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# August 2008 Eruption of Kasatochi Volcano, Aleutian Islands, Alaska—Resetting an Island Landscape

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## Abstract

Kasatochi Island, the subaerial portion of a small volcano in the western Aleutian volcanic arc, erupted on 7–8 August 2008. Pyroclastic flows and surges swept the island repeatedly and buried most of it and the near-shore zone in decimeters to tens of meters of deposits. Several key seabird rookeries in taluses were rendered useless. The eruption lasted for about 24 hours and included two initial explosive pulses and pauses over a 6-hr period that produced ash-poor eruption clouds, a 10-hr period of continuous ash-rich emissions initiated by an explosive pulse and punctuated by two others, and a final 8-hr period of waning ash emissions. The deposits of the eruption include a basal muddy tephra that probably reflects initial eruptions through the shallow crater lake, a sequence of pumiceous and lithic-rich pyroclastic deposits produced by flow, surge, and fall processes during a period of energetic explosive eruption, and a fine-grained upper mantle of pyroclastic-fall and -surge deposits that probably reflects the waning eruptive stage as lake and ground water again gained access to the erupting magma. An eruption with similar impact on the island's environment had not occurred for at least several centuries. Since the 2008 eruption, the volcano has remained quiet other than emission of volcanic gases. Erosion and deposition are rapidly altering slopes and beaches.

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## Introduction

A day-long eruption in August 2008 radically changed the landscape of tiny Kasatochi Island, an important seabird and marine mammal habitat in the Andreanof Islands of the western Aleutian volcanic arc (Fig. 1). Prior to the 2008 eruption, little was known about the geology and eruptive history of Kasatochi. There were no seismometers or other geophysical monitoring equipment on the island, but seismic networks on two nearby islands indicated that detectable (magnitude [M] greater than 2) seismicity at Kasatochi had been at background levels for several years. In addition there was no evidence from satellite remote sensing of any unusual activity. The onset of the eruption was rapid; in retrospect the earliest detectable pre-eruptive seismicity was in early July, but U.S. Fish and Wildlife Service (USFWS) biologists working on the island did not report felt earthquakes until 2 August. A rapidly escalating earthquake swarm began early in the morning of 6 August and culminated in a M5.8 event at midday on 7 August (all times used here are Aleutian Daylight Time, −9 hr UTC) followed by intense volcanic tremor (Ruppert et al., in review). An explosive eruption became noticeable from distant seismic stations shortly thereafter at about 13:00. Fortunately a fishing vessel had evacuated the field crew just before eruptive activity began.

Several eruptive processes were responsible for intense impacts on the island's surface geology and ecosystems, both on land and in near-shore areas. The following brief summary of the eruption provides some definitions of volcanological terms used in this report. The eruption consisted entirely of ejection of fragmental, or pyroclastic, material; it produced no effusive features such as lava flows or lava domes. The island's summit crater that hosted the eruption was partly filled by a ~40-ha lake (Table 1), which caused initial events to expel lake sediment and water and to generate water-rich eruption clouds. Such events are termed phreatic or phreatomagmatic explosions, depending on the absence or presence, respectively, of new, or juvenile, magma. As the eruption progressed and eruption rate increased, the role of external water diminished, and the volcano emitted a vigorous ash-rich column for hours. Juvenile ash and pumice of andesitic composition, along with lithic fragments of older lava torn from the conduit and vent, rose to high altitude. Large fragments fell out rapidly, but ash (sand size and finer) and rare fine lapilli (mostly less than 1 cm) were transported chiefly to the southwest and south by prevailing winds. A trace to 6 cm of this material fell on a few neighboring islands 25–50 km from Kasatochi, but most of it fell into the sea. Concurrently, slugs of andesitic pyroclasts, lithic debris, and hot volcanic gases flowed rapidly down the volcano's flanks in density currents called pyroclastic flows and their less-particle-rich counterparts, pyroclastic surges. Impact, erosion, heat, and burial by these density currents were responsible for most of the changes to the island's environment.

The purpose of this report is to summarize key aspects of the eruption and the new surface geology of the island in order to provide context for the biological contributions to this issue and for ongoing studies of the island and its rapidly changing environment. Our findings are largely preliminary owing to limited time on the island and laboratory investigations still in progress. One of us (Waythomas) made a short reconnaissance of the island about two weeks after the eruption and three of us (Nye, Waythomas, and Scott) visited in 2009 for several days during field work supported by the USFWS's vessel, M/V *Tiglax*. Another of us (Neal) spent part of one day on the island in 2005 and made a reconnaissance geologic map. A fuller discussion of the eruption, including seismicity, satellite remote sensing, sea-



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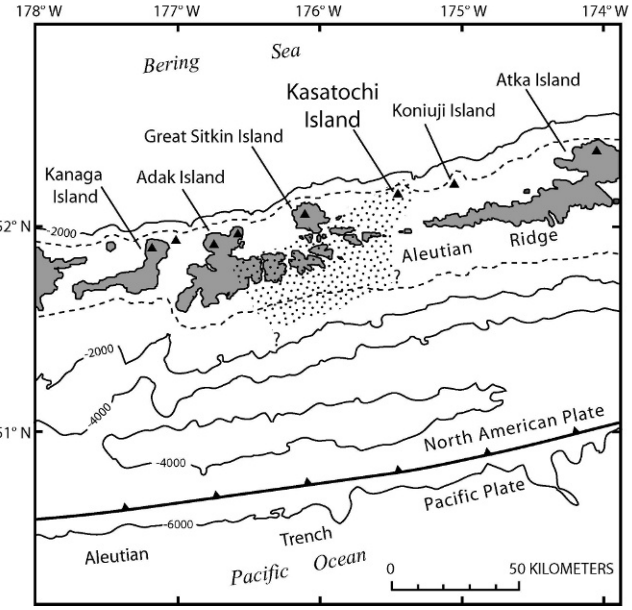


**FIGURE 1. Kasatochi Island lies on the north edge of the Aleutian Ridge, the summit of which lies within the dashed lines. Water depths on the ridge summit are typically less than 200 m. Triangles are volcanoes of Quaternary age; older rocks form much of the island area to the south. Approximate extent of tephra fallout from the 2008 Kasatochi eruption is stippled; extent south into the Pacific Ocean is poorly known. Isobaths in meters.**

surface disturbance, description of deposits, and other topics, is available in Waythomas et al. (in review). Owing to a lack of formally named geographic features on the island and to aid in discussion, we use several informal names coined by USFWS personnel (Fig. 2).

## Pre-eruption Geologic Setting

Kasatochi Island is the subaerial portion of a volcano perched on the northern edge of the broad Aleutian Ridge, a volcanic island arc of middle Eocene to Quaternary age (Fig. 1). Water depth on much of the ridge is less than 200 m and the summit altitude of the volcano is about 315 m, making it a modest-sized cone. The north flank of the volcano continues an unknown distance down the steep slope that descends from the ridge into the deeps of the Bering Sea.

Other than a brief geologic reconnaissance of the island in 2005 (by Neal) and our observations in 2009 (Fig. 2), little else is known of the details of Kasatochi's geology or eruptive history. Anecdotal reports during the 18th and 19th centuries suggest some activity at Kasatochi or perhaps nearby Koniuji Island (Grewingk, 1850; Coats, 1950), but firm evidence is scarce. Before the eruption the island was about 2.5 by 3 km, ringed by sea cliffs and small bouldery beaches, and hosted a central crater about 1.2 km in diameter, which contained a 0.8-km-diameter lake. In 2005 the lake had a surface altitude estimated at about 15 m above sea level, and USFWS biologists reported intermittent "simmering" in areas, most energetically in the lake's west end, although limited infrared observations from satellites showed no thermal anomaly (McGimsey et al., 2008). An uncredited source reported that in 1899 the lake was gone and steam was rising from the crater (Jaggar, 1927). Bailey and Trapp (1986) reported the lake water was brackish, roughly half the salinity of sea water. Together these suggest the possibility of at least intermittent fumarolic activity in the crater.

The crater is surrounded by steep walls up to 300 m high that expose chiefly lava flows with interflow zones of breccia and scoria fallout, and a few dikes. A thick unit comprising numerous unconsolidated pyroclastic-flow and -surge deposits overlies lava flows on the south crater wall. Several prominent, but undated, lava flows of basaltic andesite (two units analyzed thus far contain 53 and 56 wt. percent $SiO_2$; additional analyses pending; Waythomas et al., in review) and perhaps also basalt and andesite extend from the crater to the sea in several sectors of the northern half of the island. These form steep cliffs, talus slopes, and rugged bouldery slopes. The only sheltered beaches on the island are in coves protected by lava-flow headlands on the northwest shore. The highest sea cliffs bound the south-southwest sector of the island. They expose a sequence of indurated volcaniclastic rocks bearing abundant evidence of magma interaction with water and rapid deposition. An intriguing hypothesis is that extensive glacier cover during a past ice age on this part of an emergent, or nearly so, Aleutian Ridge, provided the conditions necessary for deposition of this thick unit, but evidence of such extensive ice cover in the region is lacking (Kaufman et al., 2004). This unit is probably one of the oldest exposed on the island.

The pre-2008 unconsolidated pyroclastic-flow deposits of the southern crater rim extended to the sea, ending in cliffs a few tens of meters high on the southeast, south, and west coasts before partial burial in 2008. These pre-2008 deposits, and less extensive but similar deposits on other flanks, formed steep to gentle slopes underlain by stony, sandy soils. They were likely the youngest eruptive deposits of consequence on the island and resemble some of the deposits of 2008 pyroclastic flows and surges. Weak weathering and soil development in the deposits suggest they may be on the order of a few centuries to at most 1000 yrs old.

Ocean currents and productivity along with island geology created exceptional conditions for seabirds and marine mammals at Kasatochi (Williams et al., 2010 [this issue]; Drew et al., 2010 [this issue]). Near-shore benches in lava flows provided rookeries for sea lions. Some taluses formed important rookeries for several species of auklets (*Aethia* spp.). Except for crater walls and sea cliffs, the island was nearly completely vegetated in grasses and herbaceous plants (Talbot et al., 2010 [this issue]). Events of 7–8 August 2008 reset the island's environment to a state probably not

**TABLE 1**

**Changes in area of Kasatochi Island, crater, and crater lake as measured from QuickBird satellite images obtained on date given in column 1. —, no data.**

| QB Image | Area (in ha) | | | % of 2004 value | | |
|---|---|---|---|---|---|---|
| | Island | Crater | Lake | Island | Crater | Lake |
| 2004.04.09 | 500.9 | 116.0 | 42.7 | — | — | — |
| 2008.09.03 | 692.0 | — | — | 138 | — | — |
| 2009.04.18 | 702.3 | 148.2 | 71.3 | 140 | 128 | 167 |
| 2009.09.13 | 685.3 | — | — | 137 | — | — |

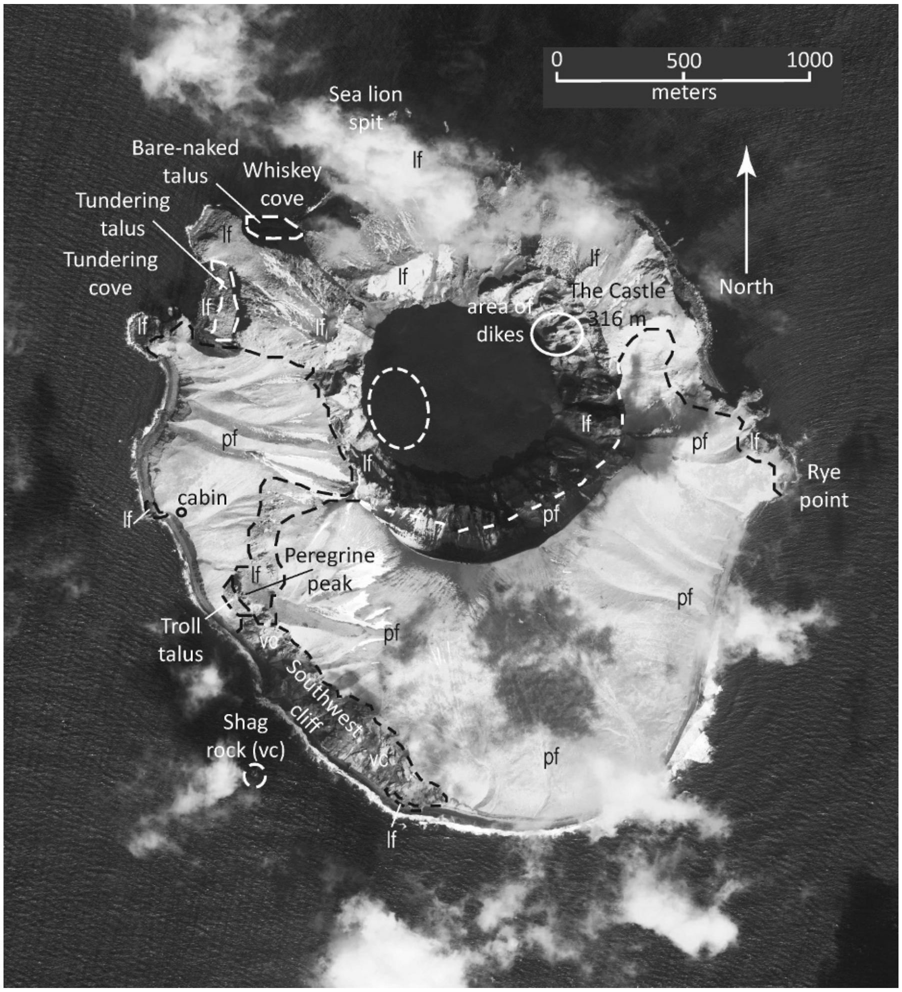


**FIGURE 2. Pre-2008 reconnaissance geologic map of Kasatochi Island on QuickBird image acquired in April 2004; wispy clouds partly cover north flank. Map units: vc, volcaniclastic rocks and subordinate lava flows and dikes of southwest cliffs, late(?) Pleistocene age; lf, lava flows chiefly younger than map unit vc, probably of latest Pleistocene or Holocene age, except for lava flow that underlies map unit vc at south end of island; pf, chiefly pyroclastic-flow deposits that overlie map unit lf and vc (some may be as young as a few centuries). Informal geographic names are those coined by USFWS. Tundering and Troll taluses were major auklet rookeries; Sea lion spit was sea lion rookery. In 2005, area of lake enclosed by white dashed line was reported by observers to have been subject to intermittent surface disturbances (see text).**

extant since the eruptions that emplaced the south-flank sequence of pyroclastic deposits at least several centuries ago.

## Eruption of 7–8 August 2008

The high level of seismicity felt by the biologists on Kasatochi in early August and detected by distant seismometers, as well as the intense tremor that followed the M5.8 earthquake midday on 7 August, prompted the Alaska Volcano Observatory to raise the alert level to Watch, signifying that the volcano was exhibiting heightened or escalating unrest with increased potential for eruption. Shortly thereafter eruption onset was indicated by seismic signals from the Great Sitkin seismic network and confirmed by an AVHRR infrared-satellite image obtained at about 13:20 (Waythomas et al., in review). Subsequent satellite images showed rapid growth of an apparently water-rich, ash-poor eruption cloud that reached an altitude of about 14 km, drifted to the southwest, and was continuously emitted until about 15:00. A second similar but briefer explosive burst and cloud was detected between 16:50 and 17:17. The clouds of both bursts passed over the village of Adak (80 km southwest), but left no noticeable ash fallout.

The character of the eruption cloud changed greatly with onset of a third burst at 19:35. The third cloud quickly reached an altitude of about 18 km and was much more ash rich than the earlier two. The *Larisa M*, a fishing vessel passing 13 km southwest of the volcano, reported darkness, lightning, and fallout of about 12 cm of ash and fine lapilli over a period of 1.5–3 hrs (Waythomas et al., in review). Unlike the first two clouds, the third initiated a ~10-hr period of continuous, vigorous ash emission that lasted until about 05:00 on 8 August and included two more explosive bursts (at 22:12, 7 August, and 02:42, 8 August) that were detected on distant seismic and infrasound instruments. The ash cloud drifted on a more southerly course than those of earlier bursts. Satellite images record an additional 6 hours of waning ash emission that ended by about 11:00 on 8 August.

The eruption was exceptional by two measures. The Infrared Atmospheric Sounding Interferometer on the MetOp-A satellite detected about 1.7 Tg of $SO_2$ in the eruption cloud (Karagulian et al., 2010), the largest injection of $SO_2$ into the atmosphere since the 1991 eruptions of the Pinatubo (Philippines) and Hudson (Chile) volcanoes. In addition, the unrest and eruption were seismically energetic; the pre-eruptive swarm contained at least 500 earthquakes >M2 and about 20 >M3.8, including a maximum of M5.8, making the unrest and eruption much more seismically energetic than other recent Alaska eruptions (Ruppert et al., in review).

Observations on several downwind islands between Kasatochi and Adak Island two weeks after the eruption (Waythomas et al., in review) showed a trace to several centimeters of ash fallout; an observer on Adak reported a trace of ash trapped in vegetation and rock crevices several days after the eruption and following several periods of rainfall. Where several centimeters thick, the ash layer was a simple normally graded (fining upward) bed, which we infer represents a single period of deposition and not a more

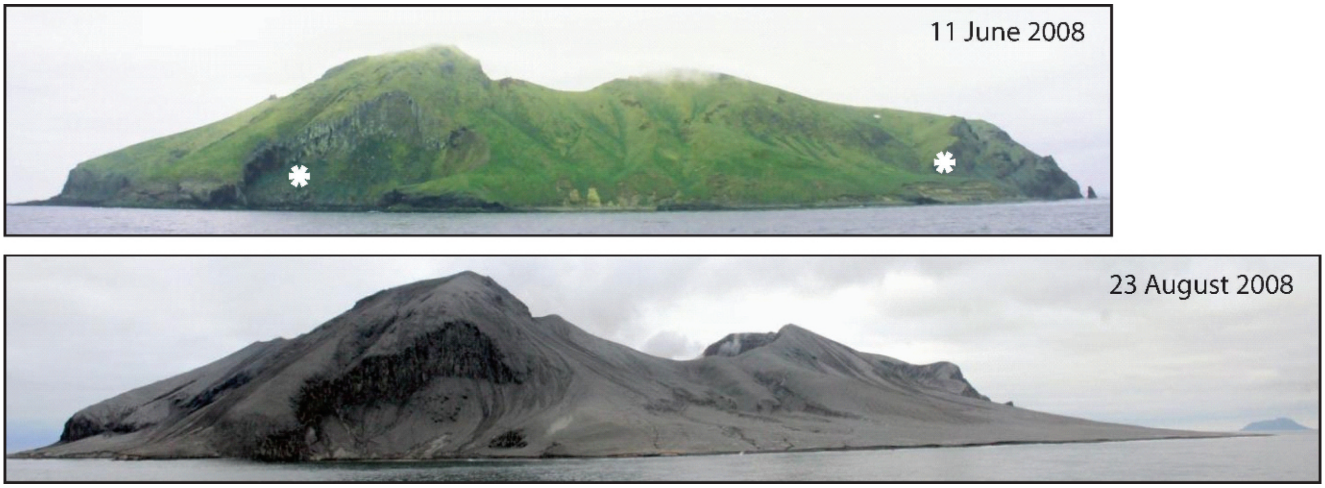


**FIGURE 3. Pre- and post-eruption photographs of Kasatochi Island taken from a ship off the northwest coast in summer 2008. Direction of view is slightly different with the lower photograph more southerly. White stars in upper panel show locations of major sea-bird nesting sites. Tundering talus, left, is clearly visible; Troll talus, right, is not visible but lies below cliff marked by star. Note the extensive fans deposited beyond the pre-eruption sea cliff and the lowering of the west crater rim by outward erosion. The sea lion rookery on the lava-flow headland at the left edge of upper photograph is partly buried by deposits that were removed by erosion during the winter of 2008–2009. USFWS photographs by R. M. Buchheit.**

complex sequence of deposition that included multiple pulses and pauses.

The following discussion describes the types and distribution of deposits that were emplaced on Kasatochi Island during and in the year since the 2008 eruption and their effect on the island's physical environment.

### *ERUPTION-INDUCED LANDSCAPE CHANGES*

The August 2008 eruption radically changed the appearance of Kasatochi Island. Areas of the island and crater increased by 40 and 28%, respectively (Table 1). The crater was enlarged laterally by up to 300 m chiefly toward the west and southwest, where the crater rim was lowered by about 60 m. This pattern of crater enlargement suggests that the eruption was focused at a vent or vents in the west and southwest portions of the pre-eruption crater. Limited views of the crater two weeks after the eruption showed tephra rims surrounding several partly submerged vents in that area. Lake level was lower than before the eruption, but several robust ground-water-fed streams flowed out of the lower crater walls and were refilling the lake (Waythomas et al., in review). Most of the island was covered by a variable thickness of pyroclastic deposits emplaced by ballistic ejection and pyroclastic fallout, flow, and surge. Only the inner crater wall, several areas of steep slopes on the upper cone, and some parts of the pre-2008 sea cliffs were left uncovered. Fans of pyroclastic deposits had locally extended the shoreline by hundreds of meters—roughly to a position between the former 10- and 20-m isobaths—burying the bouldery kelp beds that were an important marine habitat (Jewett et al., 2010 [this issue]). The once lush, green island had been transformed into a dull brownish-gray, ash-covered landscape (Fig. 3). Much of the nearly ubiquitous upper mantle of fine-grained ash was sticky and gumbo-like when wet and desiccation-cracked when dry. Two key auklet rookeries in taluses below lava-flow cliffs on the west flank (Tundering and Troll) were buried by new deposits and not utilized for nesting in summer 2009 by the approximately 200,000 auklets who had returned (Williams et al., 2010 [this issue]; Drew et al., 2010 [this issue]). In contrast, sea lions were present on the island within two weeks of the eruption. Their rookeries on lava-flow headlands at the north end of the island were thickly buried, but coastal erosion had cleared them by summer 2009. By April 2009 the level of the crater lake had risen and the lake surface area was 67% larger than it was before the eruption due largely to an increase in crater diameter.

### *ON-ISLAND AND NEAR-SHORE DEPOSITS*

The 2008 volcanic deposits that mantle much of the island consist of veneers decimeters to locally >10 m thick on middle to upper flanks and broad aprons and fans up to a few tens of meters thick along much of the lower flanks below former sea cliffs (Fig. 4). Fans originally extended up to 460 m from former sea cliffs, but by summer 2009 fans on the west, north, and east flanks had been truncated to about half that length or less by coastal erosion. They terminated in active sea cliffs about 15–20 m high. South-side fans ended either in low cliffs or, more typically, were buried by post-eruption fans of alluvium and debris-flow deposits or by accreting beach sediments that displaced the shoreline an additional 150–250 m seaward.

The character and thickness of the sequence of eruptive deposits in a given area depends on several factors, including distance and bearing from the crater rim, slope gradient, relation to pre-eruption valleys and sea cliffs, and microtopography (topographic features meters to tens of meters in size). In general, steep slopes between the crater rim and the old sea cliffs had much thinner pyroclastic-flow and -surge deposits than did the fans. Velocities of the fluidized flows were likely high ($\geq$100 km hr$^{-1}$) on these slopes and deposition was focused in topographically low areas, such as the pre-eruption valleys that fed the fans beyond the south sea cliff. At microtopographic scale, thickness varies substantially over distances of tens of meters with former hollows accumulating several meters or more and steeper slopes between hollows retaining only a thin mantle. Ripped-up turf incorporated in some pyroclastic-flow deposits and minor erosion of the pre-2008 surface on some slopes indicate that the pyroclastic flows were locally erosive. Microtopography of the pre-eruption land surface was generally smoothed by pyroclastic-flow and -surge deposits filling low areas followed by a surface mantling of fine-

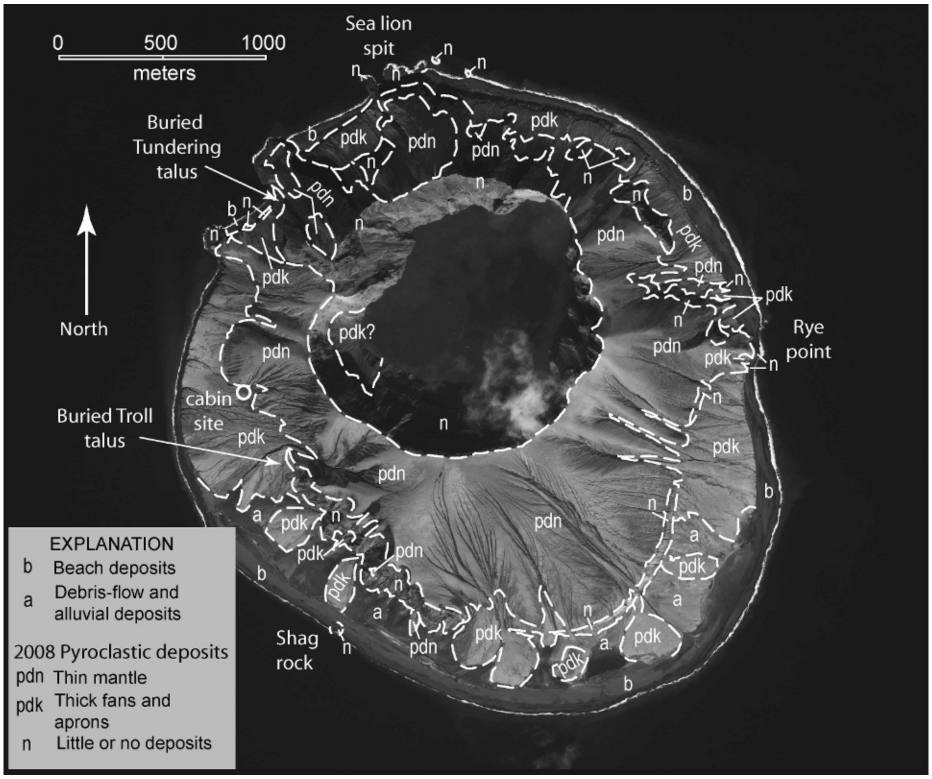


**FIGURE 4. Generalized post-eruption geologic map on QuickBird image of 18 April 2009. Image does not register well with Figure 2; note exaggerated steepness of east crater wall. Pronounced extension of crater rim about 300 m westward suggests that main eruptive vent was at western end of pre-eruption crater. Note buried taluses and former USFWS cabin site. Map units: n, chiefly bare rock of crater walls, former sea cliffs, and steep slopes of north flank; pdn, areas of thin (typically less than a few meters thick; locally >10 m) 2008 eruptive deposits; pdk, thick (up to ~20 m) of 2008 eruptive deposits chiefly in fans outboard of former sea cliffs; a, post-eruption deposits of alluvium and debris-flow sediments from erosion of 2008 and older deposits; b, beach deposits. Note that contacts are not shown between beach and alluvial deposits, or between beach and other units where a distinct sea cliff is evident on image.**

grained fallout deposits. Wang et al. (2010 [this issue]) describe detailed variations in deposit thickness in several areas, which is a key factor in exhumation of the pre-eruption turf and soil, a potential repository of viable seeds, rhizomes, organic matter, and soil.

An important aspect for the recovery of plant life is that, in many areas, the 2008 flows and deposits did not transmit enough heat to the pre-eruption ground surface to completely char plants and their underlying root mats. Even though pyroclastic flows typically have emplacement temperatures of hundreds of degrees Celsius, several factors probably limited the impact of the 2008 flows locally. Destruction was great in areas where the pyroclastic flows eroded down to mineral soil and in areas where plants and soils were buried by tens of meters of new material. But many flank areas were buried initially by relatively cool, albeit acidic (Wang et al., 2010 [this issue]), deposits of muddy ash and then accumulated only decimeters to a few meters of flow deposits; the old ground surface thereby having some protection. Furthermore, some of the pyroclastic-flow deposits were reduced in temperature by addition of a large fraction of cold accidental lithic debris derived from erosion of crater and conduit walls. The result is that in some areas where 2008 deposits had been stripped away, localized concentrations of plants were sprouting from the pre-eruption root mat (Talbot et al., 2010 [this issue]). Further exposure of the pre-2008 surface may offer additional favorable habitats for plant regeneration.

The lithologic components of the deposits comprise three categories—juvenile andesite, fragments of intrusive rocks, and accidental lithic material. The juvenile andesite (58.5–59.2 wt. percent $SiO_2$; pending analyses may expand compositional range) includes light-gray, brown, and mixed pumice that contains about 40 volume percent phenocrysts and microphenocrysts of plagioclase, ortho- and clinopyroxene, amphibole, and iron-titanium oxides (Waythomas et al., in review). Pumice density ranges widely; a portion was less dense than seawater and formed rafts of floating pumice that washed up on neighboring islands. Pumiceous clasts range in size from ash fragments (<2 mm) to blocks tens of centimeters in diameter. The intrusive-rock component consists of medium to coarsely crystalline gabbro and diorite of mineral species similar to those in the pumice and ranges in size from crystal fragments to blocks up to 50 cm in diameter. In the coarsest phases, plagioclase and amphibole crystals average ~1 cm with the largest measuring ~10 cm. Most such clasts contain voids and many can be disaggregated by hand or gentle hammer blows. Such disaggregated crystals and crystal fragments are common in pumiceous clasts. The gabbro and diorite likely represent cumulates of crystals that grew along the margins of the Kasatochi magma reservoir and conduit and were entrained by erupting magma. The accidental lithic component includes a variety of angular to subangular clasts of basalt, basaltic andesite, and andesite lava in a wide variety of color and degree of hydrothermal alteration. They range in size from ash to large blocks up to ~2 m or more in diameter. Most deposits on the flanks of Kasatochi contain a majority of accidental lithic fragments, up to several tens of percent of juvenile pumice, and a few percent of intrusive rock.

We recognize four main stratigraphic units that were emplaced during the eruption. Unit 1 is a relatively thin basal sequence of muddy and pumiceous tephra that was deposited chiefly as fallout from eruption clouds but also as surges. Unit 2 is a locally thick sequence of massive to vaguely bedded, coarsely grained pyroclastic-flow deposits. Unit 3 is a distinctly stratified sequence of interbedded, chiefly coarsely grained pyroclastic deposits of flow, surge, and fallout origin. Unit 4 forms a mantle comprising chiefly fine-grained, bedded deposits of fallout and surge origin. In describing the deposits, we use the following textural terms. Ash consists of sand-sized (2 mm to 63 μm) and

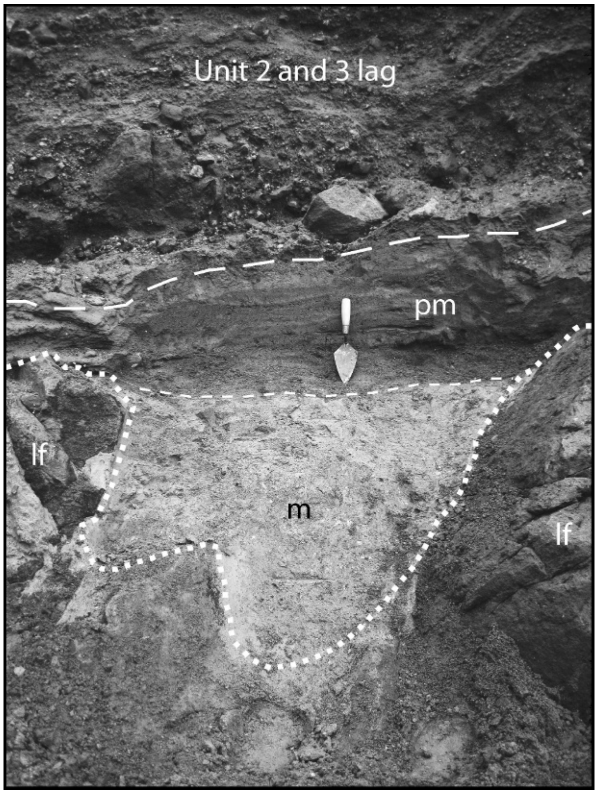


**FIGURE 5. Black-and-white photograph of unit 1 (includes both portions m and pm) exposed on lava-flow headland on the south side of Tundering cove (Fig. 4) shows muddy gray tephra (m) grading upward to interbedded mud and pumiceous ash (pm; around and just above 28-cm-long trowel). Unit 1 is overlain by stony lag deposits of pyroclastic flows of units 2 and 3. Unit 1 deposit lies in crevice in lava flow (lf); lava surface slopes toward viewer (U.S. Geological Survey [USGS] photograph by W. E. Scott).**

finer sediment; muddy refers to sediment with a substantial fraction (tens of percent) of silt and clay (<63 μm). Coarser material is described as lapilli (2–64 mm) and blocks (>64 mm).

All four units are typically not exposed in a single locality. The high sea cliffs eroding into thick fans of 2008 deposits expose mostly the upper part of unit 2 and all of units 3 and 4. In those areas that were offshore before the eruption, unit 1 and the lower part of unit 2 lie unexposed below sea level. Unit 1 is exposed discontinuously over the moderately sloping flanks above the old sea cliffs and on ridges that stand above the level of the thick coastal fans. Unit 4 is exposed over most of the island. Deposits of units 2 and 3 are thinner in mid-flank areas than in the fans and are typically represented by a sequence of granular beds from flows and surges that swept over the slopes and deposited relatively little until they reached the growing coastal fans. We are not able to reliably differentiate these deposits into units 2 and 3. Reasons for this distribution of deposits are discussed more fully below.

*Unit 1, Basal Muddy and Pumiceous Tephra*

Unit 1 consists of a variable thickness of massive gray muddy tephra and up to several beds of coarse pumiceous ash and fine lapilli that also contain gray mud (Fig. 5). The mud was chemically reduced at the time of deposition. Where in contact with the atmosphere or the pre-eruption ground surface, it readily oxidizes to a yellowish brown-gray color. Unit 1 has a much lower pH (3–4.5) than other units, which are only slightly acidic (Wang et al., 2010 [this issue]). The only logical source of such material is crater-lake sediment that was expelled by initial explosions. We hypothesize that as magma first ascended to a shallow level below the crater lake, it encountered wet lake sediments. The mix of magmatic gas and steam from interaction of hot magma and ground and lake water drove phreatic and phreatomagmatic explosions that resulted in deposition of tephra fallout and surge deposits with components of lake sediment and acidic lake water, pumiceous ash and fine lapilli, and accidental lithic material.

The thickest section of unit 1 yet found is about 50 cm and lies in a depression on the lava flow that forms the south headland of Tundering cove (Fig. 5). The top of the deposit was truncated by pyroclastic flows of units 2 and 3 that left a coarse-grained, well-bedded lag deposit of chiefly accidental lithic debris.

On moderately sloping terrain above the coastal fans where gully erosion has exposed the pre-eruption ground surface, unit 1 typically forms a discontinuous layer centimeters to a few decimeters thick on the turf or soil A horizon (Wang et al., 2010 [this issue]). Such slopes were subjected to a complex succession of erosion and deposition as the pyroclastic flows and surges of units 2 and 3 swept by, so unit 1 is sometimes absent.

*Unit 2, Massive Pyroclastic-Flow Deposits*

The full thickness of unit 2 is never seen because most exposures are in areas that were formerly offshore. No more than about 10–15 m is exposed in any one locality, but 10 m or more may be present below beach level. The distinguishing characteristic of unit 2 is its massive appearance and lack of distinct bedding (although close inspection reveals poorly defined, meter-thick layers), which suggests that the unit was deposited quickly without breaks (Fig. 6). Any significant break in flow activity would have allowed fallout of tephra and creation of distinct bedding planes between individual flow deposits. In summer 2009 slumps and slides from sea cliffs exposed loose, highly friable deposits of unit 2 that were dry and likely had not been wetted by infiltrating ground water. They were no longer hot, but probably had been hot enough to drive off infiltrating water for almost one year. On the north end of Tundering cove, a site studied in 2009 that is described more fully in Waythomas et al. (in review) was close to the pre-eruption beach, and the lowest exposed deposits of unit 2 may be within a few meters of the base of 2008 deposits. At this site both charred and uncharred grass and other organic matter were found in unit 2, suggesting that at least in some parts the deposit had been cooled well below initial magmatic (~900 °C) and typical flow temperature (~500 °C) during transport. Wang et al. (2010 [this issue]) report a low pH in this material, a characteristic shared by samples of unit 1. It is possible that the interaction of magma, lake water, and lake sediment inferred for unit 1 may have continued into the early stage of deposition of unit 2.

Unit 2 contains more than 50% by volume of accidental lithic debris as estimated by visual inspection. The high lithic content of unit 2, as well as many unit 3 deposits, likely reflects the short (<1 km) and steep (average slope ~0.3) descent from the crater rim to the former coast, and the large volume of lithic material generated by erosion of the crater walls and perhaps scavenged by flows from steep outer flanks below the crater rim. Recall that about 300 m of the west crater wall was removed. The relatively denser lithic clasts would tend to be deposited first and the less-dense pumiceous ash and lapilli would tend to pass by and either flow into the sea or, if residual flows were less dense than seawater, run out over the sea surface before losing velocity and settling out.

FIGURE 6. Black-and-white photograph of 15- to 20-m-high sea cliff along west coast that exposes massive pyroclastic-flow deposits of unit 2 at base and units 3 and 4 in upper degraded portion (in approximate position of white arrow). Unit 2 extends more than 5 m below beach. Person circled for scale; note large angular boulders on beach eroded out of 2008 deposits (USGS photograph by W. E. Scott).

*Unit 3, Well-Bedded Pyroclastic-Flow, -Surge, and -Fallout Deposits*

Unlike units 1 and 2, unit 3 is exposed completely in many cliffs where fans of 2008 deposits are being truncated by wave erosion (Figs. 6, 7). The contact between units 2 and 3 is gradational and marked by a transition to better-defined bedding. Unit 3 comprises numerous beds decimeters to ~1 m thick, most with distinct contacts, of pyroclastic deposits emplaced by flow, surge, and fallout processes. The distinct contacts, preservation of lapilli-fall beds, and presence of reddish to pinkish flow-deposit tops formed by high-temperature oxidation of iron-bearing oxide minerals attest to episodic deposition. Two, decimeters-thick beds of lapilli fallout recognized in unit 3, are the only on-island equivalent of the centimeters-thick bed of ash and fine lapilli found on neighboring islands to the south and southwest and witnessed falling by the crew of the F/V *Larisa M*. The total thickness of unit 3 in coastal cliffs ranges from about 5 to 10 m. As in unit 2, some portions of unit 3 were still dry and friable in summer 2009 reflecting their initial high temperatures and capacity to remain dry.

*Unit 4, Upper Fine-Grained Fallout and Surge Deposits*

Fine-grained (fine sand, silt, and clay) deposits of unit 4 mantle most of the island. Their contact with unit 3 is gradational and marked by a loss of the coarse clasts common in unit 3. Because their fine grain size leads to low infiltration rates, runoff is accentuated and rill and gully erosion is common (Figs. 6, 8;

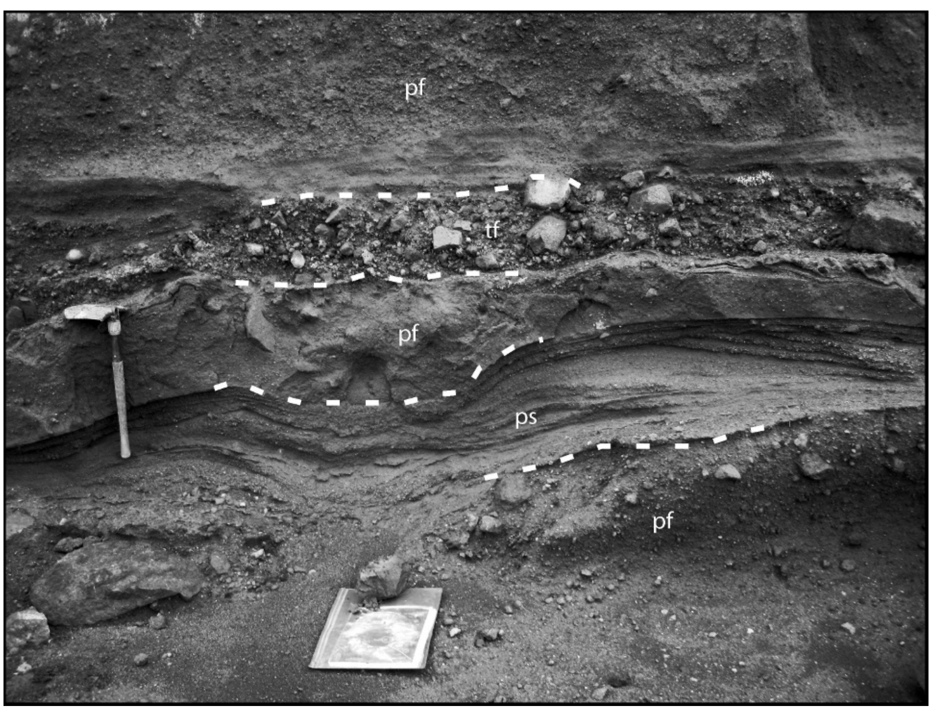


FIGURE 7. Black-and-white photograph of lower part of unit 3 shows distinctly bedded character of massive pyroclastic-flow (pf), laminated pyroclastic-surge (ps), and fines-poor tephra fallout deposits (tf; shovel about 50-cm long). Upper half of middle pyroclastic-flow deposit displays pink high-temperature oxidation. Dashed lines show partial contacts between beds. Exposure is on west coast several hundred meters south of site of Figure 6 (USGS photograph by W. E. Scott).

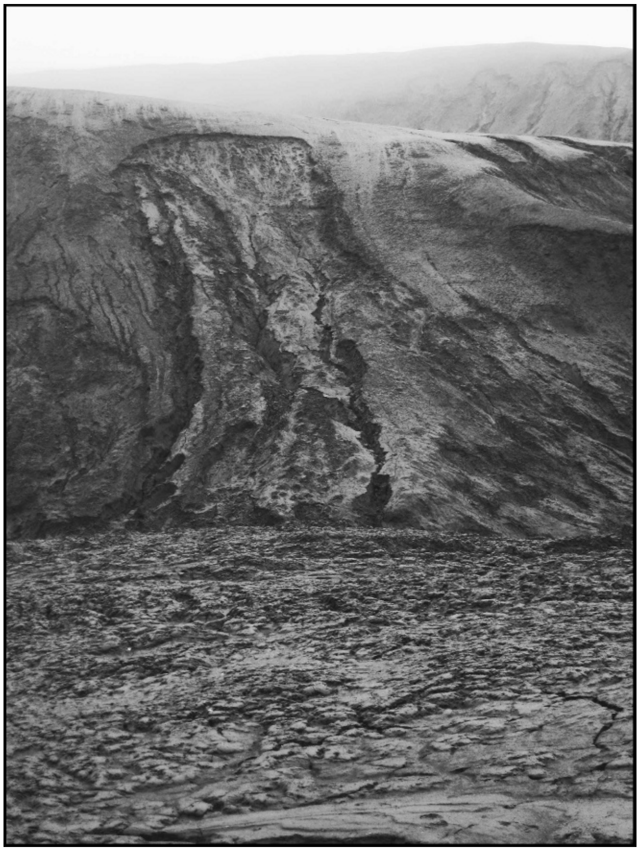

**FIGURE 8. Black-and-white photograph of fine-grained mantle of unit 4 that covers much of island and is susceptible to gullying and shallow landslides on steep slopes. Some slides transform into mud-lump debris flows (foreground). Slope in middle distance is about 30-m high and is part of former sea cliff north of former USFWS cabin (Fig. 4). Slope is covered by thin deposits of units 2 and 3 and 1–2 m of unit 4; slide chiefly involves unit 4. Crater rim is in far distance (USGS photograph by W. E. Scott).**

Waythomas et al., 2010 [this issue]). Unit 4 is typically decimeters to 2 m thick and comprises centimeters-thick beds of ash and accretionary lapilli (granule size aggregates of ash) deposited by fallout and surges. The abundance of accretionary lapilli suggests that the deposits resulted from explosions at least in part produced by interaction of lake or ground water with the magma. A likely explanation is that as the eruption waned, water was able to flow toward the vent and interact with magma, thereby generating steam-rich explosions that typically produce accretionary lapilli and surges. In numerous places this mantle of fine-grained material became sufficiently saturated by rain after the eruption to fail in shallow landslides that continued downslope as debris flows of mud, mud lumps, and pumiceous and lithic fragments (Fig. 8).

### *RELATIONSHIP OF DEPOSITS TO ERUPTION CHRONOLOGY*

Potential correlations of units 1 to 4 with the events detected by seismic, infrasound, marigram, and satellite observations are the subject of ongoing research. At this time, we do not have sufficient information to make such ties with confidence, but several possibilities exist.

The lack of evidence of ash-rich eruption clouds or of downwind ash fallout suggests that the initial and probably second eruptive pulses did not emplace voluminous deposits on the island. Unit 1, with its multiple beds and evidence of abundant lake sediment, may relate to one or both of these pulses. Perhaps explosions were expelling jets of water, muddy sediment, and a modest amount of juvenile tephra that produced high water-vapor-rich clouds but did not send much tephra to high altitude where it could be transported far downwind.

The types of deposits comprising units 2 and 3 are typical of those generated by vigorous eruption columns rich in ash and lapilli and likely relate to the time period when a high, continuous ash-rich eruption cloud was observed by satellites. We infer that, during this time, dense slugs of juvenile pyroclasts, coarse accidental lithic debris, and gas collapsed over the crater rim to produce pyroclastic flows that swept to the sea down all flanks of the volcano. Less dense juvenile ash and lapilli and some lithic material rose convectively from ash clouds elutriated from the pyroclastic flows and joined the convecting eruption column that transported significant amounts of ash to high altitude and downwind. Pauses in flow and surge activity during deposition of unit 3 allowed fallout of lapilli and ash to accumulate and be preserved on the island. The deposits of units 2 and 3 may chiefly be the products of the third explosive burst and some or all of the ensuing hours of continuous ash emission, including bursts four and five.

The deposits of unit 4 are consistent with a waning eruption rate and renewed access of water to the rising magma. Unit 4 was probably emplaced chiefly during the last six hours of the eruption.

A fuller understanding of the details of the timing of deposition of units 1 to 4 awaits additional field and laboratory studies.

## Continued Diffuse Degassing?

During fieldwork in June and August 2009 it was evident that Kasatochi was still emitting volcanic gas. Odors of both $SO_2$ and $H_2S$ were persistent on the lee side of the island, both onshore and for several kilometers downwind. We were unable to make quantitative measurements of the flux of either gas. Residents of Adak, 80 km distant, also reported that, since the August 2008 eruption, sulfurous odors were not uncommon when winds blew from the east-northeast—the direction of Kasatochi.

We and other members of the interdisciplinary team hiked over much of the island, chiefly the western, southern, and eastern outer flanks, and observed and photographed the crater from the rim. No evidence of significant fumaroles, such as condensed vapor plumes or characteristic mineral deposits, was found and recent photographs from passing aircraft and satellites revealed no evidence of bubbling through the lake. We therefore infer that gas was probably emerging from cracks and other diffuse sources, but at rates sufficiently low and at temperatures near enough to ambient that the release was not observable. We discount the possibility that the gas came solely from diffusion through the lake because solubility of sulfur gases in water is high and, without bubbling, the flux of $SO_2$ and $H_2S$ would probably be too low to produce the witnessed effects.

In emissions from arc volcanoes such as Kasatochi, $CO_2$ generally accompanies sulfur gases in at least equal, and often much greater amounts (Motyka et al., 1994). Thus we expect that the sulfur gases smelled in summer 2009 were accompanied by odorless $CO_2$, for which two apparent asphyxiation events offer some confirmation.

Two dead fork-tailed storm-petrels (*Oceanodroma furcata*) were found about 30 cm apart in a slight depression at the northern edge of Troll talus on the southwest flank (Fig. 4). In the depression, slightly warmer than ambient air was escaping from 2–3 small cracks (a few centimeters in maximum width) fringed with live moss. Because there was no obvious sign of trauma and because the two birds were found together, both in natural breast and head-down positions, and near breeding habitat, they were probably asphyxiated (J. Williams, USFWS, written and oral communications, 2009) by heavier-than-air $CO_2$ that had accumulated in the depression. We have no way to evaluate what portion of nearby nesting burrows would also have had toxic levels of $CO_2$.

In addition, a cluster of 46 dead scathophagid flies was found in a tight group in a crevice in older basaltic lava about 1 km north-northwest of the dead-bird site. Sikes and Slowik (2010 [this issue]) consider it likely that these flies were asphyxiated by $CO_2$ because the lack of decomposition indicates the flies had died recently, and the presence of so many together argues against starvation. Both locations of apparent asphyxiation span about one seventh of the circumference of the island and are closer to the coast than to the crater rim. They were found within a day or two of each other and thus are nearly coincident in time. If asphyxiation by $CO_2$ is in fact the reason for these deaths, then their location provides further evidence that gas-emitting cracks were widely dispersed.

Post-eruptive degassing over a period of many months is common at arc volcanoes and is most evident from the vent or from vigorous fumaroles. In contrast, the role of less vigorous and more diffuse post-eruptive sources is poorly known. Efflux of volcanic gases at Kasatochi as witnessed in summer 2009 was probably occurring chiefly through diffuse sources that included a widely distributed system of cracks. Despite the low flow rate inferred at individual cracks, the combined gas production may have been quite high. Kasatochi was perhaps among the chief gas-producing Alaska volcanoes during 2009.

## Summary and Outlook

The 7–8 August 2008 eruption of Kasatochi was heralded by a brief period of intense seismicity that ranks as the most energetic seen before any Alaska eruption of the recent past (Ruppert et al., in review). In addition, the eruption released the largest amount of $SO_2$ of any eruption worldwide since 1991 (Karagulian et al., 2010).

The eruption radically altered the island's landscape to a condition not extant since a similar eruption at least several centuries to ~1000 yrs ago. Initial events were marked by water-rich, ash-poor eruption plumes and ejection of water, mud, and pumiceous tephra that probably coated the island. The climax of the eruption was a ~10-hr period of continuous tephra emission, punctuated by several more intense bursts, and accompanied by pyroclastic flows and surges that swept down all flanks of the volcano into the sea. They built fans and aprons up to tens of meters thick chiefly seaward of the cliffs that ringed most of the island, which resulted in a ~40% increase in island area. What had been a rocky near-shore zone with productive kelp beds was buried out to the former 10- to 20-m isobath by sandy and gravelly deposits of pumice and lithic debris. On island slopes above the old sea cliffs, the density currents left a sequence of granular deposits decimeters to locally more than 10 m thick that tend to be thickest in former valleys and swales and thinnest on ridges. Heat, impact, erosion, and burial attributed to the flows variably affected the former vegetation, turf, and soil, but in some areas the newly exposed former surface was sprouting plants by June 2009. About 6 hrs of waning tephra emission deposited an additional mantle of chiefly fine-grained ash over most of the island. Its effects were twofold, resulting in a low-permeability surface layer that enhanced surface runoff and initiated substantial gullying and stripping of 2008 deposits from portions of the old ground surface; and creating a mucky-when-wet, desiccation-cracked-when-dry substrate to challenge revegetation.

Several important auklet nesting sites in taluses were buried or plugged; how long they will remain unusable is not known. Coastal sea-lion rookeries fared somewhat better. Although buried, erosion by waves and coastal retreat during winter 2008–2009 cleaned these sites and made them available by spring and summer 2009.

The post-eruption evolution of the island includes continuing erosion of 2008 deposits on the flanks, retreating sea cliffs in the pyroclastic fans and aprons, chiefly in the northern part of the island, and accretion of beaches chiefly in the southern part. Whether this situation continues to unfold or is interrupted by renewed eruptive activity in the coming years or decades remains to be seen. In the meantime, the island will continue to provide an exciting laboratory for ecological research, as well as for soil (Wang, et al., 2010 [this issue]) and geomorphic studies (Waythomas et al., 2010 [this issue]) that track the evolution of slopes and coasts as the landscape responds to the profound changes induced by the 2008 eruption.

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