea's summit and tremor at Pu`u `O`o was at moderate-to-high levels.

During August and September 2004, no lava entered the sea. Surface lava flows were active on the coastal flat and the Pulama pali fault scarp, and the vents in the crater of Pu`u `O`o were incandescent. Seismicity was weak beneath Kilauea's summit and tremor was at moderate-to-high levels at Pu`u `O`o. In addition, there were small periods of inflation and deflation. HVO scientists reported that all vents in Pu`u `O`o's crater were incandescent during parts of both August and September.

From 30 September to 18 October 2004, patches of incandescence were visible at the PKK lava flow on the Pulama pali scarp, and all vents in the crater of Pu`u `O`o were incandescent. Seismicity was weak at Kilauea's summit, with essentially no tremor recorded. An M 4.0 earthquake occurred on 11 October. It was focused ~ 32 km beneath Kilauea's summit and affected tilt meters. Taking earthquake- and rainfall-induced tilts into account, the volcanic tilt was minor. On 13 October 2004 an M 4.5 earthquake occurred at 1318 ~ 6 km S of Pu`u `O`o at a depth of ~ 9 km. The earthquake permanently offset the Pu`u `O`o tiltmeter and several others on the volcano. Tremor was moderate at Pu`u `O`o. In addition, small amounts of inflation and deflation occurred.

On the morning of 24 October 2004 HVO scientists noted activity at that the three arms of the PKK flow (the Kuhio flow, named for Prince Kuhio Kalaniana`ole). Largest and most vigorous, the W arm descended down to an elevation of ~ 200 m, well out onto the gentle slope below Pulama pali. A series of channels and incandescent fingers were visible along a 600-m-long stretch, and tiny spots marked the upstream course of the arm, roughly following the E side of the Mother's Day flow.

The middle arm had advanced 100-200 m since the previous morning (23 October) and reached down to an elevation of ~ 335 m. It was the smallest of the three active arms.

The E arm was quite active that morning, its front also located on the gentle slope below Pulama pali at ~ 300 m elevation; it was nearly continuously incandescent up to ~ 440 m elevation. The distance between the W and middle arms was about 400 m and between the middle and E arms, about 600 m. These distances changed constantly as flows widen and narrow. Figures 2 and 3 show lava flows since 1983 to aid the reader in locating features discussed in this *Bulletin* report.

Moderately bright glow came from the 640- to 670-m elevations farther upstream in the PKK flow. All vents in Pu`u `O`o's crater were incandescent on 24 October, creating a glow visible from several distant places. Seismicity

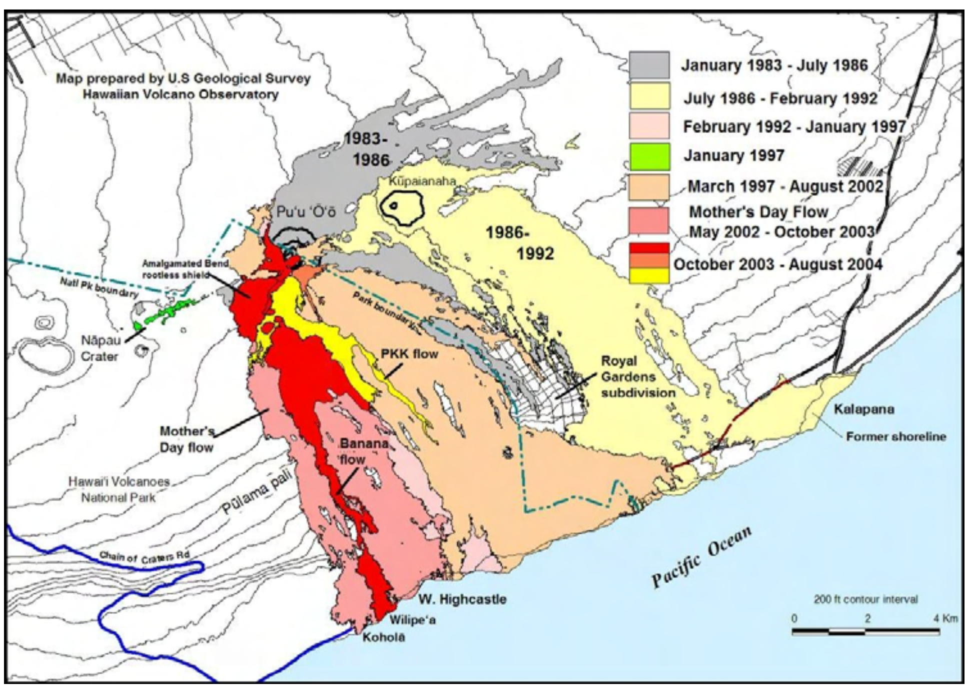

Figure 2. Map of lava flows from Pu`u `O`o and Kupaianaha from 1983 to 24 August 2004. Features shown include the Mother's Day flow field, which began erupting on 12 May 2002 and continues to the present. Lava flows erupted during November 2003-24 August 2004 include the Banana flow, which developed gradually starting in the middle of April. The MLK flow, located just S of the Pu`u `O`o vent, erupted in January and, in brief subsequent spurts. The Kuhio (PKK) flow was active most of the time from 20 March to 24 August 2004. As of 24 August, most activity was located in the Banana flow, fed by the Banana branch of the Mother's Day tube. The PKK flow also remained active. Courtesy of U.S. Geological Survey Hawaiian Volcano Observatory.

was weak at Kilauea's summit, with essentially no tremor recorded. Tremor was moderate at Pu`u `O`o. Kilauea's summit deflated moderately during 23 October and then took a plunge during the middle of the night. It lost about 0. 3 microradians before the plunge began just before midnight, and it lost another 0.5 microradians thereafter. Pu`u `O`o, too, was deflating rapidly, shifting up and down a little but maintaining an overall flat tilt until the plunge began. It also lost about 0.5 microradians after midnight.

Background. Kilauea volcano, which overlaps the E flank of the massive Mauna Loa shield volcano, has been Hawaii's most active volcano during historical time. Eruptions of Kilauea are prominent in Polynesian legends; written documentation extending back to only 1820 records frequent summit and flank lava flow eruptions that were interspersed with periods of long-term lava lake activity that lasted until 1924 at Halemaumau crater, within the summit caldera. The 3 x 5 km caldera was formed in several stages about 1,500 years ago and during the 18th century; eruptions have also originated from the lengthy E and SW rift zones, which extend to the sea on both sides of the volcano. About 90% of the surface of the basaltic shield volcano is formed of lava flows less than about 1100 years old; 70% of the volcano's surface is younger than 600 years. A long-term eruption from the E rift zone that began in 1983 has produced lava flows covering more than 100 sq km, destroying nearly 200 houses and adding new coastline to the island.

Information Contact: *Hawaiian Volcano Observatory (HVO)*, U.S. Geological Survey, Hawaii Volcanoes National Park, P.O. Box 51, Hilo, HI 96718, USA (URL: http://hvo.wr.usgs.gov/; Email: hvo-info@hvomail.wr.usgs.gov).

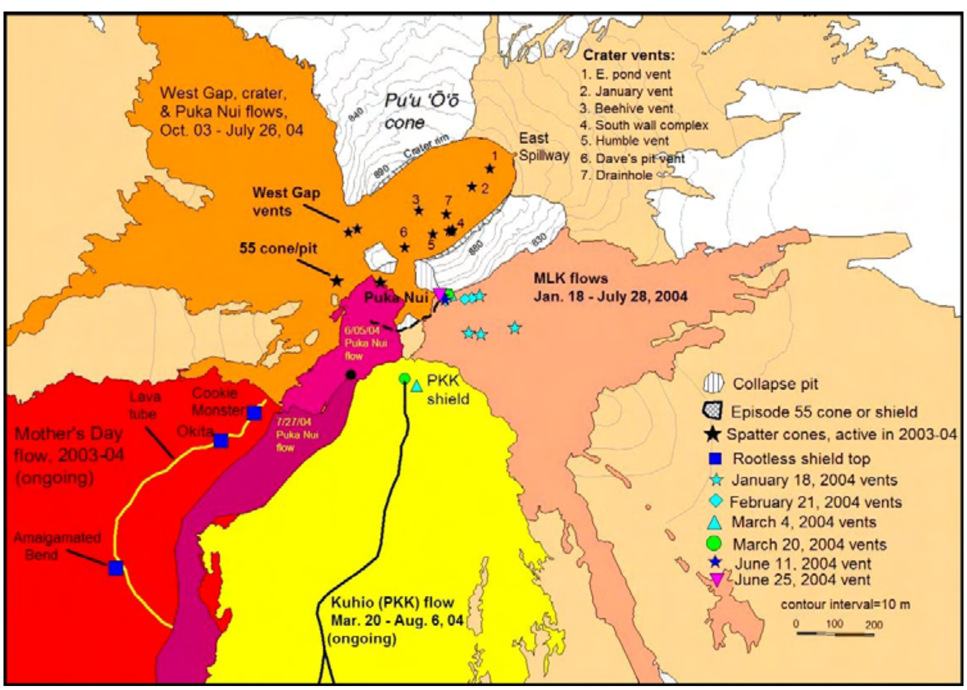

Figure 3. Map of Pu`u `O`o and vicinity as of 24 August 2004 showing vents, lava flows, and other features near Pu`u `O`o. The West Gap cones are just outside the boundary of the crater—the oval-shaped depression containing the seven numbered vents (now down to six after Humble Vent was buried by lava flows erupted from Dave's Pit/Vent in March). The Mother's Day flows in the lower left have been erupted since 12 May 2002. Other flow areas are labeled accordingly with names and dates of activity. Light shading indicates episode-55 flows erupted between March 1997 and August 2002. Courtesy of U.S. Geological Survey, Hawaiian Volcano Observatory.

Mauna Loa

Hawaii, USA
19.475°N, 155.608°W; summit elev. 4,170 m

After a swarm of deep earthquakes centered just S of Mauna Loa's summit caldera in late April 2002, seismicity remained barely elevated until July 2004. In other words, seismicity during late April 2002-July 2004 stood far lower than it did in the months prior to the 1975 and 1984 eruptions.

Starting in July 2004, a swarm of small (M < 3), deep (> 40 km), mostly long-period (LP) earthquakes occurred just S of the caldera and adjacent areas. Neither the depth nor the magnitude of the earthquakes changed significantly. Through 13 October 2004 more than 730 related earthquakes occurred beneath the summit caldera and the adjacent part of the SW rift zone.

The location and magnitude of earthquakes making up the recent swarm (seismicity from 24 April-15 October 2004, a 6-month interval) are shown in figure 4. Such a concentration of deep LP earthquakes from this part of Mauna Loa was unprecedented in the modern earthquake record dating back to the 1960s. In contrast, more typical seismicity over a 6-month period at Mauna Loa is shown in a figure in a previous issue of the *Bulletin* (v. 27, no. 9). By comparison to the interval 24 April-15 October 2004, earthquakes in a typical 6 month interval are relatively sparse.

Inflation continued at the summit through the start of the earthquake swarm. In late August 2004, however, distances across the summit caldera began to contract significantly, apparently caused by the center of inflation shifting slightly to the S, rather than by deflation. This was the first contraction since inflation started in late April or early May 2002. Toward the end of September, the contraction ended and the line once again began to lengthen. During 2004, the inflation had been at a fairly steady to slightly increasing rate until the contraction in late August. When present, the lengthening, uplift, and tilting were taken to indicate swelling of the magma reservoir within the volcano.

Background. Massive Mauna Loa shield volcano rises almost 9 km above the sea floor to form the world's largest active volcano. Flank eruptions are predominately from the lengthy NE and SW rift zones, and the summit is cut by the Mokuaweoweo caldera, which sits within an older and larger 6 x 8 km caldera. Two of the youngest large debris avalanches documented in Hawaii traveled nearly 100 km from Mauna Loa; the second of the Alika avalanches was emplaced about 105,000 years ago (Moore

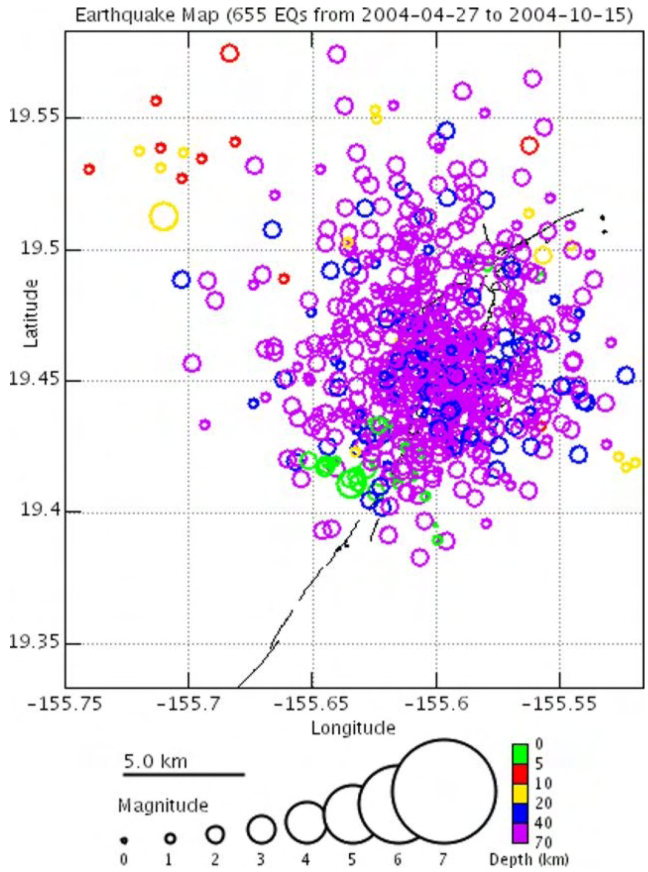

Figure 4. Seismicity for Mauna Loa for the 6-month period 24 April-15 October 2004. Courtesy of the U.S. Geological Survey, Hawaiian Volcano Observatory.

et al. 1989). Almost 90% of the surface of the basaltic shield volcano is covered by lavas less than 4000 years old (Lockwood and Lipman, 1987). During a 750-year eruptive period beginning about 1500 years ago, a series of voluminous overflows from a summit lava lake covered about one fourth of the volcano's surface. The ensuing 750-year period, from shortly after the formation of Mokuaweoweo caldera until the present, covered an additional quarter of the volcano with lava flows predominately from summit and NW rift zone vents.

Information Contact: *HVO* (see Kilauea).

Soufriére Hills

Montserrat, West Indies
16.72°N, 62.18°W; summit elev. 915 m
All times are local (= UTC - 4 hours)

According to reports issued by the Montserrat Volcano Observatory (MVO), activity at Soufriére Hills volcano remained low during 21 May-10 September 2004, becoming slightly elevated from 10 September-15 October 2004. Minor events during this period included mudflows, rockfalls, and several small, shallow earthquakes originating at upper regions of the lava dome and conduit.

On 21 May 2004, heavy rainfall caused large mudflows for about two hours (1420 to 1636). The mudflows traveled into the Belham Valley, an area within the exclusion zone on the volcano's NW side, flooding the entire width of the valley floor at Belham bridge. Scientists from MVO noted that at the peak of flow, standing waves of mud reached 2 m high. Intense rains on 25 July, 14 September, and 16 September again caused up-slope erosion and mudflows descended into the Belham Valley.

Surface water from the intense rain of 21 May percolated into the subsurface of the hot dome and vent complex, converting into steam. Steam venting may have initiated the 44 mixed earthquakes recorded the week of 21-28 May (table 2). The earthquakes were short in duration (~ 30 seconds each), and their amplitude decay characteristics suggested that they originated at shallow depths within the remnant dome and at the top of the conduit. The term 'remnant dome' refers to the fact that the late May 2004 dome was considerably reduced in size compared to the dome of about a year before, in large part because of major collapse events on 12 July 2003 and 3 March 2004.

During 18-25 June, winds blew the volcanic plume NE, and the clouds over the volcano's summit lifted, making the tallest remnants of the dome complex visible for the first time since 7 May. Observers noted a loss of material from the upper regions of the dome due to rockfalls.

Later, on 30 August, MVO personnel on an observation flight discovered a small brown pond within the dome complex (figure 5). This pond was the first seen on the volcano since the beginning of its eruption in 1995. The pond lies in a small crater formed by an explosion and dome collapse on 3 March 2004 (figure 5). It probably developed following the cooling of deposits within the crater, and after recent heavy rainfall.

Sulfur dioxide (SO_2) emissions typically remained low throughout the period. Measured fluxes ranged between about 90 and 1,100 metric tons per day (table 3). Moderate fluctuations occurred during 21-24 May (225-922 metric tons/day) and 7-11 June (169-788 metric tons/day). During 2-9 July, SO_2 emissions dropped to the lowest levels since the collapse event of 12-13 July 2003, and fell even lower during the weeks of 30 July and 17 September.

Measurements of expansion made by dilatometers embedded on either side of the Soufriere Hills edifice suggested that in July, the volcano changed from contraction to slight expansion.

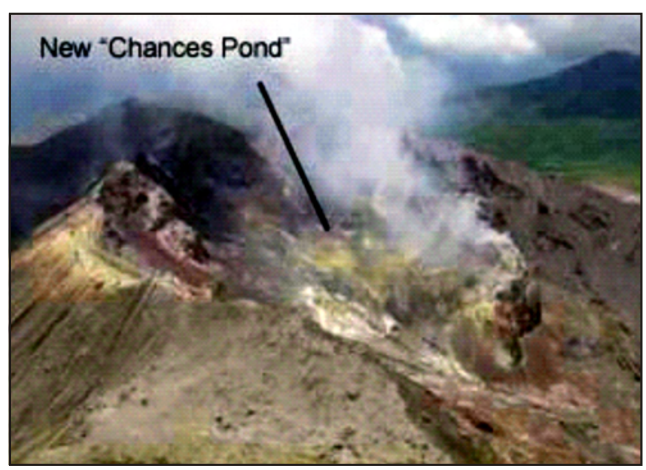

Figure 5. A view looking NW into English's crater during the week of 27 August 2004. Water collected in an explosion pit formed on 3 March 2004. The small brown water body became known as 'Chances pond.' Photo courtesy of Montserrat Volcano Observatory.

Date (2004)	Activity level	Hybrid	Mixed	Volcano-tectonic	Long-period	Rockfalls
21 May-28 May	Low	7	44	—	—	—
28 May-04 June	Low	4	16	—	—	—
04 Jun-11 Jun	Low	3	9	—	—	—
11 Jun-18 Jun	Low	5	—	—	—	10
18 Jun-25 Jun	Low	5	—	6	—	15
25 Jun-02 Jul	Low	5	—	6	2	8
02 Jul-09 Jul	Low	8	—	4	—	10
09 Jul-16 Aug	Low	6	—	1	1	5
16 Jul-23 Jul	Low	7	—	—	—	7
23 Jul-30 Jul	Low	2	—	—	—	8
30 Jul-06 Aug	Low	1	—	—	—	8
06 Aug-13 Aug	Low	1	—	—	—	3
13 Aug-20 Aug	Low	1	—	1	—	1
20 Aug-27 Aug	Low	1	—	—	—	1
27 Aug-03 Sep	Low	2	—	—	—	—
03 Sep-10 Sep	Low	—	—	1	—	2
10 Sep-17 Sep	slightly elevated	14	—	—	1	1
17 Sep-24 Sep	slightly elevated	8	—	—	2	2
24 Sep-01 Oct	slightly elevated	8	—	—	1	3

Table 2. Seismicity recorded at Soufriére Hills, 21 May to 15 October 2004. Courtesy of Montserrat Volcano Observatory.

Background. The complex andesitic Soufriére Hills volcano occupies the southern half of the island of Montserrat. The summit area consists primarily of a series of lava domes emplaced along an ESE-trending zone. Prior to 1995, the youngest dome was Castle Peak, which was located in English's Crater, a 1-km-wide crater breached widely to the east. Block-and-ash flow and surge deposits associated with dome growth predominate in flank deposits. Non-eruptive seismic swarms occurred at 30-year intervals in the 20th century, but with the exception of a 17th-century eruption, no historical eruptions were recorded on Montserrat until 1995. Long-term small-to-moderate ash eruptions beginning in that year were later accompanied by lava dome growth and pyroclastic flows that forced evacuation of the southern half of the island and ultimately destroyed the capital city of Plymouth, causing major social and economic disruption to the island.

Information Contacts: *Montserrat Volcano Observatory (MVO)*, Fleming, Montserrat, West Indies (URL: http://www.mvo.ms/).

Date (2004)	SO_2 emissions (metric tons/day)*
21 May-28 May	225-922
28 May-04 Jun	179-496
04 Jun-11 Jun	169-788
11 Jun-18 Jun	240-477
18 Jun-25 Jun	—
25 Jun-02 Jul	177-364
02 Jul-09 Jul	120-160
09 Jul-16 Aug	222-243
16 Jul-23 Jul	170-400
23 Jul-30 Jul	175-300
30 Jul-06 Aug	90-280
06 Aug-13 Aug	126-296
13 Aug-20 Aug	200-622
20 Aug-27 Aug	175-311
27 Aug-03 Sep	240-456
03 Sep-10 Sep	175-405
10 Sep-17 Sep	130-250
17 Sep-24 Sep	87-454
24 Sep-01 Oct	200-540
01 Oct-08 Oct	187-1144
08 Oct-15 Oct	156-553

Table 3. SO_2 gas flux estimates made at Soufriére Hills, 21 May to 15 October 2004. Courtesy of Montserrat Volcano Observatory.

Sierra Negra

Galápagos Islands, Ecuador
0.83°S, 91.17°W; summit elev. 1,490 m
All times are local (= UTC - 6 hours)

Sierra Negra volcano contains a six-station, continuously monitored GPS network. The instruments were installed in collaboration with a research consortium (UNAVCO) in May 2002 (figure 6).

Starting on 12 June 2004 and continuing through at least 29 August 2004, the rate of uplift of the caldera floor, as measured by this network, had accelerated to 77 cm/year (table 4). This rate was comparable to that inferred from InSAR data in the late 1990s (Amelung and others, 2000). That late 1990's uplift was attributed to trap-door faulting of the caldera floor along its southern margin, a process presumably driven by a shallow (< 2 km) intrusion of magma. Deflation occurred during 2001-2002, and slower uplift of about 12 cm/y prevailed during March 2003-May 2004 (table 4). The 12 June-29 August interval was noteworthy for the high rates of uplift (table 4).

The Instituto Geofísico in Quito, Ecuador monitors seismic activity in the Galápagos, using a network that includes a single station on Sierra Negra. Unfortunately, that network was down for the past year, in need of a variety of hardware, including the seismometer at Sierra Negra. Thus,

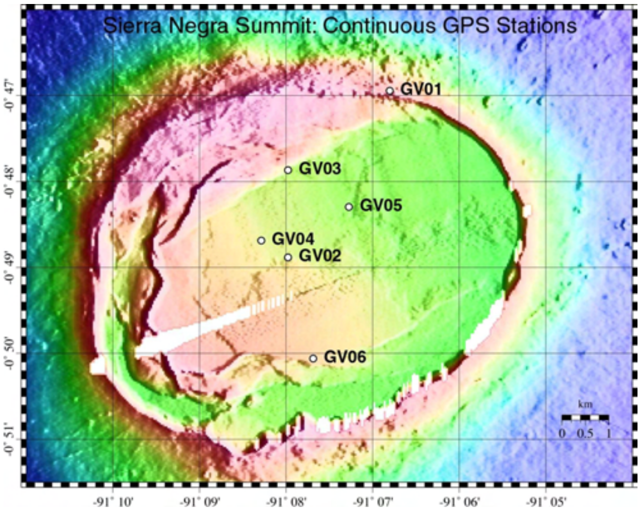

Figure 6. The summit of Sierra Negra has this dedicated GPS system continuously monitoring deformation. The shading reflects ground surface elevations; although a key to elevations was not provided, the map makes evident the caldera's broad floor and circular form. Courtesy of Geist, Chadwick, and Johnson.

for the interval of interest, seismic data were absent. Hugo Yepes estimated that to repair the Galápagos system would require about $9,000 (USD) in equipment and $4,000 (USD) in personnel transport and field expenses. He also said that the region requires more stable long-term logistical support.

The 12 June-29 August 2004 uplift was symmetrical about the caldera's center. The pattern and rate of uplift was well modeled as a 2.1 km deep sill intruded by about 12 x 10^6 m^3 of magma since June 2004.

Sierra Negra last erupted in 1979, when nearly 1 km^3 of lava erupted from a circumferential fissure near the summit, covering its N flank.

References: Amelung, F., Jonsson, S., Zebker, H., Segall, P., 2000. Widespread uplift and "trapdoor" faulting on Galápagos volcanoes observed with radar interferometry. Nature 407, 993-998.

Geist, D., Chadwick, W.W., and Johnson, D., Results from new GPS and gravity monitoring networks at Fernandina and Sierra Negra volcanoes, Galápagos, 2000-2002 (submitted to the Journal of Volcanology and Geothermal Research in 2004).

Background. The broad shield volcano of Sierra Negra at the southern end of Isabela Island contains a shallow 7 x 10.5 km caldera that is the largest in the Galápagos Islands. The 1,490-m-high volcano is elongated in a NNE direction. Although Sierra Negra is the largest of the five major Isabela volcanoes, it has the flattest slopes, averaging less than 5 degrees and diminishing to 2 degrees near the coast. A sinuous, N-S-trending ridge occupies the west part of the caldera floor, which lies only 100 m below its rim. Volcán de Azufre, the largest fumarolic area in the Galápagos Islands, lies within a graben between this ridge and the west caldera wall. The most recent lava flows of Sierra Negra occupy the upper northern flank in an area dotted with cinder and spatter cones; unlike most other Isabela island volcanoes, the caldera floor is devoid of young lava flows. Sierra Negra, along with Cerro Azul and Volcán Wolf, is one of the most active of the Isabela Island volcanoes.

Information Contacts: *Dennis J. Geist*, Department of Geological Sciences, University of Idaho, Moscow, Idaho 83844-3022 USA (Email: dgeist@uidaho.edu), *William W. Chadwick, Jr.*, Cooperative Institute for Marine Resources Studies (CIMRS), NOAA Pacific Marine Environmental Laboratory (PMEL), 2115 SE OSU Drive, Newport, OR 97365 USA (Email: bill.chadwick@noaa.gov); and *Daniel J. Johnson*, University of Puget Sound, Department of Geology, 1500 N. Warner, Tacoma, WA 98416, USA (Email: djjohnson@ups.edu); *Hugo Yepes*, Geophysical Institute (IG), Escuela Politécnica Nacional, Apartado 17-01-2759, Quito, Ecuador (URL: http://www.igepn.edu.ec/).

Montagu Island

South Sandwich Islands
58.42°S, 26.33°W; summit elev. 1,370 m

A high-resolution image of Montagu island and volcano of the same name suggests the earlier recognized, ongoing eruption (*Bulletin* v. 28, no. 2; v. 29, no. 1) continued through at least 1 October 2004. On a NASA website, scientist James Garvin posted an image of the 1-October scene (figure 7). Imagery taken prior to late 2001 showed the island as entirely white. The new image deserves and requires considerable study, but some initial observations from James Garvin and *Bulletin* editors follow.

The 1 October 2004 image shows the N flank of the central cone, Mount Belinda, emitting a NNE-drifting steam plume. Much of Montagu island sat amid a mosaic of floating ice. In contrast, on the previous image taken 7 December 2003 (*Bulletin* v. 29, no. 1), icebergs were sparse. Several square kilometers of sea ice on the island's lower right appears comparatively coherent and tightly butted against the island's margin. These changes may reflect sea-ice abundance during the S-hemisphere winter.

In addition, the higher detail in the new higher resolution image portrays a variety of patterns and features of volcanological significance that were absent or at least less clearly visible on earlier images. In the new image, the area of apparently continuous lava flows seems to have reached the island's N margin (a distance of ~ 3 km). On the 7 December 2003 image these flows had

Interval	Comments	Measurement Technique
1992-1998	240 cm of uplift punctuated by trapdoor uplift in 1997 or 1998	InSAR (Amelung and others, 2000)
1998-1999	Inflation at 65 cm/year	InSAR (Amelung and others, 2000)
2000-2001	Deceleration of uplift to 7 cm/year	Campaign GPS (Geist and others, submitted)
2001-Feb 2003	Deflation of ~ 9 cm/year	Campaign and continuous GPS
Mar 2003-May 2004	Inflation at ~ 12 cm/year	Continuous GPS
12 Jun-29 Aug 2004	Inflation at 77 cm/year	Continuous GPS

Table 4. A summary of the geophysically derived movement of the caldera floor at Sierra Negra. Courtesy of Dennis Geist, William Chadwick, and Dan Johnson.

reached little more than 1 km in length and were considerably narrower, and stood alongside broad, dark swaths of SE- to E-directed ash deposits (*Bulletin* v. 29, no. 1). These latter ash deposits have become less apparent on the newer image, conceivably due to cover beneath winter's snowfall.

The newer image depicts the S-flank's upper slopes as containing much broader areas of darkened snow and ice. Some of the sea ice N of the previously mentioned lava flows also appears darkened. To the S of the Belinda summit lies a previously unseen, sinuously shaped 'beard,' presumably composed of darkened snow. Another newly visible feature, the black area to the NNW (upper left), presumably reveals lava flows emerging from beneath the ice. This zone of lava flows resides without clear connection to the conspicuous, larger, previously mentioned one flowing from higher up-slope. The black area to the NNW may thus be a new vent area. Alternatively, the black area may represent the spot where a longer sub-glacial lava flow transited some unknown distance beneath the ice and here melted its way to the surface. Another such area may reside on the NNE flanks, midway from the summit area and the coast. On the island's W (left) side exists a newly imaged network of broken ice. It could suggest an episode of fresh crevassing there.

Although the version shown in figure 7 has reduced resolution for print and web distribution, the full-resolution version of the IKONOS color image distributed by NASA has a resolution of 4 m per pixel and another version, 1 m per pixel (creating a 3.20 Mb image). James Garvin noted that dynamic processes such as those on remote, uninhabited islands, can be monitored from orbit, thereby serving to target more intensive field studies when they are justified. As such, IKONOS imaging of localities such as active eruptions involving ice-lava interactions, represents a new form of scientific exploration of planet Earth. The eruption has produced a 'natural laboratory' for studying lava-ice interactions relevant to the biology of extreme environments as well as to processes believed to be important on the planet Mars.

The IKONOS earth-imaging satellite launched in September 1999. IKONOS includes optical, radar, and infrared sensors. These can be combined in a variety of ways to accommodate a wide range of imagery applications (including stereo images).

Geographic terminology. The nomenclature of volcanic features on Montagu Island, particularly in regard to Mount Belinda, has been quite variable. Although the name Montagu has been applied to the major volcanic edifice forming the island (LeMasurier and Thomson, 1990), the name Mount Belinda has been variously applied to the entire volcano, the currently active young cone on the northern side of the island, the 6-km-wide summit caldera, and a peak on the southern caldera rim that is the island's high point. In consultation with John Smellie of the British Antarctic Survey, we have used Montagu to refer to the volcano forming the island and Mount Belinda for the currently active cone.

Reference. LeMasurier, W.E., and Thomson, J.W. (eds.), 1990, Volcanoes of the Antarctic Plate and Southern Oceans: Washington, D C: American Geophysical Union, 487 p.

Background. The largest of the South Sandwich Islands, Montagu consists of one or more stratovolcanoes with parasitic cones and/or domes. The summit of the 10 x 12 km wide, polygonal-shaped island rises about 3000 m from the sea floor between Bristol and Saunders Islands. Around 90% of the island is ice-covered; glaciers extend to the sea over much of the island, forming vertical ice cliffs. The name Mount Belinda has been applied both to the high point at the southern end of a 6-km-wide ice-filled summit caldera and to the young central cone. Mount Oceanite, an isolated 900-m-high peak, lies at the SE tip of the island and was the source of lava flows exposed at Mathias Point and Allen Point. There was no record of Holocene or historical eruptive activity at Montagu until MODIS satellite data, beginning in late 2001, revealed thermal anomalies consistent with lava lake activity that has been persistent since then. Apparent plumes and single anomalous pixels were observed intermittently on AVHRR images during the period March 1995 to February 1998, possibly indicating earlier unconfirmed and more sporadic volcanic activity.

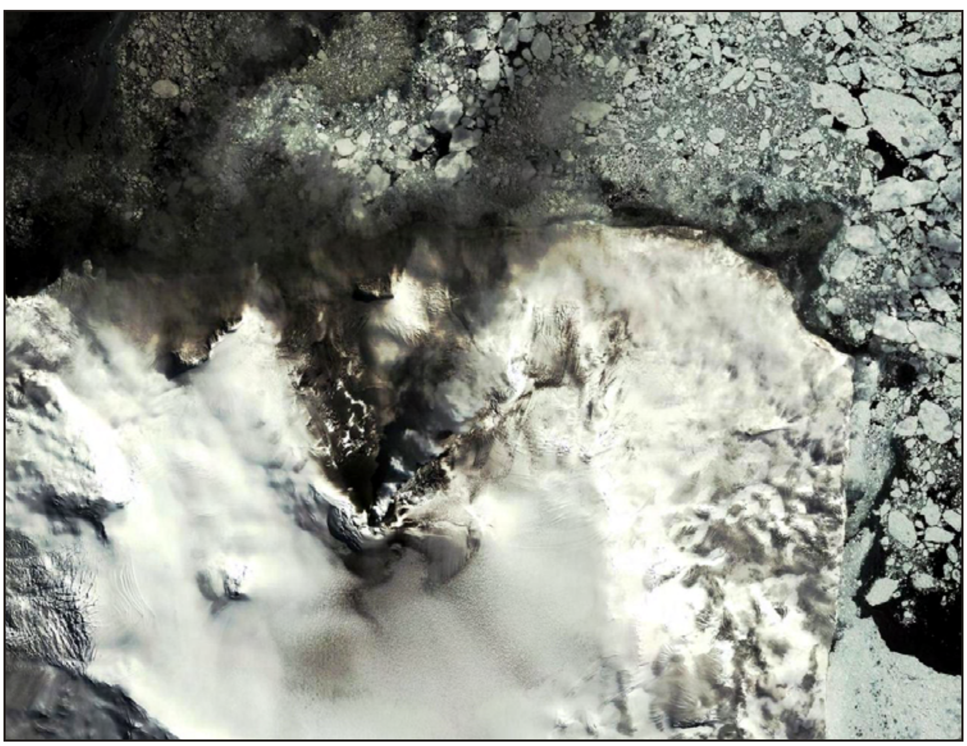

Figure 7. Montagu Island as imaged on 1 October 2004 by the IKONOS satellite. N is towards the top. The apex of the black zone of lava flows near the island's center presumably represents a vent within the summit crater. The distance from that spot to the coast is ~ 3 km. This image depicts numerous recent volcanogenic features. Montagu Island lies in the South Sandwich islands at the E edge of the Scotia plate, 2,600 km E of Cape Horn, ~ 1,000 km from the Antarctic circle, and ~ 3,500 km from the S pole. Courtesy of Space Imaging and James B. Garvin, NASA.

Information Contacts: *James B. Garvin*, National Aeronautics and Space Administration (NASA), Goddard Space Flight Center (GSFC), Code 921, Greenbelt, MD 20771, USA (Email: garvin@denali.gsfc.nasa.gov; URL: http://earthobservatory.nasa.gov/Newsroom/NewImages/); *John Smellie*, British Antarctic Survey, Natural Environment Research Council, High Cross, Madingly Road, Cambridge CB3 0ET, United Kingdom (URL: http://www.antarctica.ac.uk/, Email: jlsm@pcmail.nerc-bas.ac.uk).

Etna

Sicily, Italy
37.73°N, 15.00°E; summit elev. 3,315 m
All times are local (= UTC + 1 hour)

At about 1030 on 7 September 2004 a new effusive eruption started from the summit of Mount Etna. A N110°E-trending eruptive fissure about 230 m long opened at the base of the SE Crater without any significant seismic activity. A degassed lava flow poured from the base of the fissure, spreading towards the Valle del Bove. The lava flow had very low output rate (between 0.2 and 0.5 m^3/s), and was ~ 1 m thick, 10 m wide, and up to 250 m long. On the morning of 8 September the lava flow appeared to lack new input from its source, but the eruptive fissure continued to advance down slope. These events were not accompanied by seismicity or explosive activity.

After two days of slow expansion of the fracture field, a new effusive vent opened at a lower elevation, 2,650 m, on the upper western flank of the Valle del Bove. This occurred between 0600 and 0700 on 10 September. Lava poured from this vent, spreading over the upper wall of the Valle del Bove. No explosive activity accompanied the emission of lava, but some phreatic explosions were triggered by lava intersecting a thick cover of snow. The lava flow was degassed and flowed out at a rate of about 2-4 m^3/s. It spread E to the Serra Giannicola Piccola before splitting in two branches. At about 0930 the longest branch was about 300 m long and 50 m wide. Due to the high slope-angle, the front of the N lava flow breached. Hot blocks rolled down slope, causing the flow front to expand due to the collapse of hot debris rather than by flowage. At 1400 the lowest elevation of the lava flow front was about 2,250 m elevation. within the upper Valle del Bove. At that time, no villages were threatened by the lava flows since they had spread out over a deserted zone at least 10 km away from the nearest village.

Activity appeared similar on 14-15 September 2004, when Mike Burton, Enza Longo, and Margherita Polacci had clear views of the Valle Del Bove in fair weather. Their first observations were carried out at the Southeast Crater (SEC), where the team saw a conspicuous plume emitted from a fumarole field on the SEC's SE rim. This activity, not seen prior to the eruption, had been consistently observed during the previous 3-4 days.

A visit to a vent at 2,830 m elevation revealed behavior similar to previous days, consisting of continuous high-pressure degassing in the absence of explosive activity (figure 8). At this vent, in contrast to the one at 2,630 m (which emitted lava), incandescence was limited to a circular zone at the vent area. No recent scoria were observed near the degassing vent. At this degassing vent the peak temperature, measured with a thermal camera, was ~ 900°C (see thermal image, figure 8).

The team also visited the lava flow at 2,630 m (figure 9). Fresh scoria had fallen along the path leading to the lava flow, and samples were collected. The estimated flux rate of the lava flow was between 2 and 4 m^3/s, using an estimated flow velocity of 1 m/s, a width of 2 m, and a depth of 1-2 m. Estimates were obtained by observing the lava flow just above the rock island seen in figure 9. This flux was roughly equal to that seen on 13 September.

A pair of hornitos lay up slope of the lava flow originating at 2,630 m elevation. One hornito sat just behind the spot where lava was first observed on the surface. The second hornito was larger and resided about 20-30 m farther up slope (figure 10). It released gas at high pressure, creating noise. No scoria were emitted during their observation.

Polacci and Burton then walked down to the lava flow that began on 13 September (figure 11). The lava flow's flux rate was low. The team estimated an outflow rate of ~ 1

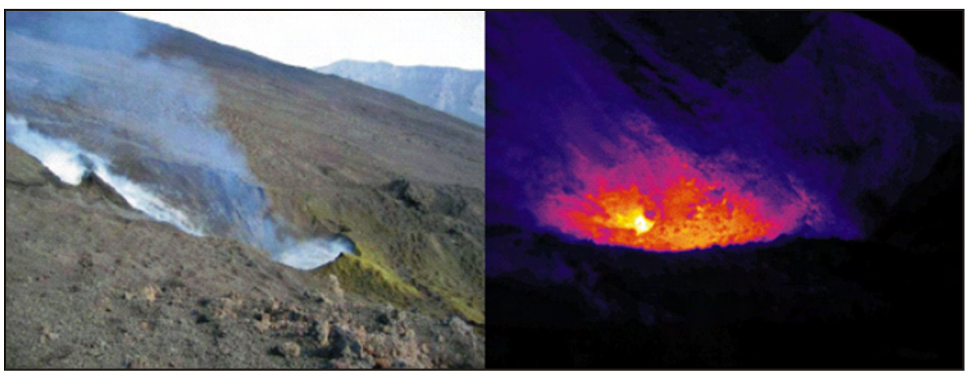

Figure 8. A vent emitting high-pressure gas at 2,830 m on Etna, 15 September 2004, with thermal image of the vent's mouth (at right). Courtesy of Mike Burton, Enza Longo, and Margherita Polacci.

Figure 9. Lava flow witnessed at 2,630 m elevation on Etna on 15 September 2004. The image at right is a closer view of the indicated area taken with a thermal camera. The thermal image shows the lava flow splitting and skirting around a small rock island. Courtesy of Mike Burton, Enza Longo, and Margherita Polacci.

m^3/s, using a width of 2 m, a flow velocity of 0.5 m/s, and a depth of 1 m, dimensions noted near the lava flow's source. The lava flow emanated from a small depression; no scoria deposits were seen nearby. GPS established the flow's source at 2,340 m elevation. The team observed several distinct overflows escaping from the principal lava flow, which originated at 2,630 m elevation (figure 12).

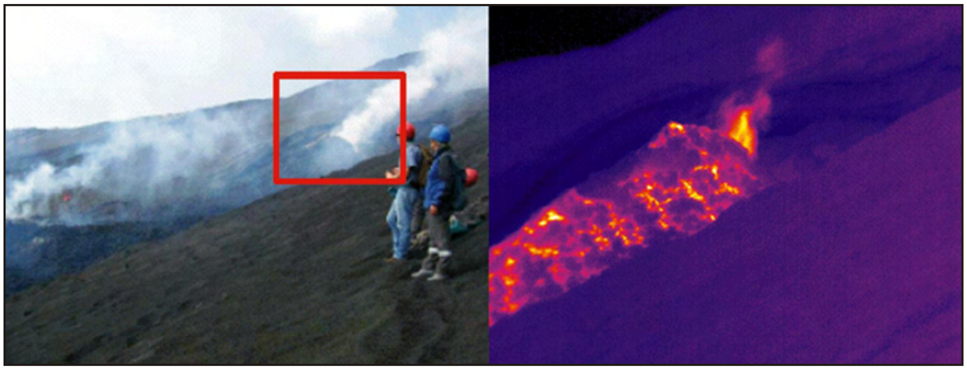

Figure 10. A hornito seen at Etna on 14-15 September up slope from the lava flow at 2,630 m elevation. The indicated area appears in an enlarged thermal image at right. Courtesy Mike Burton, Enza Longo, and Margherita Polacci.

Figure 11. The source of an Etna lava flow at 2,340 m elevation, as seen in two photographs taken on 14 or 15 September. Courtesy of Mike Burton, Enza Longo, and Margherita Polacci.

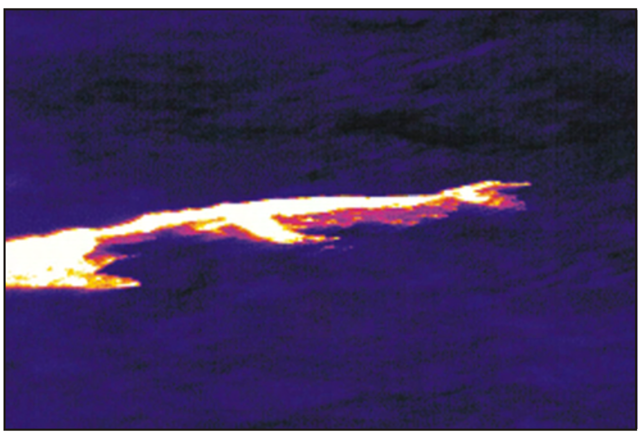

Figure 12. The lava flow that originated at 2,630 m elevation as seen in a thermal image on 14 or 15 September. The advancing lava flow broke into a series of branches. Courtesy of Mike Burton, Enza Longo, and Margherita Polacci.

Background. Mount Etna, towering above Catania, Sicily's second largest city, has one of the world's longest documented records of historical volcanism, dating back to 1500 BC. Historical lava flows of basaltic composition cover much of the surface of this massive volcano. The Mongibello stratovolcano, truncated by several small calderas, was constructed during the late Pleistocene and Holocene over an older shield volcano. The most prominent morphological feature of Etna is the Valle del Bove, a 5 x 10 km horseshoe-shaped caldera open to the east. Two styles of eruptive activity typically occur at Etna. Persistent explosive eruptions, sometimes with minor lava emissions, take place from one or more of the three prominent summit craters, the Central Crater, NE Crater, and SE Crater (the latter formed in 1978). Flank vents, typically with higher effusion rates, are less frequently active and originate from fissures that open progressively downward from near the summit (usually accompanied by strombolian eruptions at the upper end). Cinder cones are commonly constructed over the vents of lower-flank lava flows. Lava flows extend to the foot of the volcano on all sides and have reached the sea over a broad area on the SE flank.

Information Contacts: *Sonia Calvari, Mike Burton, Enza Longo,* and *Margherita Polacci*, Istituto Nazionale di Geofisica e Vulcanologia (INGV), Piazza Roma 2, 95123 Catania, Italy.

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