Alaska Park Science

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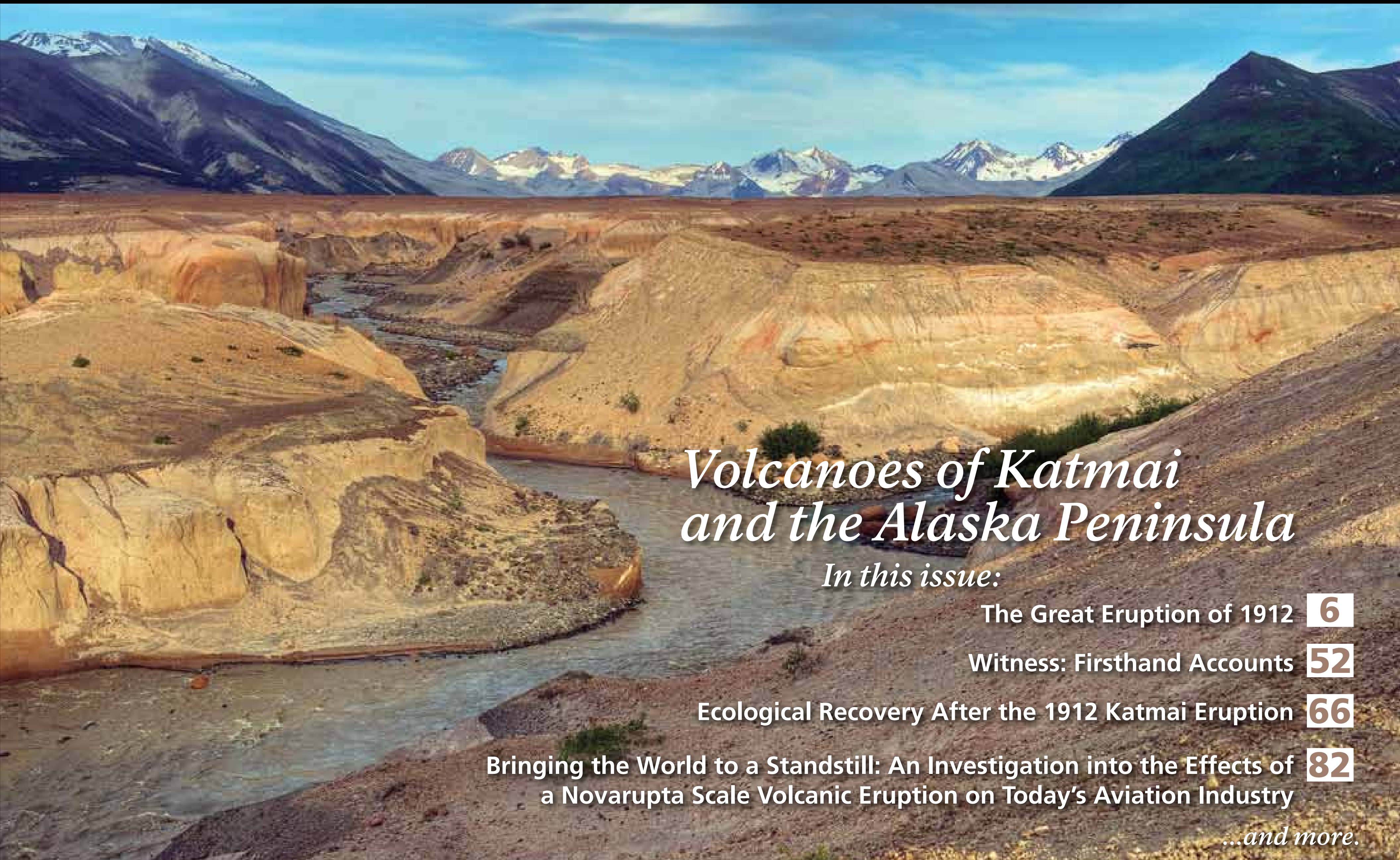

Volcanoes of Katmai and the Alaska Peninsula

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NPS photograph by Roy Woods

Backcover Photo: Lower Lethe River.

Photograph courtesy of Gary Freeburg.

Erratic boulder in Katmai Pass.

Photograph courtesy of Gary Freeburg.

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The Valley of Ten Thousand Smokes: Revisiting the Alaska Sublime

By Gary Freeburg

The story of the Valley of Ten Thousand Smokes begins on June 6, 1912, with the largest volcanic eruption recorded on Earth during the twentieth century. The eruption took place on the Alaska Peninsula 100 miles (161 km) west of Kodiak, Alaska. In three days, a new volcano, Novarupta, was born. This volcano ejected five cubic miles (21 km^3) of ash and debris into the atmosphere, with heavier deposits filling an adjacent 44 square mile (114 km^2) valley in depths up to 1,000 feet (305 m). The dense, superheated waves of magmatic spray coming from the volcano incinerated all living organisms in their path, leaving a hot bed of igneous material that, when mixed with water from the surrounding glaciers and snowfields, produced thousands of steam vents known as fumaroles.

Robert F. Griggs, Director of the National Geographic Society Katmai expeditions of 1915, 1916, 1917, and 1919, was the first person to discover the steaming valley on July 31, 1916. He ascended Katmai Pass, observed his surroundings, and wrote:

The sight that flashed into view as we surmounted the hillock was one of the most amazing visions ever beheld by mortal eye. The whole valley as far as the eye could reach was full of hundreds, no thousands – literally, tens of thousands – of smokes curling up from its fissured floor. The first glance was enough to assure us that we had stumbled into another Yellowstone Park – unseen and unsuspected by white man and native alike until this hour. I tried to "keep my head" and observe carefully, yet I exposed two films from my one precious roll in trying for pictures that I should have known were impossible. It was as though all the steam engines in the world, assembled together, had popped their safety valves at once and were letting off surplus steam in concert. (*Griggs 1918*)

Figure 1. Knife Creek Canyon revealed below a decaying snow bridge.

Photograph courtesy of Gary Freeburg.

I have visited the Valley of Ten Thousand Smokes five times between 2000 and 2011. The smokes (fumaroles) that Griggs talks about are mostly gone, that element of visual and volcanic activity has largely ceased. As I walked in the footsteps of Griggs, I imagined the deafening noise and incredible physical forces of the 1912 explosion and contrast that historic event with what I now perceive as a monumental statement of sublime beauty and geological silence.

Being completely alone in the Valley and its 44 square miles was a fulfilling experience. Like Griggs and his companions a century ago, I created these photographs to document and express what I have come to know of this special place on Earth, a landscape that nurtures my contemplative spirit and personal desire to be in wild places. I hope that as you review this issue of *Alaska Park Science*, that you will also gain a sense of the awe and respect that Robert Griggs and so many others have felt when experiencing the Valley of Ten Thousand Smokes.

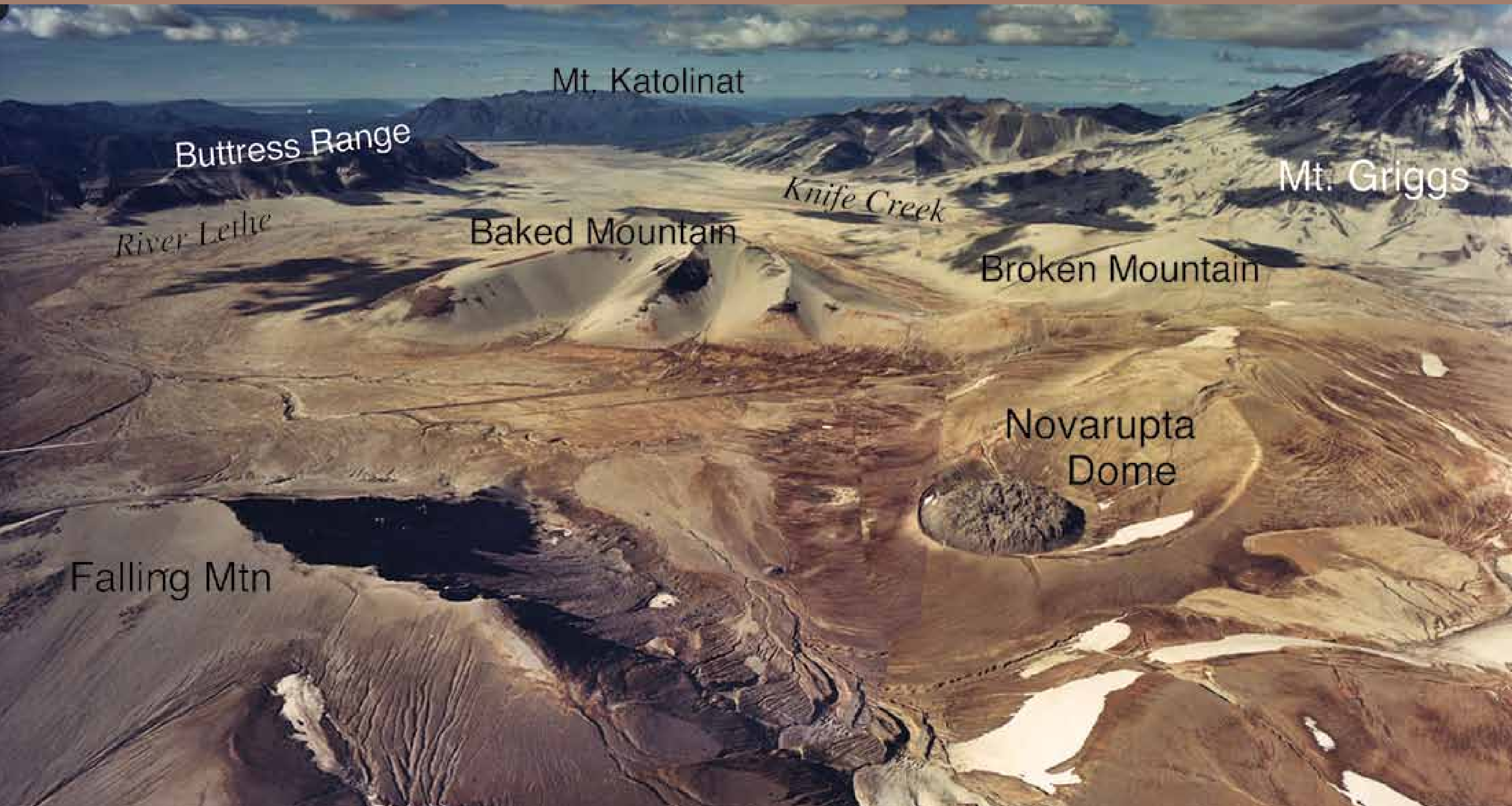
Information about Gary Freeburg's book, *The Valley of 10,000 Smokes: Revisiting the Alaskan Sublime*, and more images can be found at George F. Thompson Publishing.

Figure 2. Extinct fumarole central in the ignimbrite sheet looking northwest.

Photograph courtesy of Gary Freeburg.

REFERENCES

Griggs, R.F. 1918.
The Valley of Ten Thousand Smokes: An Account of the Discovery and Exploration of the Most Wonderful Volcanic Region in the World. The National Geographic Magazine 33(2): 115-169.


Mt. Katolinat
Buttress Range
Mt. Griggs
Knife Creek
River Lethe
Baked Mountain
Broken Mountain
Novarupta
Dome
Falling Mtn

The Great Eruption of 1912

By Judy Fierstein

Introduction

The largest volcanic eruption of the twentieth century exploded June 6, 1912, from a new volcano, Novarupta, creating Katmai caldera and the Valley of Ten Thousand Smokes (*Figure 1*). Volcanic ash, more than from all other historical eruptions in Alaska combined, devastated areas hundreds of miles away, and the huge eruption column rose so high that stratospheric winds carried the ash around the world. The great eruption of 1912 lasted for three days. It focused scientific attention on Novarupta and the hot ash flows that caused the "Ten Thousand Smokes", but its significance for the developing science of volcanology involved far more than size alone. Subsequent research there has taught us much about the processes and hazards associated with such large explosive events (*Hildreth and Fierstein 2012*). The following explains not only how the 1912 events have remained scientifically important for 100 years, but also why the 1912 deposits continue to provide insights about volcanic and magmatic processes that impact us and the land we live in.

Great Eruption of 1912, at Novarupta: The Exceptional Event

The magnitude and volume of the eruption at Novarupta in 1912 were exceptional, far larger than any other historical eruption in North America (*Figure 2*). This fueled early U.S. Geological Survey and National Geographic Society scientific investigations that provided provocative perspectives and helped to shape thinking about volcanoes and magmas (*Martin 1913, Griggs 1922*). For the first time in recorded history, a great explosive eruption deposited its pyroclastic flows on land rather than in the sea (as at Krakatau in 1883), so that they could be studied in detail. It was also one of the few places where it was recognized that a wide range of magma compositions erupted together. Rhyolite, dacite and andesite magmas (each containing different amounts of silica) swirled together to create white and black 'banded' pumice (*Figure 3*), an unusual occurrence that instigated debates about how these evolved together in the underground plumbing system. These unusual conditions and fascination with the "Ten Thousand Smokes" led President Wilson to preserve Katmai National Monument in 1918 for popular, scenic and scientific interest.

Despite this attention, the eruption and its products remained poorly understood, owing in part to remoteness and difficult field conditions, but also because of a poor understanding of explosive eruptions in general and failure to identify the actual vent for the 1912 ejecta. Many decades passed before Garniss Curtis (*1968*) established that the vent was Novarupta, not Mount Katmai as had previously been supposed. Early investigators Clarence N. Fenner and Robert F. Griggs mistakenly identified Mount Katmai as the vent for the eruption, because the near-vertical cliffs that surround the summit crater lake were fresh and glacier-free when first observed in 1916, and vigorous gas jets (fumaroles) ringed the caldera floor. Curtis' work showed clearly that although Mount Katmai did collapse during the eruption, because most of the magma had been stored beneath it, almost all the magma vented at Novarupta 6 miles (10 km) away. A magma chamber and caldera located so far from the erupting vent is highly unusual. Understanding the underground conditions or "plumbing system," which enabled this, spurred debate that continues today.

Over the last three decades, detailed studies of Novarupta deposits have contributed to a better understanding of how volcanoes work, how explosive pumice and ash erupt and are emplaced, how calderas collapse, and what happened at the vent during the 3-day eruption (*Hildreth 1983, 1987, 1991, Fierstein and Hildreth 1992, Fierstein and Nathenson 1992, Fierstein et al. 1997, Hildreth and Fierstein 2000, Houghton et al. 2004, Fierstein and Wilson 2005, Hildreth and Fierstein 2012*).

The "View from Afar" presented below is an overview of the eruption based on eyewitness reports and data recorded during the eruptions, all from a substantial distance. This is followed by "The Eruption Up-close", a summary of events as they unfolded at and near the vent. Although no eyewitnesses could have survived near the vent, volcanologists pieced together what happened through detailed observations of the deposits left behind. The unique combination of an eruption at Novarupta with collapse 6 miles (10 km) away at Mount Katmai provides an ideal opportunity for such studies. Nowhere else do young deposits from such a big eruption provide a geologic record up to the vent itself.

View From Afar

Initial signs of an impending eruption began with severe earthquakes felt at Katmai village on the Shelikof Strait coast "for at least 5 days prior to the eruption" (*Martin 1913*). More were felt on June 4 and 5, including as much as 160 miles (250 km) to the northeast, prompting the few inhabitants at Katmai village to evacuate by

Figure 1. Aerial panorama of flat-floored Valley of Ten Thousand Smokes, extending 12.5 miles (20 km) northwest from vent at Novarupta to distant Mount Katolinat. Novarupta lava dome is encircled by asymmetrical ring of accumulated pumice from eruptive Episodes II and III.

canoe down the coast toward Cold Bay (now Puale Bay). Unrest continued, as explosions were heard 140 miles (230 km) away on the morning of June 6. Not until 1 p.m. (Alaskan time) was the first towering eruption cloud witnessed by crew members of the steamer Dora, then in Shelikof Strait. Two hours later darkness abruptly enveloped the vessel as it was overtaken by the choking ash. Lightning flashed from the black cloud overhead as Captain McMullen changed course from the intended stop at Kodiak and headed toward the open Gulf of Alaska. Even “full steam ahead”, the Dora remained under the ash cloud until early the next day.

At Kodiak, 100 miles (160 km) southeast of the eruption center, the air became thick with ash and, for 60 hours, darkness was so complete that a lantern held at arm’s length could scarcely be seen. The terrified townspeople, some temporarily blinded by the sulfurous gas, crowded onto the U.S. Revenue Cutter Manning docked in Kodiak harbor, while one foot of ash (30 cm) smothered their town with three closely spaced periods of ash fall. The weight of the ash collapsed roofs in Kodiak; buildings were wrecked by ash avalanches that rushed down from nearby hill slopes; other structures burned after being struck by lightning from the ash cloud; and water became undrinkable.

Effects of the ash were felt worldwide. From the vent at Novarupta, the towering column of ash, called a plinian eruption column, jetted skyward with little interruption for 60 hours. Concurrently, it distributed ash flows that filled the Valley of Ten Thousand Smokes and fed a high umbrella cloud more than 1,000 miles (1,600 km) wide that shrouded most of southern Alaska and the Yukon Territory. Once the ash cloud had been sighted, it rapidly rose to a height greater than 100,000 ft (>30 km), where the jet stream carried much of it eastward. Strongly aided by winds blowing east-southeastward, ash fall began at Kodiak within 4 hours and by the next day had spread 625 miles (1,000 km) east and at least 60 miles (100 km) west. By midnight of the first day, 11 hours into the eruption, enough magma had escaped from beneath Mount Katmai that about 1.2 cubic miles (5 cubic km) of its summit collapsed. The collapse resulted in a 1.5-mile (2.5-km)-wide caldera, which has since accumulated a lake about 800 feet (250 m) deep (*Figure 4*). Caldera collapse was accompanied by 14 earthquakes of magnitudes 6 to 7, 100 shocks greater than magnitude 5, and countless smaller shocks (*Figure 5*). By June 9, when the main outpouring finally ceased at Novarupta and the day dawned clear at Kodiak, the advancing ash cloud had begun dropping sulfur-permeated fallout on Puget Sound in Washington State. On the following day, the cloud passed over Virginia, and by June 17 it reached Algeria. Atmospheric effects (haze, smoke, red twilights) had been observed downwind, beginning in British Columbia on June 6, and in European locations two weeks later. The great quantity of ash and aerosol not only caused unusually brilliant sunsets, but, by shielding the sun’s rays, lowered average temperatures by about 2°F (1°C) in the Northern Hemisphere for more than a year. Wind remobilization of the finest ash from the Valley of Ten Thousand Smokes during dry spells continues, a century later, to loft occasional dust clouds to elevations of thousands of meters.

The Eruption Up-Close

The 60-hour-long explosive sequence at Novarupta consisted of three discrete episodes (*Figure 6*), separated by lulls of at most a few hours duration (*Martin 1913, Hildreth 1983, Fierstein and Hildreth 1992*). During Episode I, the volume and rate at which the pumice and ash were ejected from the vent were so great that some of it went upward into the towering eruption column to be distributed widely by regional and stratospheric winds and deposited as ash fall (or, pyroclastic fall), while some flooded

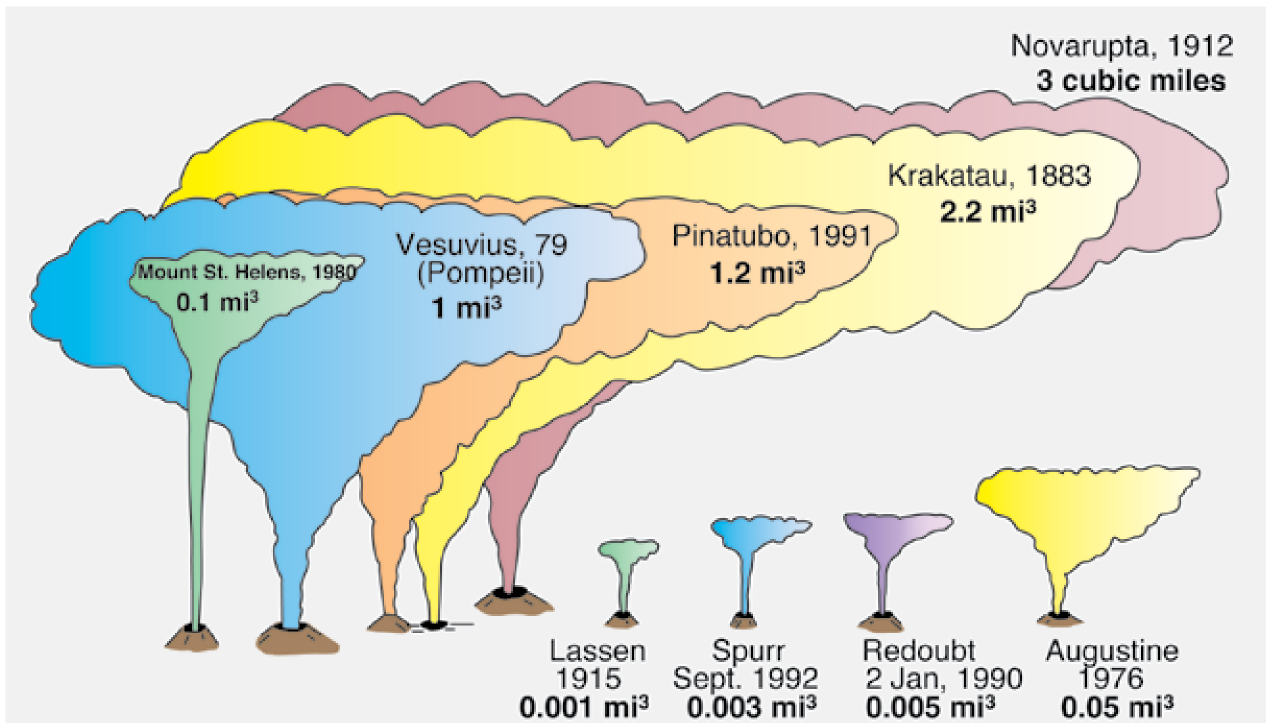


Figure 2. Comparisons of erupted magma volumes. The magnitude and volume of the eruption at Novarupta in 1912 were exceptional.

the vent area, flowing down the surrounding valleys and filling them as deep as 600 feet (200 m). These ash flows (or pumiceous pyroclastic flows, also called ignimbrites) remained hot for several decades, earning the name "Ten Thousand Smokes" for the many steaming cracks and fissures where surface waters that entered the hot ash-flow deposits were expelled as steam (*Figure 7*). Episode I left a 1.25-mile (2-km)-wide depression, filled with pumice and ash from its own eruption. Fault scarps caused by collapse and subsidence in 1912 encircle the area that provided the vent for the first day of eruption (*Figure 8*). Within this large ash-flow vent the subsequent eruptions bored through the partly consolidated deposits of Episode I, through a smaller vent that produced the ash falls of the next two days. These eruptions, Episodes II and III, also built a ring of pumice-rich ejecta around their smaller vent, which was plugged by the Novarupta lava dome that extruded after all the explosive activity was over.

In order to decipher what was happening at the vent on June 6-9, 1912, volcanologists look carefully at the surrounding deposits. The key to understanding these up-close events relies on being able to distinguish the three pumice types that make up the deposits: white rhyolite containing few mineral crystals, or phenocrysts; white to grey dacite with abundant crystals; and brown to black andesite, also with abundant crystals. Although ejected together throughout much of the eruption, their relative proportions varied with time. These variations were used to track the dispersal, character and thickness of each layer (first recognized and named Layers A through H by Curtis), both around the vent and in more distant locations, and that information was used to piece together what happened during those three days in 1912 (*Hildreth 1983*, *Fierstein and Hildreth 1992*).

Episode I

Episode I began with widespread dispersal of purely rhyolitic fallout (Layer A) and synchronous emplacement of rhyolitic ash flows from the same high eruption column. After ejection of ~0.7 cubic miles (~3 km^3) of rhyolitic magma over the course of a few hours, small amounts of andesitic and dacitic magma began contributing to the eruption column, marking the onset of plinian Layer B (*Figure 6*). Pumice proportions in Layer B change from more than 99% rhyolite at its base to only about 15% at its top, matching the progressive shifts in (rhyolite/dacite/andesite) pumice proportions in the main sequence of ash-flow pulses, or packages, emplaced concurrently in the Valley of Ten Thousand Smokes (*Fierstein and Hildreth 1992, Fierstein and Wilson 2005*). By 0910 on June 7, ash-flow emplacement was over and ash fall stopped at Kodiak for a short time. Episode I lasted about 16 hours and produced almost all of the Valley of Ten Thousand Smokes ash flows (~2.6 mi^3, 11 km^3) and roughly half of the fall deposits (2.1 of 4 mi^3, 8.8 of 17 km^3).

Episodes II and III

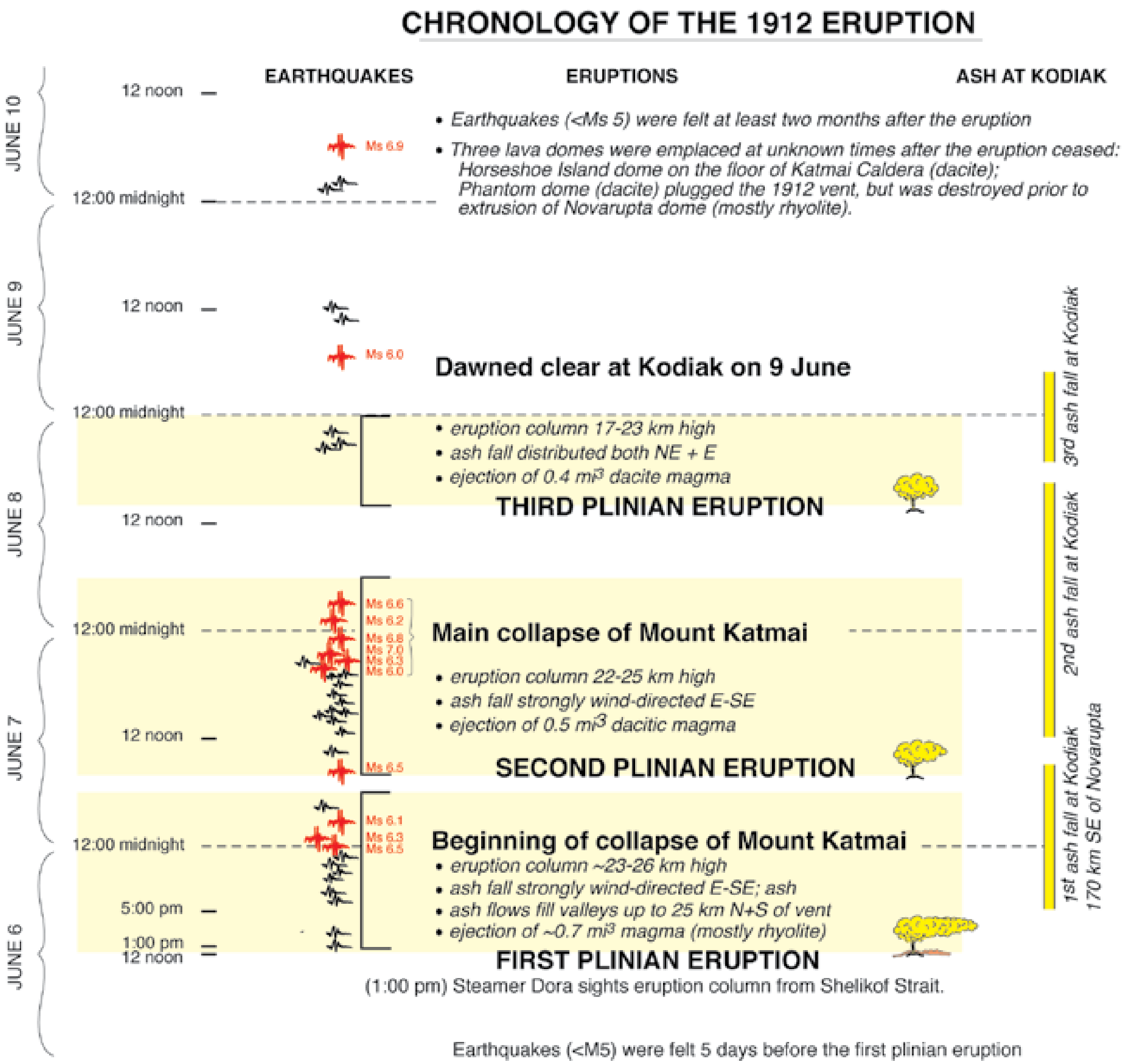
Episodes II and III were similar to one another; each began after an eruptive lull, then erupted from a smaller vent nested inside the larger one of Episode I. Each

Photograph courtesy of W. Hildreth

Figure 3. Representative pumices from 1912 eruption: white crystal-poor rhyolite, pale gray crystal-rich dacite, black crystal-rich andesite, and rhyolite-andesite banded pumice.

Photograph courtesy of J. Fierstein

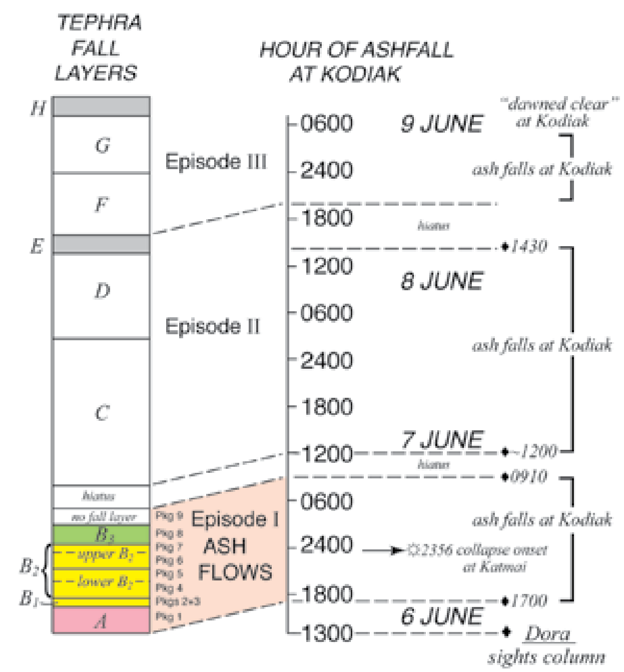
Figure 4. Aerial view southward overlooking Katmai caldera, formed by collapse in 1912, when Novarupta erupted 6 miles (10 km) away. The steep walls of the caldera truncate glacier-filled valleys that formerly continued upward to summits of two distinct peaks.



Graphic courtesy of J. Fierstein

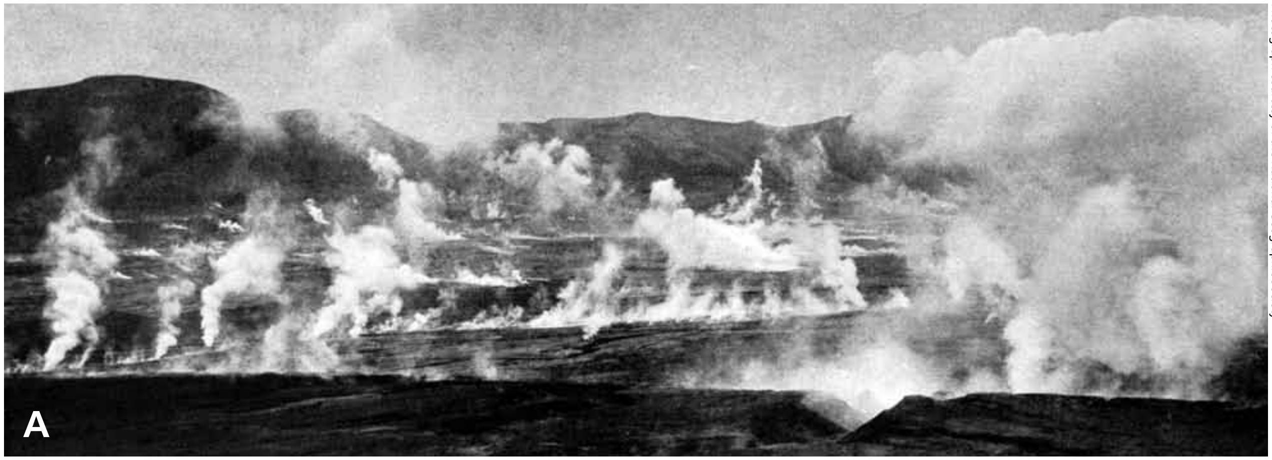
Figure 5. Chronology of 1912 eruption of Novarupta. Earthquakes felt by local residents during preceding 5 days prompted evacuation to what they hoped were safer havens. Ms=earthquake surface-wave magnitude as measured on Richter scale. Although only one seismograph was operating in Alaska at the time of the eruption, many of the earthquakes were big enough to be recorded by instruments in Europe, Asia, Japan, Hawaii, North Africa and North America (Abe 1992).

deposited widespread fall layers (Layers C-D, and F-G, respectively), which were almost entirely dacitic. As with the preceding ash falls, Layers C and D were strongly dispersed east-southeastward, but the wind relented and the subsequent ash falls were less strongly directed toward Kodiak (*Figure 9*). Layers E and H are largely accumulations of fine ash that settled regionally in the relative calm after each eruptive episode. Almost all of the deposits from these two episodes are widespread ash falls, but near the vent, short-traveled ash flows are preserved as well. Some of these, deposited from small explosions during the lull between the Episode II and III eruption columns, show the vent remained unsettled during this time.



Graphic courtesy of J. Fierstein

Figure 6. Generalized 1912 eruptive sequence and chronology of ashfall recorded at Kodiak village, about 100 miles (170 km) downwind. Four-hour offset at base represents time between initial sighting of eruption column by S.S. Dora and the beginning of ash fall at Kodiak.



Photograph courtesy of the National Geographic Society

Figure 7a. Steaming northwest arm of the Valley of Ten Thousand Smokes in 1917, view northwest toward long ridge of the Buttress Range.

Photograph courtesy of W. Hildreth

Figure 7b. (Left) Fumarolic fissure in welded ash-flow deposit on southwest bench of Baked Mountain. Deposits at top of fissure are windblown accumulations of remobilized pumice fall, with colorful alteration from steam and hot gases that deposited their dissolved minerals in and around the pieces of pumice. This fumarole was still producing a weak vapor plume when photographed in 1982, but is now filled in by wind-blown pumice and ash.

Three lava domes

The explosive episodes were followed by extrusion of three lava domes. Compared to the explosive violence of June 6-9, the growth of the domes was not much more than an afterthought of molten rock, largely rid of its former gas content, that slowly squeezed out of the vent. Though the exact timing is not known, these domes likely formed within days or as long as a year after the plinian events. One small dacite lava dome that plugged the Episode III vent was destroyed by small explosions; all that remains are lava blocks scattered atop Layer H (*Adams et al. 2006*). The same vent was plugged again by the rhyolitic Novarupta dome, which survives today. The third one is a dacite lava dome extruded on the floor of Katmai caldera, then partially disrupted explosively. Photographed by Griggs in 1916 and sampled by Fenner in 1923, it is now covered by the caldera lake.

Volcanological Significance of the 1912 Eruption

Many aspects of the three-day explosive eruption at Novarupta in June 1912 focused attention on this remote

USGS photograph

Figure 8. Aerial view southeastward over Novarupta toward Trident and Mount Katmai. The vent depression extends from pumice-covered Baked Mountain scarp on the left to 1,200-foot (400 m) high scarp of Falling Mountain on the right. It was created during the first day of the 1912 event and filled with pumice and ash from its own eruption. Compaction and welding caused arcuate fractures, and the Novarupta lava dome is surrounded by an asymmetrical ejecta ring from fallout from Episoes II and III. Katmai caldera is at upper left, and Shelikof Strait is in the distance, seen beyond the four peaks of Trident Volcano.

volcano, and it has become one of the most intensively studied in the world. Its eruptive volume of 3.1-3.4 mi^3 (13-14 km^3) of magma places it among the five largest in recorded history. At any time, such an eruption would attract much attention, but in 1912 the field of volcanology was in its infancy. Phenomena not previously seen or recognized anywhere else provided opportunities for a wide range of research. In addition to aspects already discussed, the eruption also led to pioneering studies in eruption dynamics and mechanisms of explosive eruptions, evolution of underground magma systems that produce volcanoes, and high-temperature vapor transport in fumaroles with relevance to metallic ore deposition. Investigations continue today, with recent work using state-of-the-art analytical instruments that measure things as small as bubbles of fluid trapped in individual crystals in pumices; these tell us how hot the magma was and at what depth it was stored before erupting (*Coombs and Bacon, this volume*). Other investigations consider a larger scale, like those that examine how seismic waves generated by earthquakes travel through subsurface areas beneath the volcanoes; these provide underground images of where and how magma is stored (*Thurber et al., this volume*). Each new study uses previous work as a foundation. The focus on understanding the 1912 eruption and its products has led to significant advances in understanding volcanic and magmatic processes, what makes volcanoes erupt, and has changed the way scientists think about large explosive eruptions.

The 1912 eruption has also provided opportunities for

Photograph courtesy of W. Hildreth and J. Fierstein

Photograph courtesy of W. Hildreth and J. Fierstein

Photograph courtesy of W. Hildreth and J. Fierstein

Figure 9. Fall deposits at different distances from vent. Deposits are coarsest and thickest closest to vent, and get thinner and finer with distance. (A) Coarse dacite pumice fall deposits of Episodes II and III are about 36 feet (12 m) thick, 2.5 miles (4 km) northeast of Novarupta. Fall layers are labeled C-G. (B) Complete section of dacite fall deposits of Episodes II and III are 3 feet (1 m) thick, about 7 miles (11 km) upwind northwest of Novarupta. Fall layers are labeled C-H. Debris flow (df) on top is a flood deposit that covered the 1912 fall soon after the eruption. (C) Structureless white fine ash, about 8 inches (20 cm) thick, at Brooks Camp, which is about 30 miles (50 km) upwind northwest of Novarupta. This layer includes ash contributions from all three eruptive episodes. (D) Large block about 0.6 miles (1 km) from Novarupta dome that never went into the high eruption column. Instead, it was ejected ballistically at lower angles. The block is made up of rhyolite, dacite, and andesite pumice clasts welded together by heat inside the vent, then subsequently ejected.


D

Photograph courtesy of W. Hildreth and J. Fierstein

other types of research. Some have focused on the effects of the eruption on the surrounding environment, on flora and fauna, and on the people who lived there (*see articles by Sherriff et al., Coletti, Jorgenson et al., Schaaf, and Partnow, this volume*). Griggs' (*1933*) prediction of rapid re-vegetation in years to come has not been realized in areas of thick ash inundation in and near the Valley of Ten Thousand Smokes, but where fallout was thin or eroded, plants recovered quickly. Although greenery is again lush in places where the accumulated ash was less than ~3 feet (1 m) thick, windswept ash-flow surfaces are still largely barren a century later. Today's sparse vegetation provides little cover and meager food for the few animals that do venture into the Valley of Ten Thousand Smokes.

Novarupta, The Valley of Ten Thousand Smokes, and the Katmai volcanoes have been an open-air laboratory ever since Griggs' time. Volcanological studies here have shaped how geologists think about explosive eruptions and continue to provide insights into a wide range of aspects about how volcanoes work.

REFERENCES

Abe, K. 1992.
Seismicity of the caldera-making eruption of Mount Katmai, Alaska, in 1912. Bulletin of the Seismological Society of America 82: 175-191.

Adams, N.K., B.F. Houghton, S.A. Fagents, and W. Hildreth. 2006.
The transition from explosive to effusive eruptive regime: The example of the 1912 Novarupta eruption, Alaska. Geological Society of America Bulletin 118: 620-634.

Curtis, G.H. 1968.
The stratigraphy of the ejecta from the 1912 eruption of Mount Katmai and Novarupta, Alaska. In Studies in Volcanology, edited by R.R. Coats, R.L. Hay, and C.A. Anderson. Geological Society of America Memoir 116: 153-210.

Fierstein, J., and W. Hildreth. 1992.
The plinian eruptions of 1912 at Novarupta, Katmai National Park, Alaska. Bulletin of Volcanology 54: 646-684.

Fierstein, J., and M. Nathenson. 1992.
Another look at the calculation of fallout tephra volumes. Bulletin of Volcanology 54: 156-167.

Fierstein, J., B.F. Houghton, C.J.N. Wilson, and W. Hildreth. 1997.
Complexities of plinian fall deposition at vent: An example from the 1912 Novarupta eruption. Journal of Volcanology and Geothermal Research 76: 215-227.

Fierstein, J., and C.J.N. Wilson. 2005.
Assembling an ignimbrite: Compositionally defined eruptive packages in the 1912 Valley of Ten Thousand Smokes, Alaska. Geological Society of America Bulletin 117: 1094-1107.

Griggs, R.F. 1922.
The Valley of Ten Thousand Smokes. National Geographic Society. Washington, D.C.

Griggs, R.F. 1933.
The colonization of the Katmai ash, a new and inorganic "soil". American. Journal of Botany 20: 92-113.

Hildreth, W. 1983.
The compositionally zoned eruption of 1912 in the Valley of Ten Thousand Smokes, Katmai National Park, Alaska. Journal of Volcanology and Geothermal Research 18: 1-55.

Hildreth, W. 1987.
New Perspectives on the eruption of 1912 in the Valley of Ten Thousand Smokes, Katmai National Park, Alaska. Bulletin of Volcanology 49: 680-693.

Hildreth, W. 1991.
The timing of caldera collapse at Mount Katmai in response to magma withdrawal toward Novarupta. Geophysical Research Letters 18: 1541-1544.

Hildreth, W., and J. Fierstein. 2000.
Katmai volcanic cluster and the great eruption of 1912. Geological Society of America Bulletin [GSA Overview Paper] 112: 1594-1620.

Hildreth, W., and J. Fierstein. 2012.
The Novarupta-Katmai Eruption of 1912: Largest Eruption of the Twentieth Century. Centennial Perspecitves. U.S. Geological Survey Professional Paper 1791.

Houghton, B.F., C.J.N. Wilson, J. Fierstein, and W. Hildreth. 2004.
Complex proximal deposition during the plinian eruptions of 1912 at Novarupta, Alaska. Bulletin of Volcanology 66: 95-133.

Martin, G.C. 1913.
*The recent eruption of Katmai volcano in Alaska***.** National Geographic Magazine 24: 131-181.

Katmai National Park Volcanoes

By Judy Fierstein

Introduction

The explosive eruption of Novarupta on June 6-8, 1912, was the world's most voluminous of the twentieth century and made the remote Katmai region famous. But Novarupta is hardly alone in the area. It is part of the Aleutian volcanic arc, the curving chain of volcanoes extending from southcentral Alaska to the far western end of the Aleutian Islands, and one of the most active volcanic regions in the world (*Simkin and Siebert 1994*). Geologic studies in the last two decades have identified more than 50 discrete volcanic vents in Katmai National Park and Preserve, less than half of which had been previously named. Most of these vents form a narrow line of ice-clad stratovolcanoes on the drainage divide of the Alaska Peninsula, which makes up the Aleutian arc segment that stretches from Mount Douglas to Peulik.

Twenty of the volcanic vents in the park are within 15 km of Novarupta (*Hildreth and Fierstein 2000, Hildreth et al. 1999, 2000, 2001, 2002, 2003a, 2003b, 2004*) . This unusually dense grouping around Novarupta, called the Katmai cluster, includes the four stratovolcanoes Mounts Katmai, Mageik, Martin, and Griggs; the cluster of volcanic vents called Trident Volcano; Snowy Mountain; the three lava domes Novarupta, Mount Cerberus, and Falling Mountain, and the extinct Alagogshak stratovolcano.

The Katmai cluster is still active, with fumaroles and steam vents on all of the stratovolcanoes but Alagogshak. The most recent eruptions were from a new vent on Trident Volcano (*Southwest Trident, 1953-74*), but ash deposits indicate that there have been at least eight other explosive events from the volcanoes of this area in the past 10,000 years. Activity continues in the northeast corner of the park as well, with steam explosions from Fourpeaked volcano in 2006, prolonged vigorous steaming coating snow-covered Kukak with yellow sulfur, and gas bubbling up through Kaguyak's caldera lake. All of these rugged and active volcanoes contribute to spectacular scenery in this remote and sparsely inhabited wilderness on the Alaska Peninsula, ready for exploration by the adventurous and hardy. What follows is a brief geologic summary of some of the volcanoes in Katmai National Park and Preserve, an explanation of how geologists unravel a volcano's eruptive history, and what that history can tell us about possible eruptions to come. We begin with an overview of Alaska's volcanoes in a global context, as part of the "Ring of Fire".

Figure 1. Mount Griggs andesitic stratovolcano, the highest peak in the Katmai cluster; aerial view northward across upper Knife Creek arm of Valley of Ten Thousand Smokes.

USGS photograph by W. Hildreth

Ring of Fire

Volcanoes in the park and the Aleutian volcanic arc are part of the circum-Pacific "Ring of Fire", a series of volcanic chains that ring the Pacific Ocean. This Ring of Fire marks the boundaries of the shifting plates that make up the earth's crust. Great stress accumulates along these boundaries as the plates move under, over and past each other, and the resulting strain has long been linked to seismic and magmatic activity. These stresses continue today, which is why many volcanoes in in the park are quite active.

Volcanoes of the Park: Long Histories —a Key to the Future

Understanding the eruptive history of a volcano provides the best clues as to when, how, and on what scale the volcano may erupt in the future. These histories are chronicles of past eruptions, pieced together using what we know about the lava flows and ash deposits that erupted throughout the volcano's lifetime. Geologists unravel these volcano stories in detective fashion by mapping the distribution of lava flows and ash deposits, establishing the order of eruptive events, and using radiometric dating to determine the age of the rocks and ash deposits. Ash layers are distinguished from one another by geochemical fingerprinting. By determining their chemical compositions, ash layers can then correlated to their source vents by comparison with lava compositions. This information provides geologists with insights into the behavior of individual volcanoes, how often they erupt, and permits assessment of what types of volcanic hazards are most likely associated with them.

Geologic work in the last two decades has established eruptive histories for a number of the volcanoes in the park (*Hildreth and Fierstein 2003, Hildreth et al. 2003b; Hildreth et al. 2004, Fierstein and Hildreth 2008*). The histories are long in a human timeframe (some are more than one million years old), and many people are not used to thinking about events on that timescale.

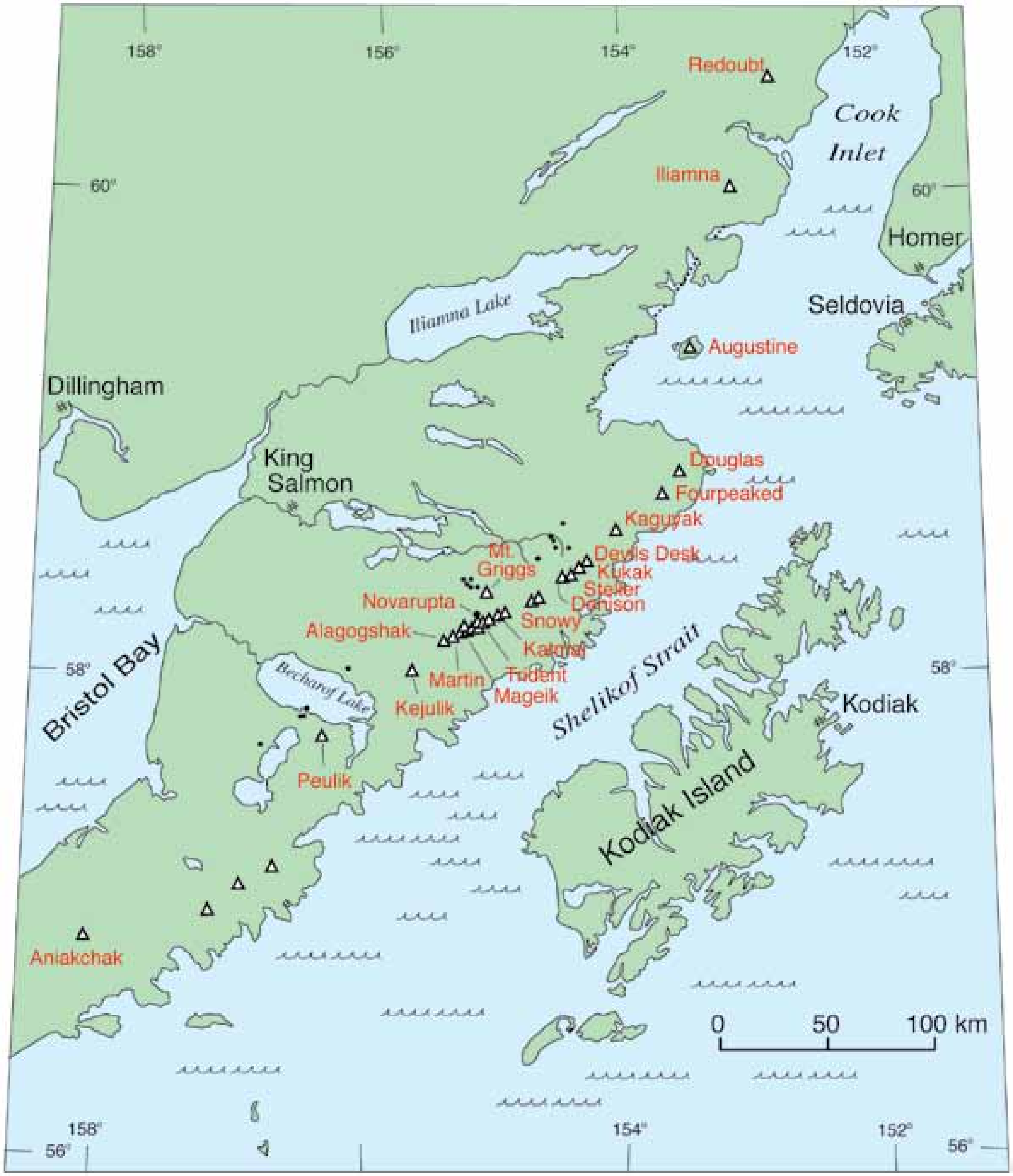


Figure 2. Map of upper Alaska Peninsula and Kodiak Island group, showing names of volcanoes (triangles) along part of Aleutian arc.

But geologists consider a volcano's entire lifetime in assessing its eruptive history so as not to miss infrequent, but important, events. Most of the time volcanoes are quiet, punctuated only sporadically by short periods of eruptive activity. These active periods, although short on a volcano timetable, are typically decades to centuries long and can have a big effect on generations of humans.

The intermittent episodes of activity that built each of the Katmai volcanoes spanned years to centuries, and even millennia, and each episode included multiple eruptive events. Some episodes are dominated by small lava flows, and some include many separate events of ash ejection as well as lava-flow extrusions. Some lava extrusions travel far from their vents and make elongate lava flows, while other extrusions are short-traveled and pile up close to their vents to build lava accumulations called lava domes. Large explosive eruptions such as Novarupta are less common. They typically last only a few days but can be followed by weeks to years of lesser events (lava-dome extrusion, small-scale explosions, and continuing seismicity). The area that is now Katmai National Park and Preserve has produced a wide variety of volcanic activity.

Katmai Volcanoes

Recent work in the Katmai area has established an eruptive history for each of the Katmai cluster volcanoes and for Kaguyak volcanic center by mapping the distribution of eruptive products, and by describing in detail both lava flows and ash layers (*Hildreth and Fierstein 2003, Fierstein 2007*). Combined with the mapping, information about the ages of the deposits constrains the timing and frequency of past eruptions, which was used to make a volcano-hazard assessment for the Katmai cluster (*Fierstein and Hildreth 2001*). Brief descriptions of some of the better-studied Katmai volcanoes are summarized below.

Mount Griggs, the tallest peak in the district, rises to 7,600 ft (2,530 m) in elevation on the eastern margin of the Valley of Ten Thousand Smokes (*Figure 1*). A relatively symmetrical cone, it has three nested summit craters and several small glaciers radiating from its summit. Mount Griggs is largely armored by young lava flows, but a few remnants of older lavas show that the volcano has existed for at least 290,000 years. Much of the volcano was built by dozens of overlapping lava flows between 85,000 and 10,000 years ago. Within the last 10,000 years, collapse of the southwest part of the volcano left a mile-wide amphitheater near the summit and shed a large debris avalanche (rapidly moving slide mass of rock and debris) into the river valley below. Subsequent andesite lava flows nearly filled this scoop-shaped depression and covered the southwest slope of the volcano with a fan of blocky lava flows. Small-volume lavas have characterized the activity of Mount Griggs for a long time, and the volcano has had no recognized large ash-fall-producing explosive events (*Hildreth et al. 2002*). Yellow sulfurous fumaroles discharging vigorously near its summit show the volcano is still active.

Mount Katmai, centered 6 miles (10 km) east of Novarupta, is a stratovolcano that once consisted of a pair of large cone-shaped volcanoes with interfingered lava flows. Both cones were beheaded by the caldera collapse of 1912 (*Figure 3*) (see previous article). The two cones of Mount Katmai had been active for more than 70,000 years. Thick stacks of lava flows and sequences of pyroclastic deposits from explosive eruptions are exposed in the caldera walls, products of at least 20 eruptive episodes. Mount Katmai has a varied volcanic history, erupting products with a wide compositional range (basalt to rhyodacite). One of the largest and most explosive events ever to occur at the Katmai volcanic cluster originated from Mount Katmai about 23,000 years ago. Rhyodacite pumice-fall and ash-flow deposits from the eruption were widely distributed, but have since been largely scoured away by glaciers. Remnants of the pumice fall preserved in nearby creeks are so thick that it seems likely the eruption was more voluminous than that of Novarupta in 1912. Since then, Mount Katmai erupted at least four more times, with

USGS photograph by J. Fierstein

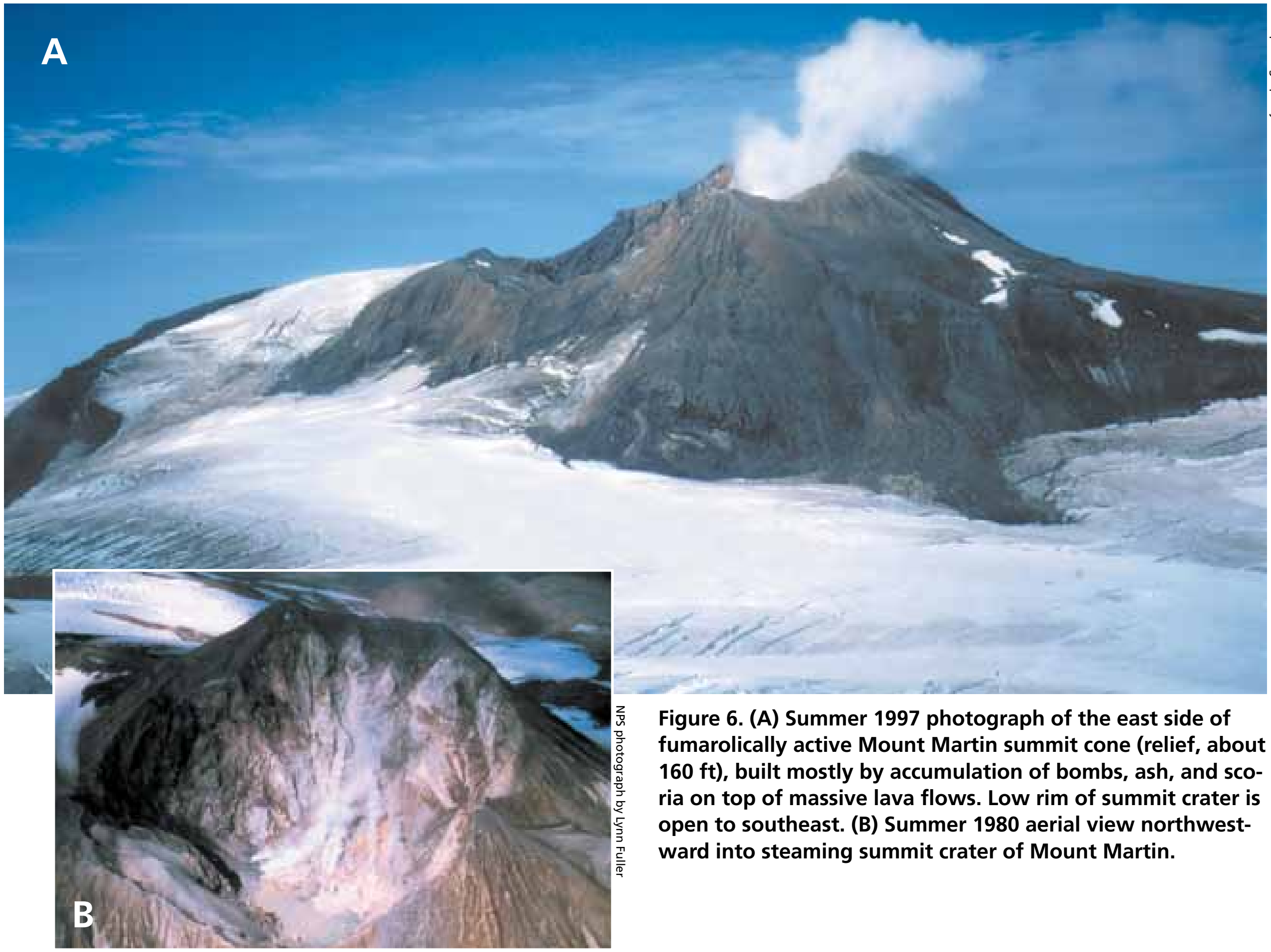
Figure 3. Aerial view looking southwestward of Katmai caldera with Trident peaks beyond and snowy Mount Mageik in the distance. Flat-floored Valley of Ten Thousand Smokes is in the right middle distance.

USGS photograph by J. Fierstein

Figure 4. Aerial view southwestward of four eroded peaks of Trident volcano.

USGS photograph by W. Hildreth

Figure 5. Aerial view of ice-clad Mount Mageik toward south-southwest. To its right is Mount Martin, with Alagog-shak volcano at extreme right edge of photograph. At lower left is Mount Cerberus dacite dome, in front of the entrance to Katmai Pass.



USGS photograph by W. Hildreth

NPS photograph by Lynn Fuller

Figure 6. (A) Summer 1997 photograph of the east side of fumarolically active Mount Martin summit cone (relief, about 160 ft), built mostly by accumulation of bombs, ash, and scoria on top of massive lava flows. Low rim of summit crater is open to southeast. (B) Summer 1980 aerial view northwestward into steaming summit crater of Mount Martin.

both lava flows and ash falls. The largest of these is an explosive eruption thought to have occurred sometime between 16,000 and 12,000 years ago. Because pumice that fell near the vent landed on glaciers that occupied the valleys at that time, no undisturbed fall deposits remain near the volcano (*Hildreth and Fierstein 2000, Hildreth and Fierstein 2003*), but a fine ash layer on the Kenai Peninsula (225 km away) is probably equivalent (*Reger et al. 1996, Fierstein 2007*). It is clear that Mount Katmai has a history that includes more explosive eruptions than any of the other stratovolcanoes in the cluster.

Trident Volcano (*Figure 4*) is a group of four overlapping stratovolcanoes and several lava domes as old as 150,000 years (*Hildreth et al. 2003a*). Although more deeply eroded by glaciers and in part older than adjacent Mageik and Katmai volcanoes, Trident Volcano produced the area's most recent eruptive episode, from 1953 to 1974 (*see Coombs and Bacon, this issue*). The central and highest cone is considerably eroded and certainly inactive over the last 10,000 years, but nonetheless supports a vigorous field of sulfur-producing fumaroles on its lower southeast flank, first recorded in 1916 by botanist R.F. Griggs (*Griggs 1922*). Another fumarole, visible in 1951 aerial photographs as a 200-foot-wide steaming pit on the southwest ridge of the central cone, became the vent site for the new volcanic cone (Southwest Trident) that began to grow in 1953. In contrast to Mount Katmai, no large explosive deposits have come from any of the Trident peaks, although a few small remnants of pyroclastic-flow deposits south of the peaks are evidence of some minor explosive activity. Most of the eruptions of Trident Volcano have been lava domes and short-traveled blocky lava flows accompanied sporadically by small ash plumes.

Mount Mageik, a compound stratovolcano just higher than 7,100 ft (2370 m), rivals Mount Katmai as the most extensive (80 km^2) and most voluminous (30 km^3) edifice in the Katmai cluster (*Hildreth et al. 2000*). Each of its four ice-mantled summits is a discrete eruptive center, and each is the source of numerous lava flows (*Figure 5*). Three of the eruptive centers are severely eroded by glaciers. They are each made up of sets of lava flows piled on top of each other that erupted during intervals 10,000 to 20,000 years long. Some of these lava flows are as old as 93,000 years, and eruptions at all three centers were long over by the time the fourth eruptive center began. The East Summit was the only part of Mageik built during the last 10,000 years. It erupted a dozen lava flows and seven explosive ash-fall-producing events, the youngest of which is about 4,000 years old. Because soil has developed on some of the lava flow surfaces but not on others in the sequence, it is likely that at least hundreds, if not thousands of years passed between eruptive episodes. The youngest Mageik eruption about 2,500 years ago was an explosion that formed a crater between two of the summits. Evidently, no magma erupted from this vent, but the crater is filled with a yellow-green acid lake that sends up curls of steam often mistaken for eruption plumes.

Mount Martin, just southwest of Mount Mageik, is a small volcanic cone and ten overlapping blocky lava flows that stretch northwestward for 6 miles (10 km). The cone is smaller than it seems, for although its summit exceeds 6,100 ft (2030 m) in elevation, it is built on a high ridge of much older sedimentary rocks. Several ash-fall layers from Mount Martin are preserved in soils nearby and suggest that at least three eruptive episodes separated by 1,000 years to as much as several thousand years built Mount Martin between about 6,000 and 2,800 years ago (*Fierstein 2007*). Still active, the cone is marked by a persistent steam plume that coalesces from as many as 20 fumarolic jets that precipitate sulfur around a shallow lake on the floor of its 300-ft (100-m)-wide summit crater (*Figure 6*).

Alagogshak volcano, the southwesternmost member of the Katmai volcanic cluster, is marked by hydrothermally altered remnants of the summit crater of a severely eroded vent complex (*Figure 7*). Such rocks, when permeated by acidic hot water and gas from the volcano's core, turn into colorful red, white, yellow and orange remnants rich in clay minerals. Lava flows extending as much as 6 miles (10 km) in most directions are all glacially ravaged. Alagogshak, oldest by far of all the Katmai cluster volcanoes, is made of lavas as old as 680,000 years and no younger than 40,000 years (*Hildreth et al. 1999*). This is the only Katmai cluster volcano that is no longer active.

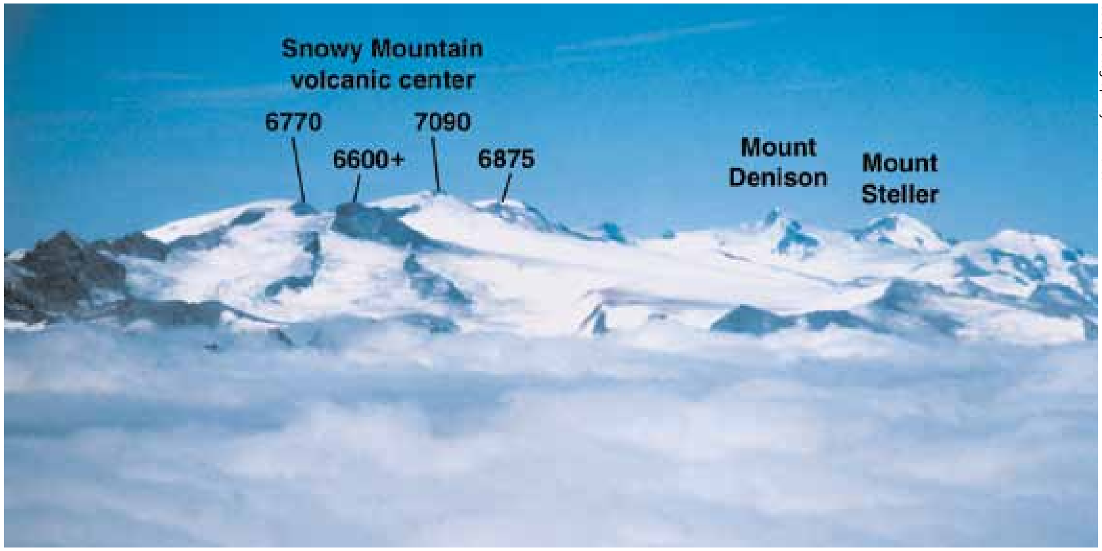
Snowy Mountain, the northeastern most volcano of the Katmai cluster, is largely ice-covered. It is made of a contiguous pair of small, deeply glaciated volcanic cones as well as a young lava dome that fills what was the summit crater for the northeastern one. Along the range crest, Snowy Mountain has three main summits, Peaks 6770, 7090, and 6875 (*Figure 8*). Only Peak 6875, the young dacite lava dome, is a vent. The other peaks are eroded remnants of lava flows from the two cones that are as much as 200,000 years old. The young lava dome sits in a scoop-shaped amphitheatre created by collapse of the upper part of the northeastern cone that had been weakened by persistent hydrothermal activity in the volcano's core. The collapse produced a 22-km² debris-avalanche deposit that came down in the last 1,500 years (*Hildreth et al. 2001*); the lava dome, therefore, is younger still.

USGS photograph by W. Hildreth

Figure 7. Glacially eroded summit of Alagogshak volcano (center), about 2 miles (3 km) southwest of Mount Martin (left cone). View toward southwest.

USGS photograph by J. Fierstein

Figure 8. Aerial view northeastward over Kaguyak caldera with its 490-ft (150-m)-deep lake. Nine separate dome complexes once made up the area in and around the lake until a large explosive eruption reamed out the center about 5,800 years ago. Remnants of three dome complexes are marked: Northern edifice (N), Eastern edifice (E), and Southern edifice (S).



USGS photograph by W. Hildreth

Figure 9. Aerial view northeastward over clouds to multiple summits of Snowy Mountain volcanic center. Highest summit (7,090 ft; 2,161 m) is a remnant of the west flank of Northeast Snowy, and the 6,875-foot (2,096-m) peak is a young lava dome, filling the summit crater of that edifice.

NPS photograph by Roy Wood

Figure 10. 1977 aerial view, looking east, of Aniakchak caldera that formed about 3,400 years ago. The caldera is about 6 miles (10 km) across.

Kaguyak caldera in the northeast corner of the park is a steep-walled collapse caldera filled with a 500-foot (150-m)-deep lake that was created ~5,800 years ago in a large explosive eruption. Once thought to be a collapsed stratovolcano, recent work (*Fierstein and Hildreth 2008*) shows that ancestral Kaguyak was, instead, nine closely spaced but discrete clusters of lava domes. The domes, ranging from basalt to rhyolite in composition, are each stacks of short-traveled lava flows. Kaguyak is a good example of the episodic nature of volcanic activity. The earliest lava flows are as much as 300,000 years old. An especially active eruptive period between 60,000 and 30,000 years ago built five multi-component lava domes where the lake is now. All that activity was followed by a quiescent interval more than 20,000 years long. Then, about 6,000 years ago, another dome was extruded near the center of the cluster. This triggered explosions and culminated in the big event 200 years later that produced ash flows and falls, erupting enough magma that a 1.6-mile (2.5-km)-wide area collapsed to form the caldera, truncating the field of lava domes. Fine ash, largely winnowed out of the ash flows, is now found as a distinctive orange ash-fall layer (*Fierstein*) preserved widely in soils as far as the Valley of Ten Thousand Smokes, 50 miles (80 km) to the southwest. Some activity continued after the caldera-forming eruption, with emplacement of two more domes inside the new caldera that are now islands in the lake. Gas seeps still bubble up to the caldera lake surface, some with a strong sulfurous smell.

Volcanic Landscapes, Spectacular Parks

Volcanoes create spectacular and dynamic landscapes. The Valley of Ten Thousand Smokes so impressed Griggs that he urged President Wilson's administration to preserve it for posterity, establishing Katmai National Monument in 1918. Created with the dual intention of protecting both the scenic wonders and preserving possibilities for continued scientific study of phenomena related to the 1912 eruption, the intent has been well fulfilled here. Expansion of the protected area and redesignation as a national park in 1980 validated and intensified both values. Clearly, the volcanoes of Katmai National Park and Preserve have provided geologists and other scientists with a range of possibilities for exploring and understanding volcanic phenomena. The compelling scenery and geology of other volcanic landscapes on the Alaska Peninsula and in the Aleutians have also been preserved in national parks and monuments. Among these are Iliamna and Redoubt Volcanoes in Lake Clark National Park and Preserve and Aniakchak caldera in Aniakchak National Monument (*Figure 9*). Much geologic work has already been done at Redoubt and Aniakchak (*e.g., Coombs and Bacon, this issue*). All three have been recognized as National Natural Landmarks (NNL) by the Secretary of the Interior and have been designated as nationally significant geological features. They are ready for the next generation of explorers and geologists.

REFERENCES

Fierstein, J. 2007.
Explosive eruptive record in the Katmai region, Alaska Peninsula: An overview. Bulletin of Volcanology 69: 469-509.

Fierstein, J., and W. Hildreth. 2001.
Preliminary volcano-hazard assessment for the Katmai Volcanic Cluster, Alaska. U.S. Geological Survey Open-File Report 00-489.

Fierstein, J., and W. Hildreth. 2008.
Kaguyak dome field and its Holocene caldera, Alaska Peninsula. Journal of Volcanology and Geothermal Research 177: 340-366.

Griggs, R.F. 1922.
The Valley of Ten Thousand Smokes. National Geographic Society. Washington, D.C.

Hildreth, W., and J. Fierstein. 2000.
Katmai volcanic cluster and the great eruption of 1912. Geological Society of America Bulletin [GSA Overview Paper] 112: 1594-1620.

Hildreth, W., and J. Fierstein. 2003.
Geologic map of the Katmai Volcanic Cluster, Katmai National Park, Alaska. U.S. Geological Survey Map I-2778, scale 1:63,360.

Hildreth, W., J. Fierstein, M.A. Lanphere, and D.F. Siems. 1999.
Alagogshak volcano: A Pleistocene andesite-dacite stratovolcano in Katmai National Park. Geologic Studies in Alaska by the U.S. Geological Survey 1997. U.S. Geological Survey Professional Paper 1614: 105-113.

Hildreth, W., J. Fierstein, M.A. Lanphere, and D.F. Siems. 2000.
Mount Mageik, a compound stratovolcano in Katmai National Park. Geologic Studies in Alaska by the U.S. Geological Survey 1998. U.S. Geological Survey Professional Paper 1615: 23-34.

Hildreth, W., J. Fierstein, M.A. Lanphere, and D.F. Siems. 2001.
Snowy Mountain: A pair of small andesite-dacite stratovolcanoes in Katmai National Park. Geologic Studies in Alaska by the U.S. Geological Survey 1999. U.S. Geological Survey Professional Paper 1633: 13-34.

Hildreth, W., J. Fierstein, M.A. Lanphere, and D.F. Siems. 2002.
Mount Griggs: A compositionally distinctive Quaternary stratovolcano behind the main volcanic line in Katmai National Park. Studies by the U.S. Geological Survey in Alaska, 2000. U.S. Geological Survey Professional Paper 1662: 87-112.

Hildreth, W., J. Fierstein, M.A. Lanphere, and D.F. Siems. 2003a.
Trident Volcano: Four contiguous stratocones adjacent to Katmai Pass, Alaska Peninsula. Studies by the U.S. Geological Survey in Alaska, 2001. U.S. Geological Survey Professional Paper 1678: 1-28.

Hildreth, W., J. Fierstein, D.F. Siems, J.R. Budahn, and J. Ruíz. 2004.
Rear-arc vs arc-front volcanoes in the Katmai reach of the Alaska Peninsula: A critical appraisal of across-arc compositional variation. Contributions to Mineralogy and Petrology 147: 243-275.

Hildreth, W., M.A. Lanphere, and J. Fierstein. 2003b.
Geochronology and eruptive history of the Katmai Volcanic Cluster, Alaska Peninsula. Earth and Planetary Science Letters 214: 93-114.

Simkin, L., and T. Siebert. 1994.
Volcanoes of the world. Geoscience Press. Tucson, AZ.

Reger, R.D., D.S. Pinney, R.M. Burke, and M.A. Wiltse. 1996.
Catalog and initial analyses of geologic data related to middle to late Quaternary deposits, Cook Inlet region, Alaska. State of Alaska Department of Natural Resources, Division of Geological and Geophysical Surveys Report of Investigations 95-6.

Volcanic National Natural Landmarks in Alaska

By Margi Brooks

The National Natural Landmarks (NNL) Program was established in 1962 by the Secretary of the Interior under the authority of the Historic Sites Act of 1935 (16 U.S.C. 461 et seq.). Managed by the National Park Service, the primary goals of the program are to recognize and encourage the preservation of the best remaining examples of the major biotic communities and geologic features in the nation's natural landscape. There are currently 591 sites designated in 48 states, 3 territories, and the Commonwealth of Puerto Rico.

Sites considered for possible NNL designation are identified primarily through inventory studies, such as the Works of Volcanism (*Rose 1977*), which identified many volcanic sites in Alaska as potential NNLs. Six of these sites have received NNL designation as outstanding examples of a variety of different volcanic structures. Stretching down the Alaska Peninsula, these volcanoes are important and dynamic landscape features that continue to affect human life and activities. Three are within National Park Service units and three in units of the National Wildlife Refuge System.

Figure 1. Castle Rock on Bogoslof Island. Castle Rock is the eroded remnant of a dome extruded in 1796.

Photograph by Ann Harding, Alaska Volcano Observatory, USGS

Aniakchak Crater

Aniakchak Crater, located 24 miles (39 km) southeast of Port Heiden on the Alaska Peninsula, is one of the world's largest explosive craters, averaging 6 miles (10 km) wide and 2,000 feet (610 m) deep. Contained in the caldera is Surprise Lake, which is the headwaters of the Aniakchak River, the largest river flowing into the Pacific Ocean from the Alaska Peninsula. The interior of the caldera provides textbook examples of many volcanic features such as lava flows, cinder cones and explosion pits. The volcano's most recent eruption occurred in 1931, when it hurled 15.4 cubic miles (64 km^3) of debris out of its core, scattering it for 20 miles (32 km) over the surrounding landscape. The topography and setting of the caldera make it climatologically unique in that it is able to generate its own weather. The caldera and its surroundings are in a pristine natural condition and visitation is infrequent.

Bogoslof Island

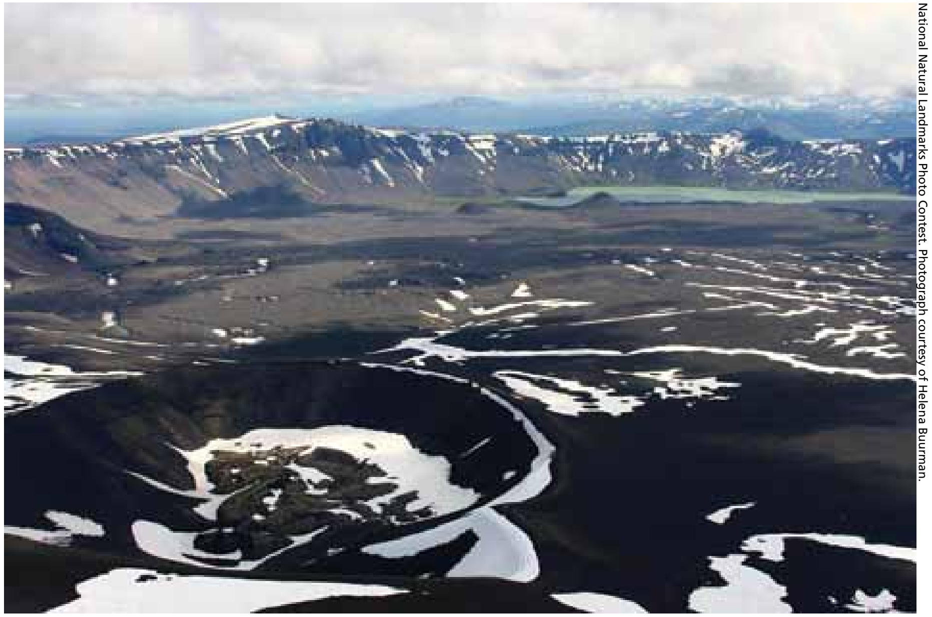
Bogoslof Island is a historic geologic feature 25 miles (40 km) north of Umnak Island in the Aleutian Archipelago. It is the summit of a largely submarine stratovolcano, and at least six volcanic island masses rose here in the past 130 years. Remnants of the last three eruptions, the most recent in 1992, form the present island. Its major significance as a landmark is attached to the community of Steller sea lions that haul out on the island. Over 50,000 sea birds including puffins, murres, and rare red-legged kittiwakes use the island as a nesting ground. The swarming mass of sea lions and fur seals together with the sea birds on a relatively small island presents a biological spectacle. The colonizing plant communities that occupy a narrow band just above high tide line are of extreme value in botanical succession studies.

Iliamna Volcano

Iliamna Volcano, located 135 miles (217 km) southwest of Anchorage, is a typical cone-shaped volcano rising some 5,000 to 6,000 feet above the mountains of the Aleutian Range. It rises to a summit height of 10,016 feet (3,053 m) and is a typical stratovolcano composed of a sequence of lava flows and pyroclastic rocks. Iliamna Volcano is not a simple symmetrical cone, but is the northern-most and highest of four peaks within the landmark, which form a 3-mile (5 km) long ridge. Most of the volcano and its flanks are covered by snow and ice, and at least ten glaciers radiate from its summit. Little of the original constructional surface remains, as the volcano has been deeply dissected by erosional processes. The volcano has a relatively minor recorded history of volcanic activity. Present activity appears to be confined to two small sulfur vents located at about 9,000 feet (2,740 m) near the summit on the eastern face.

Mount Veniaminof

Mount Veniaminof is a unique active volcano of uncommon size. The caldera is almost six miles across, and contains a cupped ice field of 25 square miles (65 km^2), the most extensive crater-glacier in the nation. Located on the Alaska Peninsula, Mt. Veniaminof is 20 miles (32 km) northeast of Port Moller on the Bering Sea and 20 miles northwest of Chignik on the north Pacific

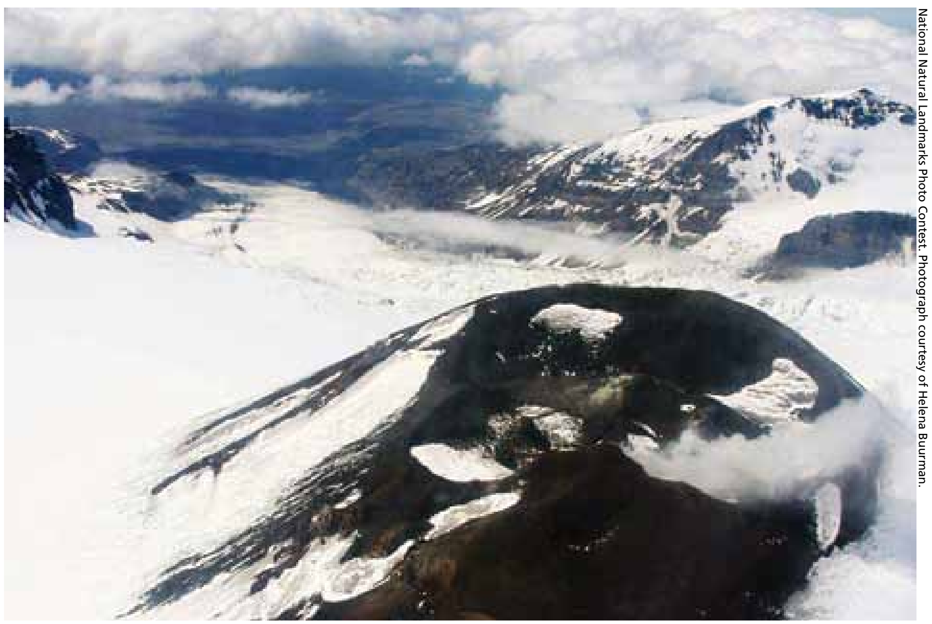


National Natural Landmarks Photo Contest. Photograph courtesy of Helena Buurman.

Figure 2. Aniakchak Crater.

National Natural Landmarks Photo Contest. Photograph courtesy of Carol P Murdock.

Figure 3. Iliamna Volcano.



National Natural Landmarks Photo Contest. Photograph courtesy of Helena Buurman.

Figure 4. Mount Veniaminof.

National Natural Landmarks Photo Contest. Photograph courtesy of Kate Bull.

Figure 5. Redoubt Volcano.

Ocean. It is the only known glacier on the continent with an active volcano vent in its center. Volcanic activity at the mountain has been recorded since 1830; major explosive eruptions occurred in 1838 and 1892. Often shrouded in clouds, Mt. Veniaminof has had numerous small eruptions in modern times, the last of which was in 2008. All recent eruptions have taken place from a cinder cone that pokes up through the ice in the caldera.

Redoubt Volcano

Redoubt Volcano is an excellent example of a classic symmetrical stratovolcano. The volcano is a broad cone-shaped mountain about six miles in diameter at its base, and at a summit elevation of 10,197 feet (3,108 m), it towers some 5,000 to 6,000 feet above the surrounding rugged peaks of the Aleutian Range. The volcano is composed of layers of pyroclastic material, mud flows, and lava flows, and it rests on Mesozoic granitic rocks. Extensive glaciers and ice fields cover much of the volcano. It has a history of recorded volcanic activity dating back to 1778. The most recent eruptive period occurred in March 2009. The eruption was characterized by powerful ash explosions with resulting plumes between 30,000 to 60,000 feet (9,100 to 18,200 m) above sea level. The Alaska Volcano Observatory observed 11 major explosive events during the first week, and a total of 19 events over the 14-day eruptive period in March and early April. Redoubt is located 110 air miles (180 km) southwest of Anchorage.

Shishaldin Volcano

Shishaldin Volcano is the tallest of 11 known volcanoes on Unimak Island. Eruptions have been recorded from the volcano since 1775, with major eruptions occurring in 1824 and 1830. It is active today and completely unpredictable, making extensive on-site study difficult. Located 50 miles (80 km) west of Cold Bay in the Aleutian Archipelago, the scenic aspects of this tall, symmetrical volcano are magnificent and make it readily identifiable. It was last active in 2008, but emits a steady plume of steam from a small summit crater.

Photograph by Cyrus Read, Alaska Volcano Observatory, USGS

Figure 6. Shishaldin Volcano.

REFERENCES

Rose, R.H. 1977.
The works of volcanism: sites recommended as potential natural landmarks. National Park Service. U.S. Department of the Interior.

Using Rocks to Reveal the Inner Workings of Magma Chambers Below Volcanoes in Alaska's National Parks

By Michelle L. Coombs and Charles R. Bacon

Introduction

Alaska is one of the most vigorously volcanic regions on the planet, and Alaska's national parks are home to many of the state's most active volcanoes. These pose both local and more distant hazards in the form of lava and pyroclastic flows, lahars (mudflows), ash clouds, and ash fall. Alaska's volcanoes lie along the arc of the Aleutian-Alaskan subduction zone, caused as the oceanic Pacific plate moves northward and dips below the North American plate. These volcanoes form as water-rich fluid from the down-going Pacific plate is released, lowering the melting temperature of rock in the overlying mantle and enabling it to partially melt. The melted rock (magma) migrates upward, collecting at the base of the approximately 25 mile (40 km) thick crust, occasionally ascending into the shallow crust, and sometimes erupting at the earth's surface.

During volcanic unrest, scientists use geophysical signals to remotely visualize volcanic processes, such as movement of magma in the upper crust. In addition, erupted volcanic rocks, which are quenched samples of magmas, can tell us about subsurface magma characteristics, history, and the processes that drive eruptions. The chemical compositions of and the minerals present in the erupted magmas can reveal conditions under which these magmas were stored in crustal "chambers". Studies of the products of recent eruptions of Novarupta (1912), Aniakchak (1931), Trident (1953-74), and Redoubt (2009) volcanoes reveal the depths and temperatures of magma storage, and tell of complex interactions between magmas of different compositions. One goal of volcanology is to determine the processes that drive or trigger eruptions. Information recorded in the rocks tells us about these processes. Here, we demonstrate how geologists gain these insights through case studies from four recent eruptions of volcanoes in Alaska national parks.

Methods

Investigation of the magmatic processes beneath volcanoes starts with field study of the erupted deposits. For recent eruptions, volcanologists use photographs, satellite images, seismic data, and field observations to correlate deposits with individual explosions or other types of activity such as lava-dome growth. For older eruptions, we use the order and distribution of layered deposits (stratigraphy), such as those from ash falls and pyroclastic flows, to ascertain the sequence of events.

Volcanic rocks typically contain a few to nearly 50% relatively large crystals of rock-forming minerals (phenocrysts, ≥0.04 inches/1 mm) in a finer grained matrix of glass (quenched melt) or sub-millimeter crystals called groundmass. Chemical analyses of "whole rock" geologic specimens, such as rocks or individual pumice lumps, typically are performed on finely pulverized samples. Whole-rock compositions yield information about magma source regions and tell whether new erupted material is the same or different from that previously erupted by the volcano. Often, composition will shift subtly during an eruption, heralding a new eruptive style or participation of melt from a different part of the magma system.

In addition to whole-rock chemical analysis, geologists use microphotographs and compositions of individual crystals and glass to further unravel rocks' magmatic histories. High-resolution images of rock textures or chemical analyses of microscopic regions of crystals are obtained with tools broadly classified as microbeam instruments because the analyzed area is excited or extracted by an electron, ion, or light beam. For example, Fourier Transform Infrared Spectrometry (FTIR) can determine water and carbon dioxide concentrations in glass and minerals. Combining these concentrations with models of volatile (e.g., water and carbon dioxide) solubility in silicate melts allows estimates of pressure (and thus depth) of pre-eruptive magma storage. Mineral and glass compositions can also be used to estimate pressure and temperature conditions of crystallization, using geobarometers and geothermometers, respectively.

Finally, petrologists (geologists who specialize in the chemistry of rocks) conduct laboratory experiments that replicate pre-eruptive magma conditions (temperature, pressure, volatile contents, even decompression rates that mimic magma ascent). By varying experimental conditions in order to form minerals and melt found in natural rock samples, we can determine storage and ascent conditions for particular magma compositions and systems. Together, these types of studies give us both a time and space history of the movement of magma beneath a volcano towards the surface.

Case Studies

2009 eruption of Redoubt Volcano

Redoubt Volcano is an ice-covered, 10,197-ft (3,108-m) high stratovolcano 110 miles (177 km) southwest of Anchorage, Alaska, on the west side of Cook Inlet (*Figure 2*). Redoubt has erupted four times historically

Figure 1. A geologist samples ash nine days after the March 22, 2009, eruptions of Redoubt Volcano. The site is near Lake Clark Pass, 16 miles (26 km) northeast of the volcano.

USGS photograph by A. Diefenbach

prior to 2009: in 1902, 1933, 1966-68, and 1989-90. The last two eruptions included a sequence of lava dome extrusions and multiple explosive events that produced ash plumes higher than 40,000 ft (12 km) above sea level (ASL). In addition, they produced floods and lahars that swept down the Drift River valley and impacted an oil storage facility at the coast 22 miles (35 km) distant.

The 2009 eruption was preceded by about eight months of low-level seismic activity, volcanic gas emissions, and steady melting of summit ice (*Schaefer 2011*). January 29, 2009, marked the onset of six weeks of volcanic tremor and shallow repeating earthquakes. Eighteen explosive events from March 22-28 produced ash columns between 17,000 and 62,000 ft (5.2 and 18.9 km) ASL, ash fall (*Figure 1*), and pyroclastic flows down the volcano's north flank. Lahars, with flow depths to 33 ft (10 m) in the upper Drift River valley, inundated the Drift River oil terminal on March 23 and smaller lahars were observed on March 26, 27, and 28.

Dome growth starting on March 28 was followed by an explosion on April 4 that produced an ash cloud, pyroclastic flows on the volcano's north flank, and voluminous lahars down the Drift River valley. Fine-grained, blocky ash that was erupted from this event suggests that it was triggered by collapse and depressurization of the new lava dome. Following the final explosive event, a final lava dome grew in the crater through July 1, 2009. The total magma volume erupted in 2009 is estimated to be about 0.02 cubic miles (0.1 km^3) (*Bull and Buurman In review*).

The 2009 magmas are compositionally classified as andesites, typical for Redoubt and other subduction-zone volcanoes. They are rich in crystals such as plagioclase feldspar and range from 57.5 to 62.5 weight

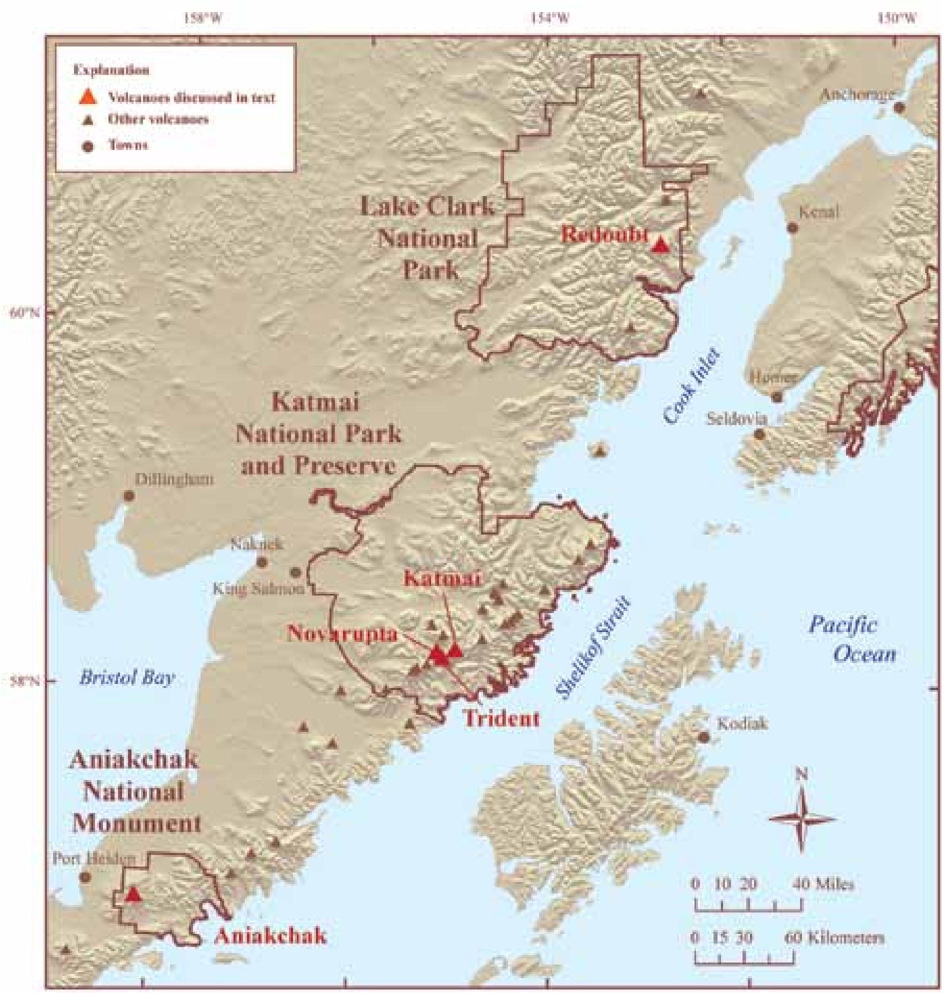


Figure 2. Map showing southcentral Alaska, national park boundaries, and volcanoes in the Aleutian-Alaska arc. Volcanoes discussed in this paper are shown in red.

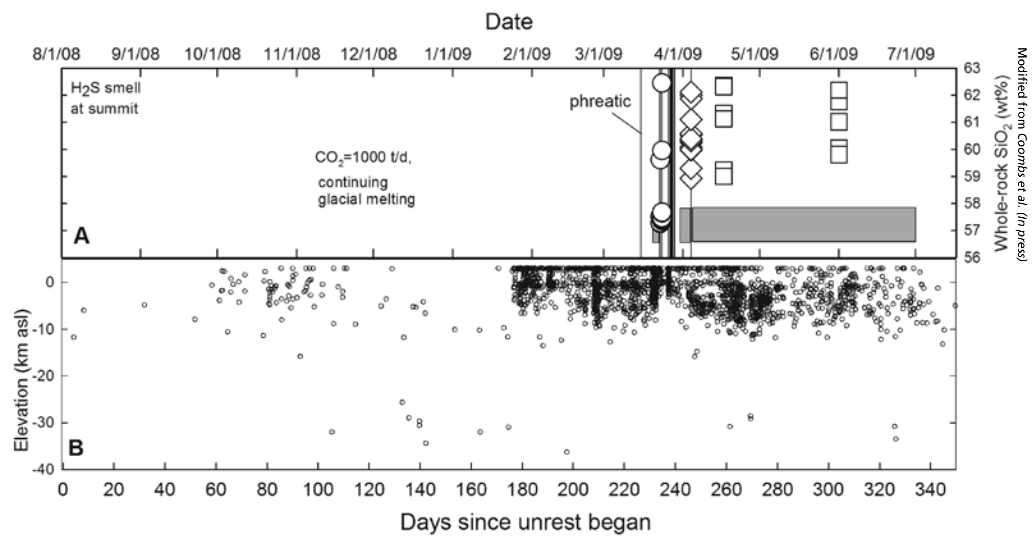


Figure 3. Silicon dioxide content of erupted andesite (A) and depths of located earthquakes (B) charted during the 2009 eruption of Redoubt. In (A), vertical lines are explosions, grey bars indicate periods of lava effusion, circles represent tephra from explosions, diamonds are samples from April 4 explosion, and squares are lavas from the final dome. Timing of hydrogen sulfide (H^{2}S) smell and rates of carbon dioxide (CO^2) are noted. Initial explosion on March 15 was gas-rich (phreatic); no new magma was ejected. Note that eruptive products become more SiO_2-rich with time.

percentage (wt%) silicon oxide (SiO^2) (*Coombs et al. In review.*) (*Figure 3*). Magmas from the early 2009 explosions and domes are almost all low-silica andesites (<58 wt% SiO^2), but a transition to higher SiO_2 and cooler magmas by about March 26 corresponded to a switch to predominantly effusive dome growth.

Comparison of plagioclase feldspar and melt (glass) compositions (*Figure 4*) from the andesites with results of experiments are consistent with pre-eruptive storage 2.5-3.7 miles (4-6 km) below the surface, coincident with many earthquakes located during the eruption (*Figure 5*). We interpret this as evidence that the 2009 low-silica andesite ascended from depth during the eight or more months prior to the first eruption, stalling and accumulating in the upper crust where its crystal rim and enclosing melt compositions were established. Ascent of this magma mobilized shallow, cooler, pre-existing magma pockets that fed the subsequently erupted lava domes. These latter magmas have compositions that suggest they are "leftovers" from previous eruptions. This pattern of newer melt "flushing" leftover magma from previous eruptions may be typical of small-volume dome-forming eruptions in Alaska and elsewhere.

Aniakchak 1931 eruption

Aniakchak caldera is a striking physical feature on the central Alaska Peninsula, 420 miles (670 km) southwest of Anchorage (*Figure 2*). The caldera formed by collapse of the Aniakchak volcano during a major eruption approximately 3,400 years B.P. (before present) (Miller and Smith 1987). It was notable for its voluminous, compositionally zoned pyroclastic-flow deposit of cream-colored rhyodacite overlain by dark gray andesite. Since then, postcaldera volcanism has formed four lava domes, three tuff cones, a small scoria cone, and the larger edifices of Half Cone and Vent Mountain within the 6-mile-diameter (10 km) caldera (*Neal et al. 2001*) (*Figure 6*).

The most recent eruption of Aniakchak took place during May and June 1931. The six-week-long eruption, the strongest from May 1-11, rained "egg-sized" rock fragments 19 miles (30 km) to the west in Port Heiden, left millimeters of ash as far as Kodiak Island, and repeatedly interfered with radio communications in the area. New lava flows were emplaced in the Main (1931) crater and as small flows at Doublet crater and Slag Heap toward the end of the activity. The total volume of erupted magma was about 0.07 cubic miles (0.3 km³) (*Nicholson et al. 2011*), less than 1% of which was lava flows. Similar to a circa 400 year B.P. eruption of Half Cone (*Figure 7*), the 1931 Aniakchak eruption began with relatively silica-rich dacitic magma (as much as 69 wt.% SiO_2)

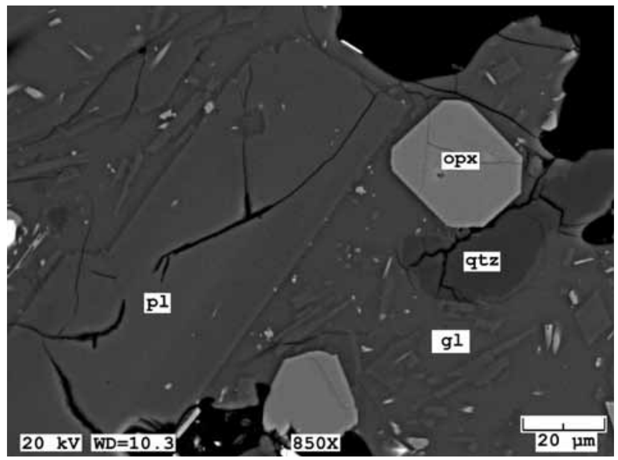


Figure 4. Scanning electron micrograph, at 850x magnification, shows groundmass in andesite lava from the final 2009 dome. Chemical compositions of the plagioclase (pl) crystals and glass (gl) allow estimates of pre-eruptive magmatic water content. Opx=orthopyroxene and qtz=quartz crystals. Scale bar is 20 micrometers (0.001 inch).

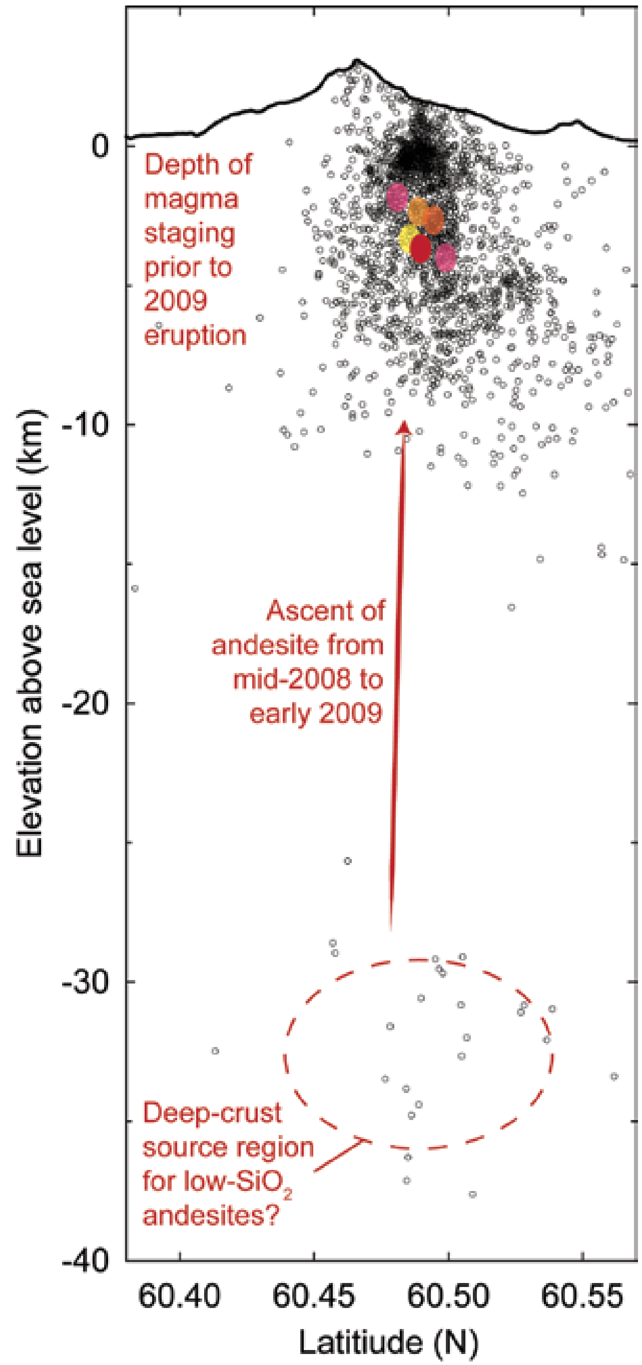


Figure 5. (Right) North-south cross section through Redoubt Volcano showing schematic pre-eruptive magma storage. Black circles represent hypocenters of earthquakes from mid-2008 through December 2009, as located by the Alaska Volcano Observatory. Scattered earthquakes between 19 and 25 miles (30-40 km) depth are "deep long-period" events that may represent withdrawal of magma from this depth as it began to rise towards the surface (*Power et al. In review*). The red oval between 1.2 and 2.5 miles (2-4 km) below sea level represents new low-silica andesite that arrived and erupted in 2009. Other colored ovals represent older, stagnant magma pods, some of which were remobilized and erupted in 2009 as well. All have been enlarged for clarity.

Figure 6. A 1977 aerial photograph of Aniakchak caldera, with the wide variety of volcanic landforms and deposits labeled.

and ended with relatively silica-poor basaltic andesitic magma (as little as 56 wt.% SiO_2) (*Nicholson et al. 2011*).

Chemical analysis of crystals and their glass inclusions in Aniakchak postcaldera eruption products yield estimates of magma temperatures, dissolved volatile concentrations, and storage depths (*Bacon 2002*) (*Figure 8*). Results indicate that dacite magma resided at only 2 miles (3 km) depth prior to the circa 400 year B.P. explosive eruption of Half Cone. The subsequent eruption of Blocky Cone produced basaltic andesite that had partially crystallized at about 2 miles depth, possibly as a response to eruptions of Vent Mountain and Half Cone having expelled a relatively large volume of dacitic magma. The 1931 eruption drew dacitic magma from about 3 miles (5 km) depth. Interestingly, analysis of interferometric synthetic aperture radar (InSAR) images from 1992-2002 by Kwoun et al. (*2006*) indicates subsidence of the caldera center with a source modeled at about 2.5 miles (4 km) depth that the authors attributed to contraction caused by cooling or degassing of a shallow magma body.

Novarupta and the great eruption of 1912

The largest eruption of the twentieth century anywhere on Earth, the events of June 9-12, 1912, left an indelible mark on the landscape of the Katmai region. The eruption produced 3.4 cubic miles (14 km^3) of magma, deposited more than a foot of ash on Kodiak, and lowered temperature in the northern hemisphere by as much as 1.8°F (1°C) for a year (*Hildreth and Fierstein 2012*). This eruption has intrigued geologists because of its size, great compositional diversity, and unusual magma plumbing system. Most notably, some magma was withdrawn from beneath Mount Katmai volcano, despite nearly all being erupted at Novarupta, 6 miles (10 km) away (*Figure 9*).

The eruption was preceded by several days of earthquakes felt in local villages, and on June 9, 2.2 cubic miles (9 km^3) of high-silica rhyolite (77 wt% SiO_2) erupted as pyroclastic flows and fall from a new vent, Novarupta. A few hours into the sequence, dacite and smaller amounts of andesite erupted, and Mount Katmai collapsed to form a 2-mile-wide caldera.

Recent studies have proposed contrasting models for

Figure 7. Geologists examine deposits from postcaldera eruptions at Aniakchak caldera, July 12, 1994. Tan and dark gray layers at top are coarse ashfall deposits from Half Cone vent.

the plumbing system that fed the 1912 eruption. Hildreth and Fierstein (*2012*) posit a single, compositionally zoned chamber that resided beneath Mount Katmai. Analyses of melt inclusions in crystals from the rhyolite suggest that the magma was fluid saturated ("gas" bubbles present) and contained ~4 wt% water dissolved in the melt. This is consistent with experiments on rhyolite pumice that show at those temperatures the rhyolite magma was stable between depths of 1.1-2.7 miles (1.8-4.4 km) below the surface (*Coombs and Gardner 2001*). Similar experiments on the 1912 andesite and dacite indicate that these magmas were also stored at a relatively shallow depth (*Hammer et*

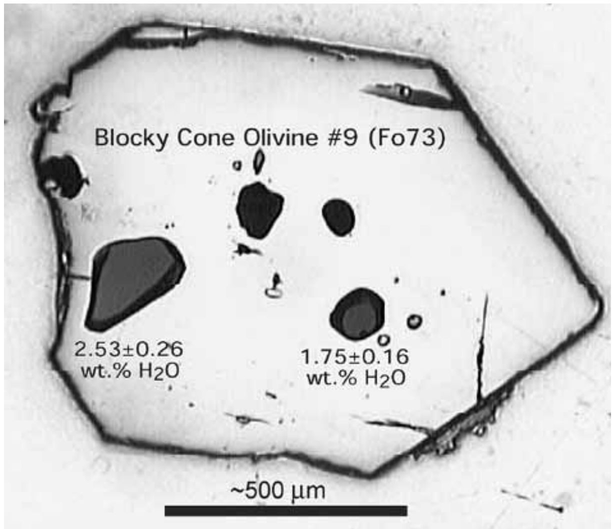


Figure 8. A polished slice of an Aniakchak olivine crystal from intracaldera Blocky Cone, showing melt inclusions. Water content, in weight percent, is shown for two of the melt inclusions as measured by FTIR. Fo73 refers to the forsterite (Mg_2SiO_4) percentage in olivine.

Figure 9. (Right) True-color composite Landsat satellite image of volcanoes in Katmai National Park and Preserve. Most of the pyroclastic deposits from the 1912 eruption of Novarupta were deposited in what is now known as the Valley of Ten Thousand Smokes.

al. 2002), perhaps even more so than the rhyolite. These results are somewhat difficult to reconcile with a single zoned chamber, where denser andesite and dacite would reside below rhyolite. Deeper storage for the andesite and dacite was possible, however, if they contained appreciable carbon dioxide (CO_2) in addition to water.

An alternate hypothesis is that multiple, separate magma bodies were tapped, though their pre-eruption locations are not clear. Geophysical evidence from the last several years suggests low-velocity zones consistent with magma beneath Katmai and near Trident, but not under Novarupta itself (*Thurber et al., this issue*). The configuration of the magma plumbing system for this unusual eruption is still not fully resolved and remains the topic of active research.

1953-1974 eruption of Trident Volcano

In winter 1953, a new vent formed on the southwest flank of Trident Volcano, just south of Novarupta on the Pacific side of Katmai Pass (*Figures 9-10*). Ash was ejected as high as 40,000 ft (12 km) ASL, and lava effused from the vent over the next several months. Activity at this new vent, coined Southwest Trident, continued in the form of ash eruptions and lava flow effusion intermittently through 1960, and sporadic explosions occurred for 14 years after, making the eruption the longest known in historical times in Alaska.

Study of Trident lavas and pumice shows that the eruption commenced with andesite, and that the magma became progressively more silica-rich through time (*Coombs et al. 2000*), similar to the 2009 eruption of Redoubt. Compositional profiles across olivine and magnetite crystals within the lavas suggest that in the months prior to the 1953 eruption, a new andesite magma invaded a shallow dacitic magma reservoir. This process may have triggered the eruption by releasing heat and gas from the

Photograph courtesy of the U.S. Navy

Figure 10. This photograph was taken February 21, 1953, showing the eruption of the new Southwest Trident andesite lava flow and ash plume. Mount Griggs can be seen to the left, and Katmai caldera to the right.

andesite into the dacite causing overpressure within the reservoir. Experiments and melt inclusions suggest that the mingled magmas were stored at a depth of approximately 2.5 mi (4 km) below the surface prior to eruption.

Unlike the exceptional eruption of 1912, the modest (0.2 miles^3 / 0.7 km^3) eruption of Southwest Trident probably represents a more typical Katmai-region eruption—in size, eruptive style, and magma composition. Scientists anticipate that the next eruption in this area could follow a similar pattern. And while modest in size, it is wise to remember that the eruption did continue for over two decades, and another such event could pose long-term hazards and nuisance in the region, especially to aviation.

Conclusions

Volcanic rocks from recent eruptions tell a story of magma rising and "staging" in the upper levels of the earth's crust prior to ultimately erupting or cooling in place. The residence time for such shallow magmas may range from thousands to hundreds of thousands of years in the largest caldera systems to as short as weeks or months in smaller reservoirs. In some cases, there is evidence that some magma was newly introduced into a shallow magma reservoir shortly prior to the eruption. The Alaska Volcano Observatory's seismic networks and other monitoring techniques can often detect precursory signals associated with magma on the move. These signals can be used in tandem with insights gleaned from the rocks themselves to assist scientists in forecasting future eruptions and warning of the associated hazards.

For more information, visit www.avo.alaska.edu

REFERENCES

Bacon, C.R. 2002.
Depths of magma reservoirs inferred from preeruptive dissolved volatiles in the most recent postcaldera eruptions of Aniakchak volcano, Alaska. EOS, Transactions American Geophysical Union 83: S378.

Bull, K., and H. Buurman. In review.
An overview of the 2009 eruption of Redoubt Volcano, Alaska. Journal of Volcanology and Geothermal Research.

Coombs, M.L., J.C. Eichelberger, and M.J. Rutherford. 2000.
Magma storage and mixing conditions for the 1953-1974 eruptions of Southwest Trident volcano, Katmai National Park, Alaska. Contributions to Mineralogy and Petrology 140: 99-118.

Coombs, M.L., and J.E. Gardner. 2001.
Shallow-storage conditions for the rhyolite of the 1912 eruption at Novarupta, Alaska. Geology 29: 775-778.

Coombs, M.L., T.W. Sisson, H. Bleick, S. Henton, C.J. Nye, A. Payne, C. Cameron, J.F. Larsen, K. Wallace, and K. Bull. In review.
Andesites of the 2009 eruption of Redoubt Volcano, Alaska. Journal of Volcanology and Geothermal Research.

Hammer, J.E., M.J. Rutherford, and W. Hildreth. 2002.
Magma storage prior to the 1912 eruption at Novarupta, Alaska. Contributions to Mineralogy and Petrology 144: 144-162.

Hildreth, W., and J. Fierstein. 2012.
The Novarupta-Katmai eruption of 1912: Largest eruption of the twentieth century: Centennial perspectives. U.S. Geological Survey Professional Paper 1791.

Kwoun, O.-I., Z. Lu, C. Neal, and C. Wicks, Jr. 2006.
Quiescent deformation of the Aniakchak caldera, Alaska. Geology 34: 5-8.

Neal, C., R.G. McGimsey, T.P. Miller, J.R. Riehle, and C.F. Waythomas. 2001.
Preliminary volcano-hazard assessment for Aniakchak Volcano, Alaska. U.S. Geological Survey Open File Report 00-0519.

Nicholson, R.S., J.E. Gardner, and C.A. Neal. 2011.
Variations in eruption style during the 1931 A.D. eruption of Aniakchak volcano, Alaska. Journal of Volcanology and Geothermal Research 207: 69-82.

Miller, T.P., and R.L. Smith. 1987.
Late Quaternary caldera-forming eruptions in the eastern Aleutian arc, Alaska. Geology 15: 434-438.

Power, J.A., S.D. Stihler, B.A. Chouet, M.M. Haney, and D.M. Ketner. In review.
Seismic observations of Redoubt Volcano, Alaska, 1989-2010 and a conceptual model of the Redoubt magmatic system. Journal of Volcanology and Geothermal Research.

Schaefer, J.R. (ed.) 2011.
The 2009 eruption of Redoubt Volcano, Alaska. Alaska Division of Geological and Geophysical Surveys Report of Investigations 2011-5.

Earthquake Studies Reveal the Magmatic Plumbing System of the Katmai Volcanoes

By Clifford Thurber, Rachel Murphy, Stephanie Prejean, Matthew Haney, Ninfa Bennington, Lee Powell, and John Paskievitch

Introduction

The 1912 eruption of Novarupta was the largest of the 1900s (*Fierstein and Hildreth 2001, Hildreth et al. 2003*). A century later, fundamental questions remain regarding the source of the magma for that eruption. A previous seismic study of the Katmai area (*Jolly et al. 2007*) identified a single large area of anomalous structure in the subsurface centered beneath Katmai Pass (*Figure 2*), but the magma source for the 1912 eruption is thought to have been beneath Mt. Katmai (*Hildreth et al. 2003*). This mystery was a prime motivation for the research project described here.

In summer 2008, scientists and staff from the Alaska Volcano Observatory (AVO) and the University of Wisconsin-Madison installed 11 temporary seismic recording instruments around the Katmai Pass area, complementing the existing AVO seismic network stations (*Figure 3*). The primary goal of the deployment was to record data from local earthquakes in order to yield an improved model of the three-dimensional structure of the upper crust beneath and surrounding Katmai Pass, using an analysis method known as double-difference seismic tomography (*Zhang and Thurber 2003*). The method yields a three-dimensional image of the velocity of seismic waves in the subsurface, and also produces improved estimates of the locations of the earthquakes beneath the seismic stations.

Our main finding is that there is not a single large anomalous zone centered beneath Katmai Pass; rather there are several separate anomalous zones, one each beneath Katmai, Trident-Novarupta, and Martin-Mageik. Furthermore, the earthquakes are tightly clustered beneath the various volcanic centers, and are found to be systematically deeper than previously thought. Linear trends of earthquakes are also revealed, similar to features observed at other volcanoes, possibly outlining previously unidentified fault structures or indicating the path of migrating magma or magmatic fluids and gases.

Figure 1. Lee Powell and John Paskievitch installing temporary seismic station at Mt. Mageik.
USGS AVO photograph by Stephanie Prejean

Seismic Waves and Seismic Tomography

There are two main categories of seismic waves: body waves that travel through the Earth's solid interior, and surface waves that have their energy trapped near the Earth's surface. Body waves come in two types, P (for primary, arriving first) and S (for secondary, arriving after P). P waves are compressional waves analogous to sound waves in the air, propagating pressure disturbances. S waves are shear or transverse waves that can only travel through a solid. Rayleigh waves, the most important surface waves, are caused by an interaction between P and S waves, although they are most sensitive to the S-wave velocity structure. The velocity of Rayleigh waves also varies with the frequency (or wavelength) of the wave. These different waves provide complementary information about the Earth's interior. The S-wave velocity is particularly sensitive to temperature as well as the presence of fluids, gases, and cracks. Higher temperatures and a greater proportion of fluids, gases, and/or cracks all cause a reduction in seismic wave velocity.

Seismologists construct images of the Earth's interior using a method analogous to medical CAT (Computed Axial Tomography) scans. For body-wave tomography, the seismic waves generated by earthquakes play the role of the CAT scan X-rays, with the observed arrival times for waves traveling from the earthquakes to the seismic stations being used to infer the velocity of the seismic waves in three dimensions. The locations (including origin times) of the earthquakes are estimated at the same time. A basic review of seismic tomography can be found in Thurber and Aki (*1987*). The body-wave tomography method we use is known as "double-difference" tomography (*Zhang and Thurber 2003*), which takes advantage of a technique called waveform cross-correlation, a computerized method to "line up" seismograms, yielding more accurate seismic wave arrival times (*Figure 4*).

An entirely independent technique for obtaining an image of the S-wave velocity structure is called ambient noise tomography. The Earth is constantly vibrating, normally imperceptibly, and these vibrations are known as ambient noise. This noise is caused mainly by ocean waves and wind, but also by vehicles and machinery. Snieder and Wapenaar (*2010*) present an excellent overview of this and other correlation-based seismic imaging techniques.

This method proceeds in three main steps. The first step is the cross-correlation of continuous records of up to months of seismic noise for each pair of seismic stations in an area. It has been shown both theoretically and empirically that the cross-correlation of the ambient noise produces a "seismogram" that represents surface waves traveling from one station to the other. This happens because the noise is predominantly made up of surface waves traveling in random directions, and the

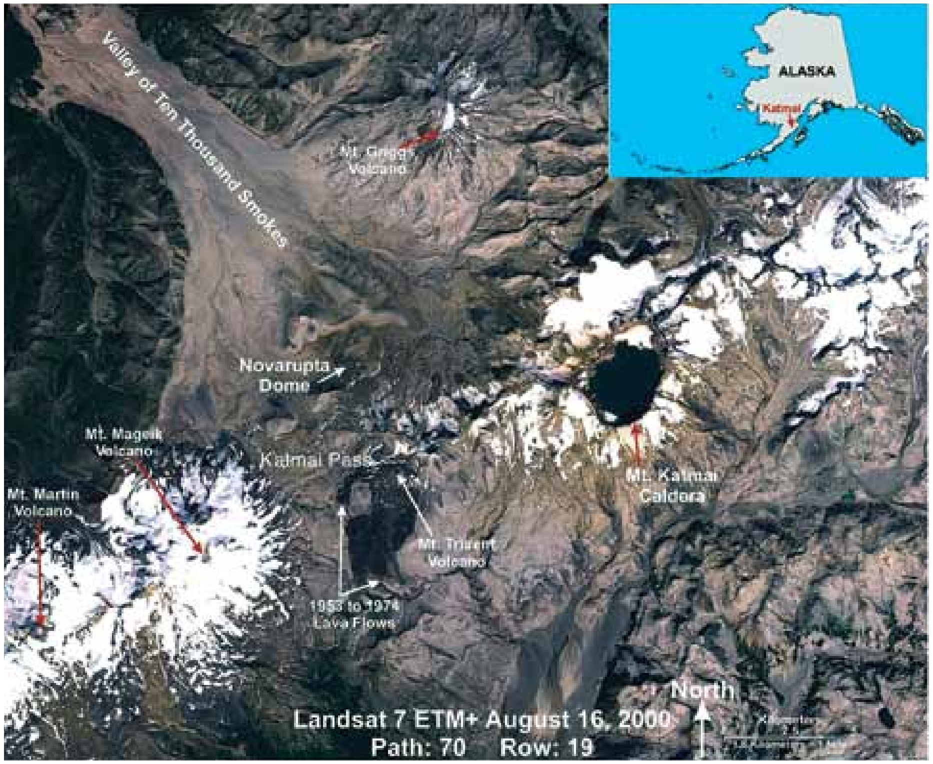


Figure 2. Composite satellite image of the Katmai National Park and Preserve region. Modified image courtesy of Steve Smith and AVO/University of Alaska Fairbanks, Geophysical Institute.

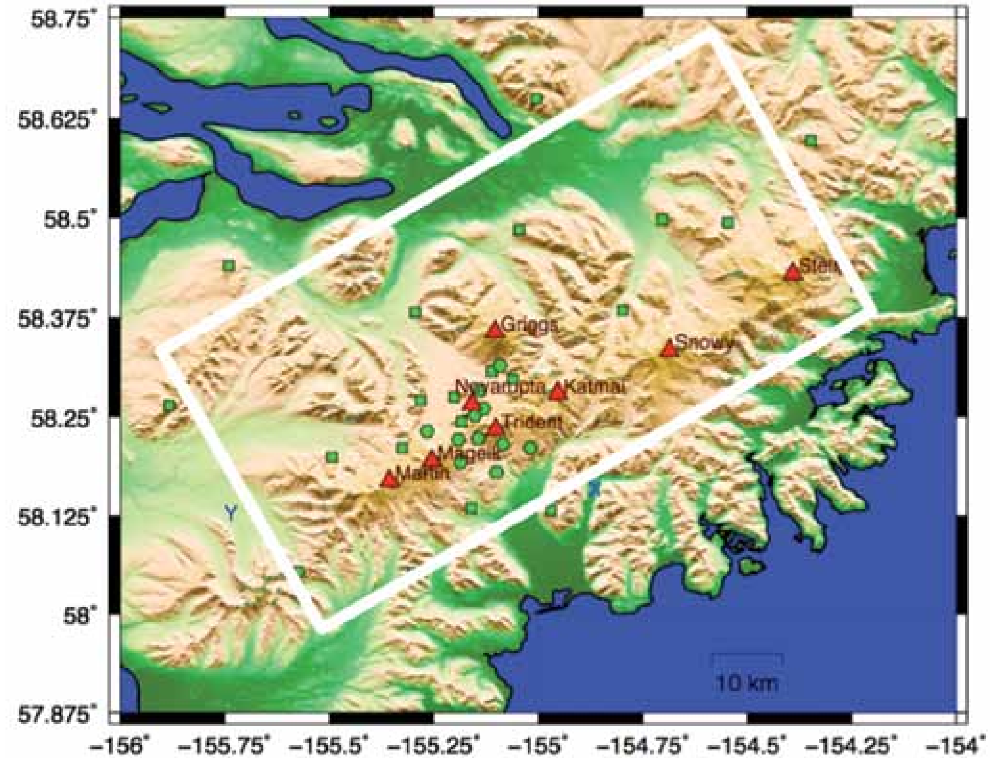


Figure 3. Map of seismic stations in the Katmai area. Green squares represent AVO permanent stations; green circles are AVO/UWM temporary stations. Red triangles are volcanoes with names indicated. The white rectangle is the outer edge of the body-wave seismic velocity model.

cross-correlation analysis brings out those waves that happen to pass by both stations. An example is shown in Figure 5, where the ambient noise "seismograms" (known technically as Green's functions) for the Katmai area are lined up according to the distance between the two stations. The second step is the estimation of the velocity of the surface wave, which as noted above is a function of the frequency of the wave (a phenomenon known as dispersion), for all pairs of stations. The dispersion behavior is most sensitive to the S-wave velocity structure. For the third and final step, the dispersion results for all station pairs are used to construct the image of the S-wave velocity structure in three dimensions.

Images of the Seismic Velocity Structure

Figures 6 and 7 display slices through the three-dimensional models of the body-wave P and ambient noise S velocity models, respectively. Warm colors represent areas of the models with relatively low seismic wave velocity, and conversely cold colors represent areas with relatively high seismic wave velocity. We note that seismic wave velocity normally increases with depth (mainly due to the effects of increasing pressure), so areas that are anomalous can be identified by deviations from this general pattern.

There are several key features that we interpret in the P-wave (body-wave) model (*Figure 6*). One is the very low velocity at 2 km depth in the Katmai Pass area, between Mageik and Novarupta/Trident. Jolly et al. (*2007*) found very low seismic velocity at shallow depths in this area as well. At greater depths, we identify separate zones of relatively low P-wave velocity that are visible in the 4 km depth slice beneath Mt. Mageik and in the 4 and 6 km depth slices beneath Trident. The latter extends northeastward toward Katmai. This result is in contrast to that of Jolly et al., who found a single, large anomalous zone of low P-wave velocity centered beneath Katmai Pass. The difference is likely due to increased seismic station coverage in our study, which provides us with a sharper focus in imaging the subsurface. We can image multiple low-velocity bodies that were blurred together in the results of Jolly et al.

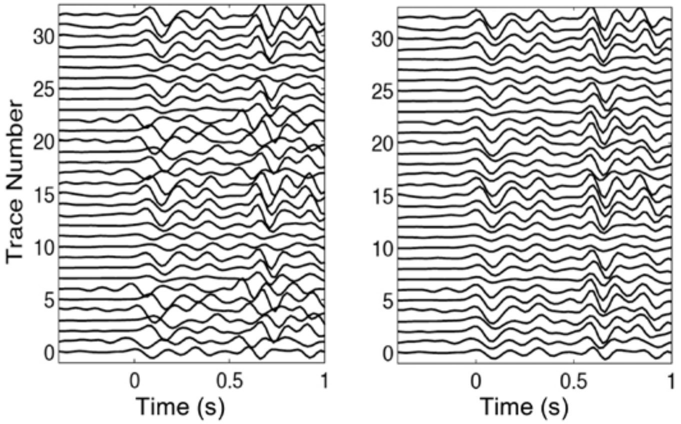


Figure 4. Comparison of seismic waveforms aligned on (left) catalog data versus (right) cross-correlation for a Katmai-area station, showing the improved alignment of the arriving waves.

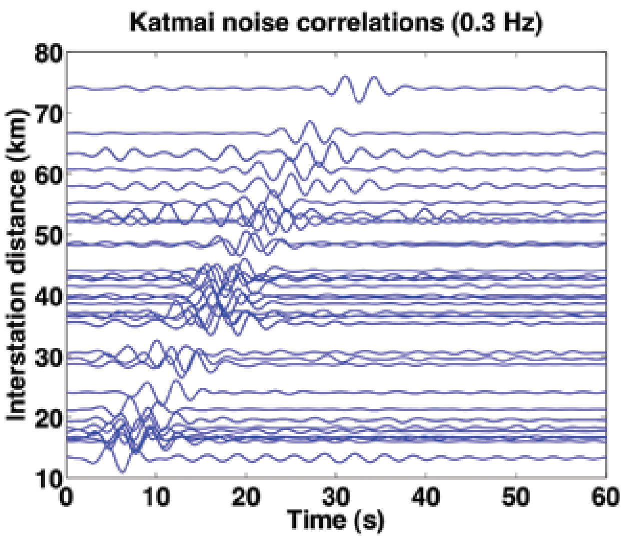


Figure 5. Ambient noise correlation results ordered by separation between the seismic stations, showing the surface waves that emerge from the method.

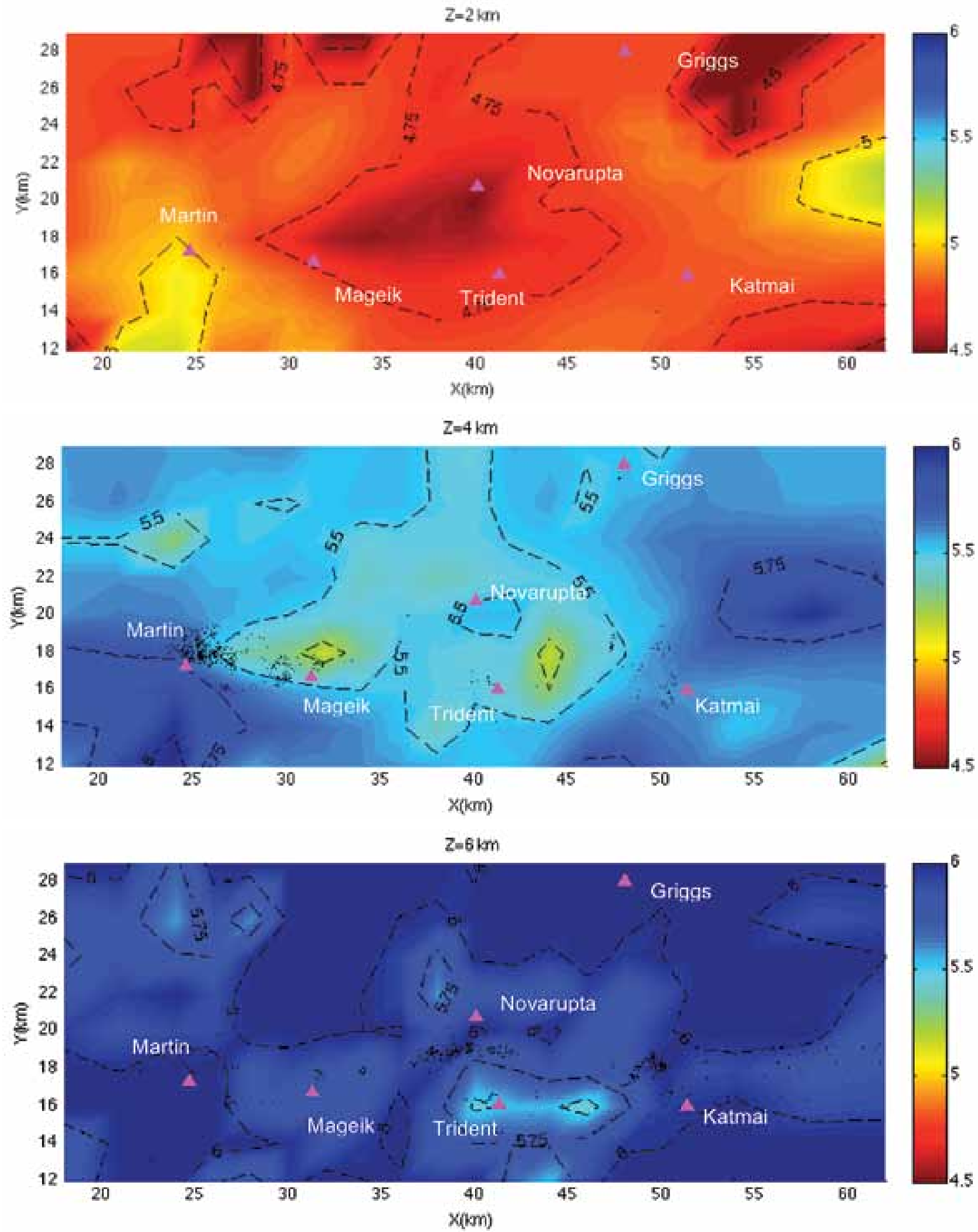


Figure 6. (Right) P-wave velocity image from body-wave tomography in horizontal slices at 2, 4, and 6 km depth (relative to sea level) for the boxed area in Figure 2. The structure shallower than 2 km is not adequately resolved by the body-wave data, so is not shown. Velocities are in kilometers per second. This model is represented mathematically as smoothly varying between points spaced 2 km apart where the seismic velocity value is defined.

The "noise tomography" results for S-wave velocity in Figure 6, which are based on the analysis of data only from AVO network stations, are generally consistent with the body-wave image. Near the surface (0 to 2 km depth), a region of very low S-wave velocity is evident in the Katmai Pass area, similar to the P-wave model (*Figure 6*). There is also a low velocity anomaly at 4 km depth roughly beneath Trident that extends toward Katmai, similar to the body-wave model. One feature in the ambient noise model that is not present in the body-wave model is the low velocity anomaly just northeast of Katmai at 2 km depth. This is an area lacking in seismic station coverage, so the body-wave model is not well imaged there. The separate low-velocity anomaly beneath Mageik present in the body-wave model at 4 km depth is not present in the noise tomography model. It may be that the body-wave data have enough resolving power in this area to distinguish two features, whereas they are blurred together in the noise tomography model.

Earthquake Locations

As part of the body-wave imaging process, the locations of the earthquakes are refined. With the improved accuracy from the cross-correlation analysis (Figure 4), the earthquake locations are more accurate, "sharpening" our view of the seismicity distribution. In Figure 7, we compare the routine AVO catalog locations to our refined locations. There is a systematic deepening of the earthquakes throughout the region, as well as a slight shift to the north. These changes result from including the data from the temporary stations and from the effect of the three-dimensional velocity model. The clusters of earthquakes near the various volcanoes also are much more compact, although some of the smaller earthquakes still have scattered locations.

One aspect that is particularly noteworthy is the relatively sharp cutoff in the earthquake depths, at roughly 4 km beneath Martin and Mageik and 5 km beneath Trident, Novarupta, and Katmai. There are two plausible explanations for this. The temperature of the rocks may increase rapidly at these depths, so that the rocks flow in a ductile manner under stress rather than failing in a brittle manner (i.e., as earthquakes). Alternatively, these earthquakes may be sitting on top of magma storage zones, which would be weak areas that would concentrate stresses just above them. The presence of the low velocity zones in the tomographic images supports the second explanation, but other evidence is necessary in order to distinguish definitively between these two possibilities, or possibly reveal a third explanation.

Conclusions and Future Work

Our seismic imaging research has provided important insight into the magmatic plumbing system of the Katmai volcanoes. The body-wave and surface-wave models display similar features that, along with the spatial distribution of earthquakes, suggest the presence of multiple areas of magma storage below 4 to 5 km depth. Further research will be able to refine the results shown here. Noise tomography can be applied to a combined set of data from the AVO network and the temporary stations (Figure 3) to enhance the surface-wave imaging capability. Body-wave tomography using S waves can be added to the P-wave modeling to provide another estimate of the S-wave structure. Ultimately, the body-wave and surface-wave models can be determined together in a joint inversion that will combine the imaging power of both data types to yield a clearer picture of the magmatic system beneath Katmai.

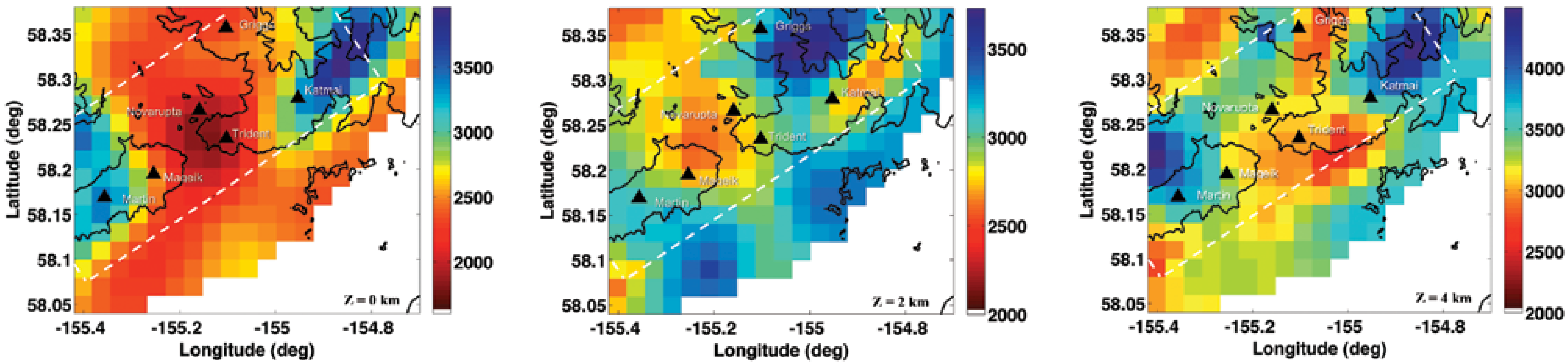


Figure 7. S-wave velocity image from ambient noise tomography in horizontal slices at 0, 2, and 4 km depth (relative to sea level), with the partial dashed white box indicating the area of the P-wave model in Figure 5. The structure deeper than 4 km is not adequately resolved by the ambient noise data, so is not shown. Velocities are in meters per second. This model is represented mathematically as cubes 2 km in size of constant seismic velocity.

Acknowledgements

The research presented here was supported by National Science Foundation grant EAR-0910674 and by the USGS Volcano Hazards Program. We also thank the National Park Service for permission to deploy seismic instruments in Katmai National Park and Preserve.

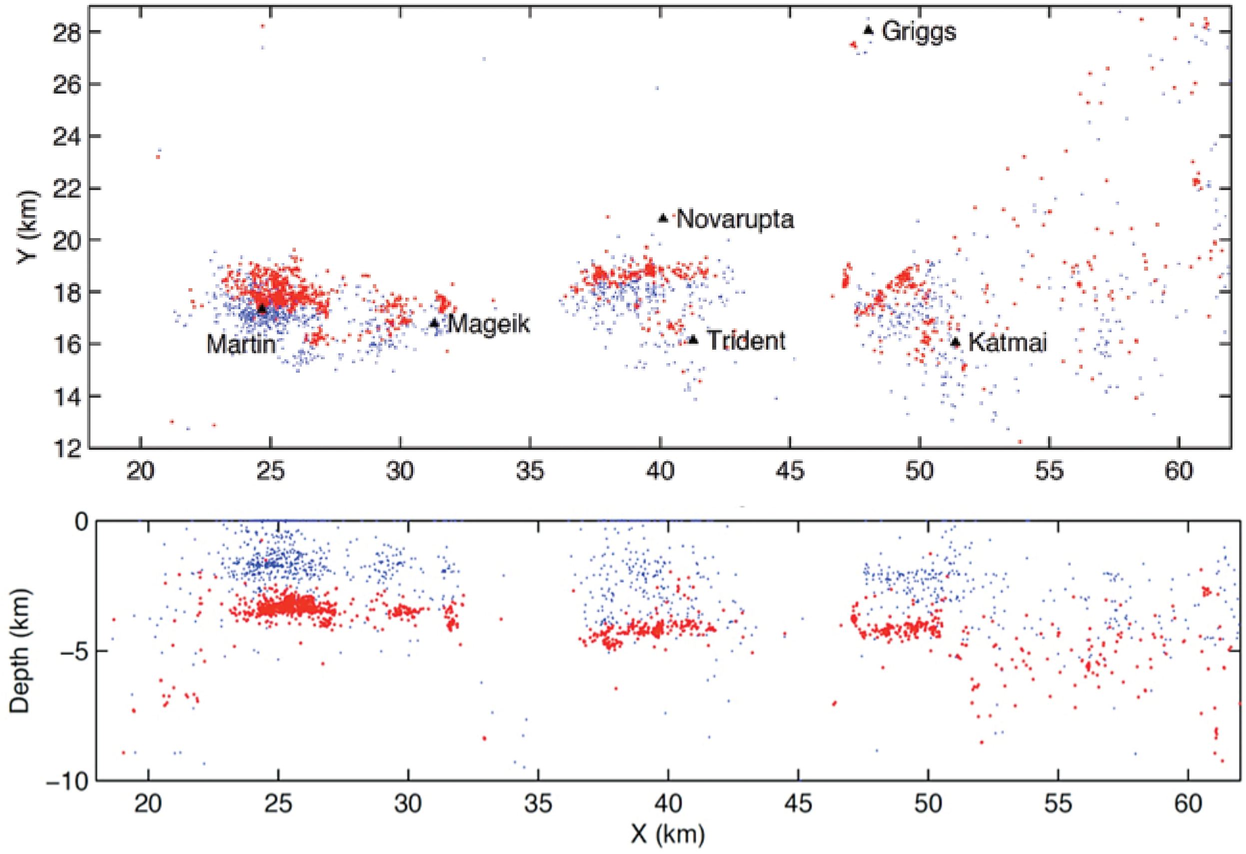


Figure 8. Comparison of catalog (blue) to relocated (red) earthquakes, (a. Top) map view and (b. Bottom) northeast-southwest cross-section. Note the greater degree of clustering in both views and the greater depths evident in (b) for the relocated earthquakes.

REFERENCES

Fierstein, J., and W. Hildreth. 2001.
Preliminary volcano-hazard assessment for the Katmai volcanic cluster, Alaska. U.S. Geological Survey Open-File Report OF 00-0489.

Hildreth, W., M.A. Lanphere, and J. Fierstein. 2003.
Geochronology and eruptive history of the Katmai volcanic cluster, Alaska Peninsula. Earth and Planetary Science Letters 214: 93-114.

Jolly, A.D., S.C. Moran, S.R. McNutt, and D.B. Stone. 2007.
Three-dimensional P-wave velocity structure derived from local earthquakes at the Katmai group of volcanoes, Alaska. Journal of Volcanology and Geothermal Research 159: 326-342.

Snieder, R., and K. Wapenaar. 2010.
Imaging with ambient noise. Physics Today 63: 44-49.

Thurber, C.H., and K. Aki, 1987.
Three-dimensional seismic imaging. Annual Review of Earth and Planetary Sciences 15: 115-139.

Zhang, H., and C.H. Thurber. 2003.
Double-difference tomography: the method and its application to the Hayward fault, California. Bulletin of the Seismological Society of America 93: 1875-1889.

Volcanic Earthquakes in Alaska's National Parks

By Stephanie Prejean, Seth Moran,and John Power

Introduction

Alaska's national parks contain 11 historically active volcanoes (*Figure 2*), which produce thousands of small earthquakes every year. These earthquakes are voices of the magmatic and geothermal systems within the volcanoes. The Alaska Volcano Observatory (AVO), a joint program of the U.S. Geological Survey, the Geophysical Institute at the University of Alaska Fairbanks, and the Alaska Division of Geological and Geophysical Surveys, monitors volcanic earthquakes year round with networks of seismometers (*Figure 4*). Data from these networks allow AVO to evaluate the state of magmatic systems and provide warning of volcanic unrest, potential eruptions, and hazards. The key to correctly interpreting earthquakes lies in understanding the physical processes that trigger earthquakes at volcanoes.

Earthquakes Triggered by Magma Ascent

The rise of magma through the Earth's crust can trigger seismicity for many reasons. Ascending magma puts pressure on the surrounding crust, often creating small fractures as rock breaks to accommodate the increased volume (*McNutt 2005*). In addition, gases released from rising magma (water, carbon dioxide, and others) can further pressurize the surrounding rock, generating earthquakes. For these reasons, earthquake swarms (bursts of many earthquakes closely spaced in time and location) almost always precede volcanic eruptions.

The relationship between seismicity and magma ascent is controlled by many factors including: the chemistry and gas content of the magma, regional tectonic stresses, the temperature of the surrounding crust, the type of rock surrounding the conduit system (e.g., granite vs. sedimentary rock), and whether there are pre-existing faults in the area or an existing, recently occupied conduit to facilitate magma migration. Because of these variables, there is an impressive diversity in seismicity characteristics associated with magma ascent.

For example, prior to the 2008 eruption of Kasatochi volcano (Aleutian Islands), the largest earthquake associated with magma ascent was magnitude (M) 5.8. In contrast, the largest pre-eruption earthquake of the 2009 eruption of Redoubt Volcano was only M 3.1, and the largest pre-eruption earthquake of the 2006 eruption of Augustine Volcano was M 2.1. Some eruptions, such as the 2009 Redoubt eruption, produce strong volcanic tremor (continuous vibration of the Earth's crust) prior to large explosions, while other volcanoes do not exhibit this type of activity at all. Given this range of seismic behavior, correct eruption forecasts rely on interpreting seismicity in the context of many other data streams, including historical activity at the volcano, the chemistry of magma typically erupted from the volcano, and other clues to magma ascent gleaned from ground deformation, satellite, and gas monitoring data.

Seismic activity in the months leading up to the 2009 eruption of Redoubt Volcano displayed many classic signs of earthquake triggering by magma ascent. Four months prior to eruption onset, earthquakes known as deep-long-period events (DLPs) began occurring in the Earth's lower crust at 15-22 miles (25-35 km) depth. DLPs radiate lower frequency seismic energy than typical brittle-failure earthquakes and likely result from slugs of magma or other fluids forcing their way upward through rock (see Figure 5 on page 29 for schematic). Thus, these DLPs signaled renewal of magma ascent from lower crustal depths. Three months prior to eruption onset, vigorous shallow volcanic tremor and earthquake swarms began in and below the volcano. This shallow seismicity was likely triggered by pressurization due to injection of magma into the near-surface rocks, release of gases from magma, and heating and boiling of ground water. Earthquake activity increased markedly in the two days prior to eruption (*Figure 3*), as the final ascent of magma perturbed the surrounding rocks. At that time, small earthquakes occurred at a rate of 1-5 per minute. This build up in the number of earthquakes with time is fairly typical for a stratovolcano prior to eruption, although precursory activity at many volcanoes veers from this pattern markedly. Okmok

Figure 1. John Paskievitch (USGS AVO) servicing a webcam mounted on solar panels at seismometer site KABU in Katmai National Park and Preserve, August 2009. Trident (right) and Katmai (left) Volcanoes are visible in the background.

USGS AVO photograph by Stephanie Prejean

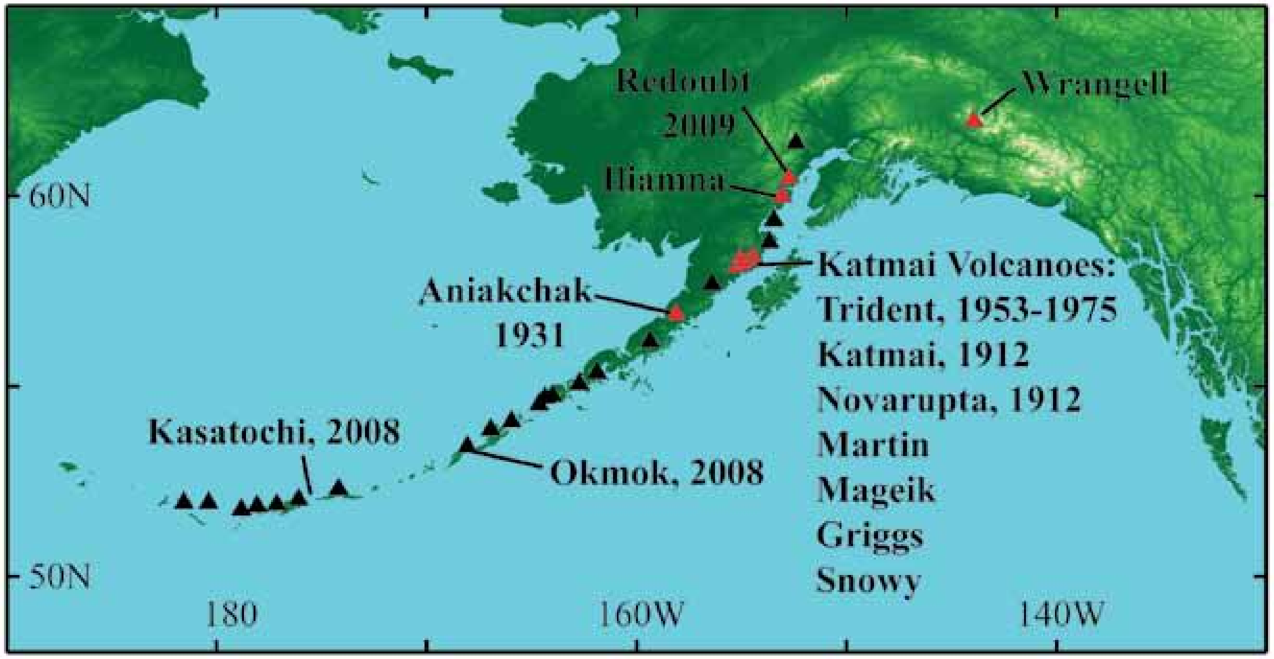


Figure 2. Map showing volcanoes in Alaska that are seismically monitored by AVO. Those labeled with dates of most recent significant eruptions when known, are mentioned in this article. Those colored red are in national parks. Redoubt and Iliamna are in Lake Clark National Park and Preserve, Mount Wrangell is in Wrangell-St. Elias National Park and Preserve, Aniakchak caldera is in Aniakchak National Monument and Preserve, and seven volcanoes are in Katmai National Park and Preserve (Novarupta, Trident, Katmai, Martin, Mageik, Griggs, and Snowy).

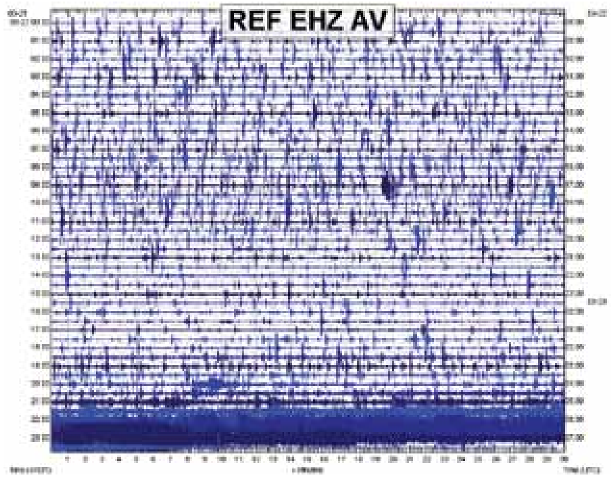


Figure 3. 'Webicorder' plot showing 24 hours of seismic data from station REF on Redoubt Volcano, March 21 and 22, 2009. Time goes forward from top to bottom and left to right; each horizontal line represents 30 minutes. Spikes in first 21 hours are individual earthquakes often occurring at a rate of two to three per minute. Large amplitude seismic waves at bottom of figure result from eruption onset.

USGS AVO photograph by Game McGimsey

Figure 4. Michelle Coombs (USGS AVO) and Sarah Henton (University of Alaska Fairbanks, AVO) performing maintenance on a seismic station, September 22, 2009. Redoubt Volcano is visible in the background.

Volcano in the Aleutian Islands, for example, erupted in 2008 with only 60 minutes of elevated seismicity (*Larsen et al. 2009*). The clear precursory earthquake sequence associated with the 2009 eruption of Redoubt Volcano allowed scientists at AVO to supplement the monitoring network prior to the eruption with additional equipment (*Figure 4*) and to correctly forecast the eruption.

Earthquakes Triggered by Distant Large Earthquakes

After a large earthquake in Alaska, AVO scientists are frequently asked, "Does that earthquake affect the volcanoes?" The answer to this question is complex and is the subject of ongoing research. In general, large earthquakes in Alaska and around the globe that result from the relative motion of tectonic plates do not cause volcanoes to erupt. However, there are a few cases globally where large regional earthquakes have clearly initiated volcanic activity, such as the 1975 summit eruption of Kilauea Volcano, Hawai'i, following the M 7.2 Kalapana earthquake (*Hill et al. 2002*).

There is abundant evidence that large earthquakes can trigger small earthquakes (M≤2.0) at volcanoes over amazingly large distances. For example, the 2007 M 8.2 earthquake in the Russian Kurile Islands triggered a small earthquake swarm at Martin Volcano in the Katmai volcanic cluster, over 2,000 miles (3,500 km) distant (*Figure 5*). More impressively, the 2004 M 9.2 Sumatra earthquake triggered an 11 minute swarm of small earthquakes at Mt. Wrangell volcano, almost 6,900 miles (11,000 km) distant.

In these and similar cases, local earthquakes were triggered when the highest amplitude seismic waves from the large distant event rolled through the area. This phenomenon, known as remote dynamic triggering, has been observed all over the world (*Prejean and Hill 2009*). Volcanoes in Katmai National Park and Preserve appear to be particularly susceptible to this type of triggering. Moran et al. (*2004*) summarize four episodes of remotely triggered seismicity at Martin Volcano in addition to the 2007 example. Generally, these small, triggered earthquakes do not perturb the volcanic system significantly, nor are they related to movement of magma through the crust. Rather, they can be thought of as earthquakes that might have occurred anyway over the subsequent months. The oscillation of the ground from seismic waves of the distant earthquake simply caused them to occur earlier than they would have otherwise. Moran et al. (*2004*) inferred that the triggered earthquakes may have resulted from shaking of the shallow hydrothermal system and movement of hydrothermal fluids. Others have argued, however, that the preponderance of remote dynamic triggering suggests that the Earth's crust is in a state of incipient failure everywhere (*Gomberg et al. 2004*).That is, rocks in the shallow crust are poised to break, and it only takes a tiny nudge to trigger these small earthquakes in almost any volcanic region.

Ongoing Research

Due to the high earthquake rates and relatively frequent volcanic eruptions in Alaska (one per year on average), many researchers are focusing on volcanoes in Alaska's national parks to better understand how volcanic earthquakes are triggered. For example, data from a recent seismic experiment in Katmai National Park and Preserve (*see Thurber et al., this issue*) reveal that many recent earthquakes in the area of Trident and Novarupta volcanoes are likely triggered by increased fluid pressure in a geothermally active region of the Earth's crust. In another example, Roman and Power (*2011*) examine earthquake characteristics to infer stress changes in the crust due to magma movement at Iliamna Volcano during a failed eruption (an intrusion of magma into the shallow crust that did not result in an eruption) in 1996-97.

Discriminating between earthquake swarms triggered directly by magma movement and those triggered indirectly by magma (e.g. by high-pressure, magmatically-derived fluids and gases like water and carbon dioxide) is an ongoing challenge at potentially dangerous volcanoes worldwide. We must address this problem to correctly interpret the state of the magma system and resulting volcanic hazards. For these reasons, Alaska's national parks will continue to be important laboratories for testing and refining our understanding of earthquake triggering at volcanoes.

For more information:

The Alaska Volcano Observatory has a comprehensive web page that includes daily images of activity on seismometers at monitored volcanoes and a database of recent publications: http://www.avo.alaska.edu/

The USGS Volcano Hazards Program web page provides information about volcanic activity and resulting hazards throughout the U.S.: http://volcanoes.usgs.gov/

The Alaska Earthquake Information Center provides information about recent and historical earthquakes in Alaska: http://www.aeic.alaska.edu/

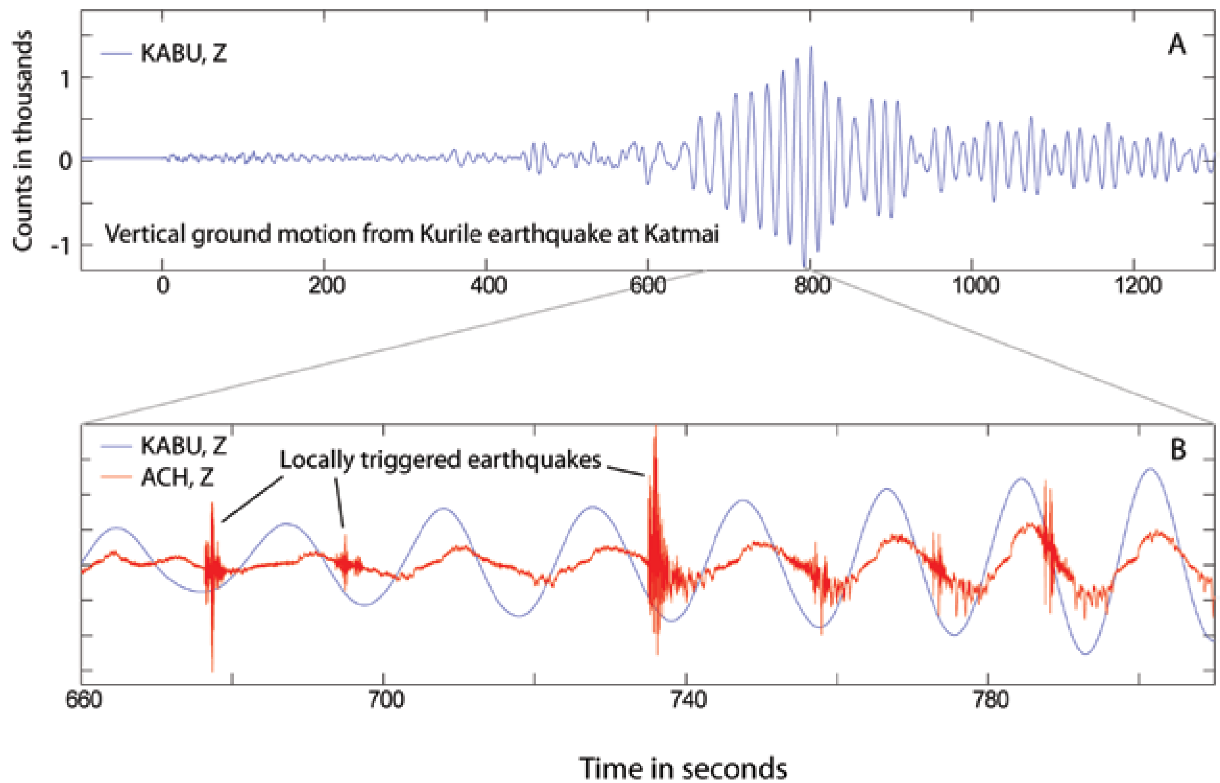


Figure 5. Dynamically triggered earthquakes at Mt. Martin Volcano following the 2007 M 8.2 Kurile earthquake: A) broadband record from seismic station KABU showing dominantly low-frequency ground motion of the Kurile earthquake in the Katmai area; B) seismic data from ACH (located near Mt. Martin) and KABU zoomed in to show how local earthquakes (spikes in red) are occurring during specific ground motion phases from the Kurile earthquake (*Prejean and Hill 2009*).

Photograph courtesy of Gary Freeburg

Figure 6. The eastern rim and lake of Mount Katmai's caldera, as seen from the western rim.

REFERENCES

Coombs, M., and C. Bacon. 2012.
Using rocks to reveal the inner workings of subvolcanic magma chambers in Alaska's National Parks. Alaska Park Science, this issue (page 26).

Gomberg, J., P. Bodin, K. Larson, and H. Dragert. 2004.
Earthquake nucleation by transient deformation caused by the M = 7.9 Denali, Alaska, earthquake. Nature 427: 621-624.

Hill, D.P., F. Pollitz, and C. Newhall. 2002.
Earthquake-volcano interactions. Physics Today 55: 41.

Larsen, J., C. Neal, P. Webley, J. Freymueller, M. Haney, S. McNutt, D. Schneider, S. Prejean, J. Schaefer, and R. Wessels. 2009.
Eruption of Alaska volcano breaks historic pattern. Eos, Transactions, American Geophysical Union 90 (20): 173-174.

McNutt, S. 2005.
Volcano Seismology. Annual Review of Earth and Planetary Sciences 33: 461-491.

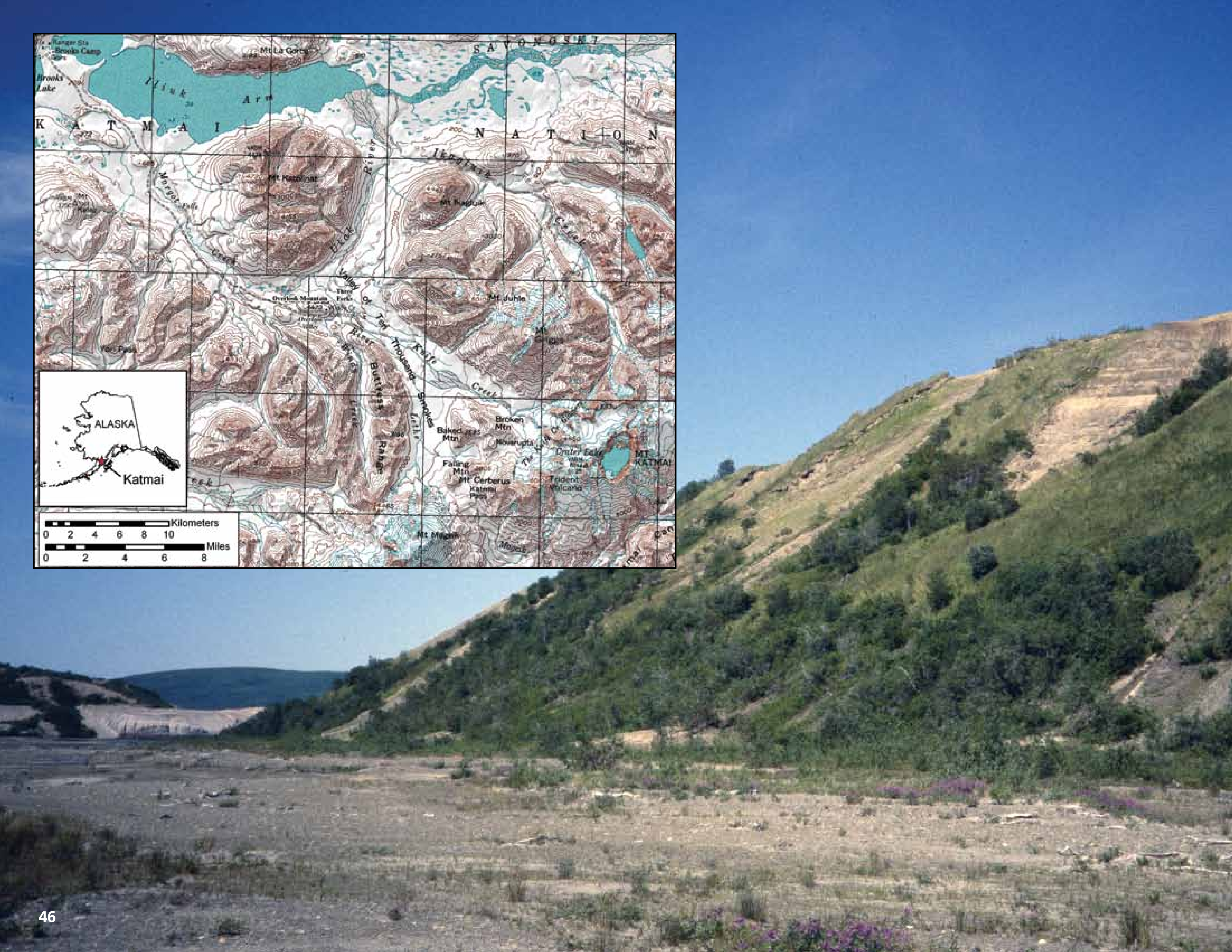
Moran, S.C., J.A. Power, S.D. Stihler, J.J. Sanchez, and J. Caplan-Auerbach. 2004.
Earthquake triggering at Alaskan volcanoes following the 3 November 2002 Denali Fault Earthquake. Bulletin of the Seismological Society of America 94: S300-S309.

Prejean, S.G., and D.P. Hill. 2009.
Earthquakes, Dynamic Triggering of. In Encyclopedia of Complexity and System Science, edited by R.A. Meyers. Springer.

Roman, D.C. and J.A. Power. 2011.
Mechanism of the 1996-97 non-eruptive volcano-tectonic earthquake swarm at Iliamna Volcano, Alaska. Bulletin of Volcanology 73: 143-153.

Thurber, C., R. Murphy, S. Prejean, N. Bennington. 2012.
Earthquake studies reveal the magmatic plumbing system of the Katmai volcanoes. Alaska Park Science, this issue.

West, M., J.J. Sanchez, and S.R. McNutt. 2005.
Periodically triggered seismicity at Mount Wrangell, Alaska, after the Sumatra Earthquake. Science 308: 1144-1146.



Ranger Sta
Brooks Camp
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SAVONOSKI
Iliuk Arm
K A T M A I
N A T I O N
Mt Katolinat
Mt Juhle
Mt Griggs
Overlook Mountain
Three Forks
Valley of Ten Thousand Smokes
Knife Creek
Buttress Range
Baked Mtn
Broken Mtn
Novarupta
Falling Mtn
Mt Cerberus
Katmai Pass
Trident Volcano
MT KATMAI
Mt Mageik
ALASKA
Katmai
Kilometers
0 2 4 6 8 10
Miles
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Pre-1912 Glacial and Volcanic History near Windy Creek, Katmai National Park and Preserve, Alaska

By De Anne Pinney Stevens

Introduction: Fire and Ice

The Alaska Peninsula hosts a chain of glacier-clad volcanoes that generally hug the southern coastline of the peninsula. More than 50 percent of the Alaska Peninsula is composed of Quaternary-age deposits (younger than about 2.6 million years) that are primarily glacial or volcanic in origin. Pleistocene (between 2.6 million and 11,700 years) ice caps and glaciers blanketed much of the peninsula with glacial deposits, with most preserved deposits being of Wisconsin age (between about 110,000 and 11,700 years) or younger (*Detterman 1986*).

One of the most notable chapters in the recent geologic history of the Alaska Peninsula took place in 1912, when a major ignimbrite-producing eruption occurred in the Katmai area. Much has been published on the 1912 Katmai eruption, but much less well known are the geologic events preceding that event. Here I discuss pre-1912 surficial deposits of the Katmai area and develop a Quaternary geologic history of the region. The study area is centered on Windy Creek valley, just west of the Valley of Ten Thousand Smokes, and includes Overlook Mountain (*Figure 1*).

Figure 1. Map showing Windy Creek area and locations mentioned in text.

Figure 2. Glaciolacustrine deposits form 130-ft (40-m) bluffs in Windy Creek valley. This thick sequence of silt and clay was deposited in a glacier-dammed lake that inundated the lower 3.7 mi (6 km) of Windy Creek during the Iliuk stade. The 1912 ignimbrite is visible in middle distance at the mouth of the valley.

Photograph courtesy of De Anne Stevens

Glacial Deposits

Prior to Quaternary time, the Alaska Peninsula southwest of Port Heiden was a string of islands (*Detterman 1986*), much like today's Aleutians. During the Pleistocene these islands were connected first by ice, then by the deposits left behind by repeated glaciations. Located adjacent to the Gulf of Alaska, a vast moisture source, the Alaska Peninsula was ideally situated to produce large glaciers. During times of maximum glaciation, an ice cap in Shelikof Strait sent outlet glaciers north through passes in the Aleutian Range to the coastal plain along Bristol Bay and south into valleys on Kodiak Island, burying the peninsula in ice (*Péwé 1975*).

Pleistocene glacial deposits recognized on the Alaska Peninsula include an unnamed pre-Wisconsinan drift, pre-Wisconsinan Johnston Hill drift, early Wisconsinan Mak Hill drift, and late Wisconsinan Brooks Lake drift (*Muller 1952, 1953, Detterman and Reed 1973, Detterman 1986*). The Brooks Lake Glaciation has been subdivided into four substages, or stades (from oldest to youngest): the Kvichak, Iliamna, Newhalen, and Iliuk (*Muller 1952, 1953, Detterman and Reed 1973, Detterman 1986*). In the Katmai area, ice of the Iliamna, Newhalen and Iliuk stades extended 60 mi, 45 mi, and 30 mi (100 km, 70 km, and 50 km), respectively, downvalley from modern glaciers with the type Iliuk moraine forming the narrows separating Iliuk Arm from Naknek Lake (*Riehle and Detterman 1993*).

Glacial deposits of probable Iliamna and Newhalen age are locally exposed in Windy Creek valley, which was subsequently dammed by Iliuk ice to form a proglacial lake. In the study area, Iliuk drift is best preserved in Overlook valley (informal name), the east-west trending valley immediately south of Overlook Mountain. Glaciers in the Valley of Ten Thousand Smokes flowed west through Overlook valley during Iliuk time and blocked drainage in Windy Creek valley. Glacial-lake deposits form bluffs up to 130 ft (40 m) high along the margins of the river floodplain (*Figure 2*). The upper surface forms a terrace up to 0.3 mi (0.5 km) wide on either side of the valley and extends more than 3.7 mi (6 km) upvalley. Maximum height of the Iliuk moraine exceeds 165 ft (50 m) at the mouth of Windy Creek.

Two late-stage readvances of Iliuk ice were recognized in the Windy Creek area. The older of these was informally named "Ukak drift" (*Pinney and Begét 1991a, Pinney 1993*). Ukak drift represents a late Pleistocene ice readvance and is preserved in upper Margot Creek and lower Windy Creek. The upper part of associated glacial-lake deposits date between ca. 10,000-12,000 radiocarbon years before present (RC yr B.P.) (*Pinney and Begét 1991a, Pinney 1993*). Alpine glaciers in Windy Creek did not advance all the way down the valley during this time, leaving the earlier glacial deposits intact. In the Valley of Ten Thousand Smokes, Ukak-age glaciers advanced several kilometers beyond Overlook Mountain and a tongue of ice extended past the mouth of Windy Creek. There is no evidence of an ice-dammed lake in Windy Creek valley during this time, but Windy

Photograph courtesy of De Anne Stevens

Figure 3. Early Holocene-age Katolinat moraines form vegetated mounds protruding through the 1912 ignimbrite near Three Forks. The moraines arc across the lower Valley of Ten Thousand Smokes and obstructed the flow of the ignimbrite, funneling it against the base of Overlook Mountain.

Creek drainage was at least intermittently impounded in Overlook valley prior to draining to the west.

The youngest glacial deposits recognized in the lower Windy Creek area are informally named "Katolinat drift" (*Pinney and Begét 1991a, Pinney 1993*), and form a nested pair of well-formed, modestly-sized terminal moraines (*Figure 3*). Katolinat-age glaciers advanced down the Valley of Ten Thousand Smokes almost as far as glaciers did during Ukak time. Windy Creek drainage was diverted by the ice margin and once again dammed to form a small lake in Overlook valley. Katolinat drift is best exposed along the 2.5 to 3.1 mi (4-5 km) reach of Windy Creek immediately south of Three Forks, where moraine ridges overrun by the 1912 ashflow can be clearly seen in the canyon walls. Katolinat moraines extend across the lower Valley of Ten Thousand Smokes and obstructed the flow of the ignimbrite, funneling it against the base of Overlook Mountain. The early Holocene (younger than 11,700 years) Katolinat drift dates between ca. 8,500 and 10,000 RC yr B.P. (*Pinney and Begét 1991a, Pinney 1993*).

Volcanic Deposits

Ranging from massive ignimbrites that may have rivaled or even exceeded the 1912 deposit to thin layers of the finest ash, the Windy Creek area preserves an extensive record of volcanism. Deposits of a pre-1912 rhyolitic ashflow are exposed on the west side of lower Windy Creek valley (*Figure 4*). Hildreth et al. (*2003*) map correlative ashflow deposits in Mageik Creek that are dated to 19,240 ±70 RC yr B.P. and posit that the plinian eruption generating these deposits might have been greater in magnitude than that of 1912. The source of these deposits is probably Mount Katmai (*Hildreth et al. 2003*).

The informally named Lethe volcaniclastic deposits (*Pinney and Begét 1990, 1991a, 1991b; Pinney 1993*) comprise an extensive suite of dacitic deposits, including pyroclastic flows, lahars, lahar-runout flows, and primary and reworked fallout tephra. These deposits are exposed in river gorges in the Valley of Ten Thousand Smokes as far as 1.0 mi (1.5 km) upvalley from the mouth of Windy Creek and extend about 3.1 mi (5 km) past Windy Creek in Overlook valley (*Figure 5*). Lethe deposits overlie Iliuk drift in the Windy Creek area and are overlain by and incorporated into Ukak and Katolinat drifts (*Pinney and Begét 1991b, Pinney 1993*). Organic silt immediately underlying the younger glacial deposits yields a minimum age of 12,640 ±100 RC yr B.P. for Lethe deposits (*Pinney and Begét 1991a, Pinney 1993*). Hildreth et al. *(2003)* correlate the Lethe volcaniclastics to a remnant of a proximal pumice-and-scoria fall in the Katmai caldera rim, suggesting that the deposits were erupted from Mount Katmai. Lethe ash has been used as an important stratigraphic marker horizon at Iliamna and Naknek lakes (*Kaufman and Stilwell 1997*), and 185 mi (300 km) away on the Kenai Peninsula (*Reger et al. 1996*). Organic material beneath the Lethe tephra on the Kenai Peninsula gives a maximum age for the tephra of 16,480 ±170 RC yr B.P. (*Reger et al. 1996*), and lake-core studies in lower Cook Inlet suggest a minimum age of 13,730 RC yr B.P. (*Rymer and Sims 1982, Riehle et al. 2008*). These dates

Photograph courtesy of De Anne Stevens

Figure 4. The oldest volcanic deposits mapped in the Windy Creek area are exposed at this single location, where a rhyolitic ashflow is preserved in section with overlying and underlying glacial deposits. Diagonal fractures are interpreted as clastic dikes resulting from the weight of overriding ice when glaciers advanced during the Newhalen stade of the Brooks Lake Glaciation. Exposure is approximately 70 ft (21.5 m) high.

Photograph courtesy of De Anne Stevens

Figure 5. Yellow-brown Lethe deposits comprising moderately indurated glass-rich sands from lahar-runout flows, overlain by pale pink to white 1912 ignimbrite deposits near lower Windy Creek. Pre-1912 topography is evident where the upper contact of the Lethe sands plunges steeply beneath the ashflow, which has buried the former valleys and river channels.

correlate well with the minimum date from the Windy Creek area and indicate that the Lethe volcaniclastics were erupted between about 16,600 and 13,730 RC yr B.P.

Other volcanic deposits in the Windy Creek area include numerous individual ash layers whose origins and correlations remain largely unknown, with a few notable exceptions. Distal ash from the caldera-forming eruption of Aniakchak Crater (ca. 3,400 RC yr B.P.), 140 mi (230 km) away, was preserved in one Windy Creek sample site. Another tephra, ash "Y", correlates with proximal deposits 100 mi (160 km) away at Augustine volcano that date approximately 1,700 RC yr B.P. (*J.E. Begét, personal communication*).

Summary of pre-1912 Geologic History

Figure 6 illustrates the pre-1912 geologic history of the Windy Creek area summarized in Figure 7. The oldest recognized Quaternary deposits are sediments believed to have been deposited during the late Wisconsinan Iliamna glacial advance. An eruption at the Mount Katmai volcanic center buried Windy Creek valley in thick ashflow deposits, which were subsequently overridden and deeply incised by glacial ice of the Newhalen stade and then buried by drift. Another late Wisconsinan ice advance, the Iliuk, blocked drainage from Windy Creek and dammed a lake in the valley, leaving thick glaciolacustrine deposits in addition to well-preserved lateral moraines. Sometime between approximately 16,000 and 13,730 RC yr B.P., another major volcanic eruption, the Lethe, which probably originated at Mount Katmai, deposited a wide variety of volcaniclastic deposits over much of the area. Winds carried Lethe ash across Cook Inlet to blanket large parts of the western Kenai Peninsula. Alpine glaciers advanced between 10,000 and 12,000 RC yr B.P. and deposited the Ukak drift. A glacial readvance between 8,500 and 10,000 RC yr B.P. may have occurred in response to a brief period of climatic cooling, depositing the early Holocene Katolinat drift. The remainder of the Holocene record is characterized by deposition of tephra-rich eolian silts and multiple discrete ash layers that record eruptions from distant sources such as Aniakchak caldera and Augustine volcano.

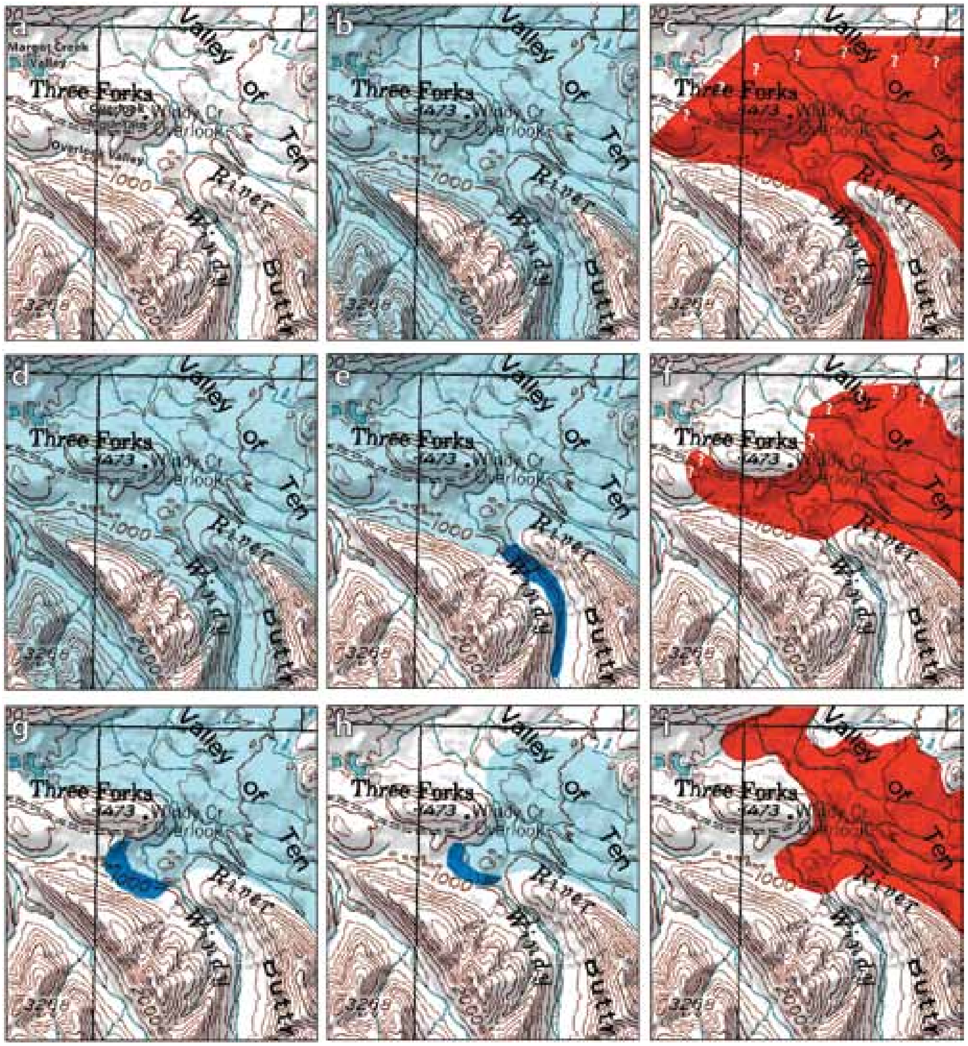


Figure 6. Late Quaternary paleogeography of the Windy Creek area. Light blue – glacial ice; dark blue – glacially dammed lakes; red – volcanic deposits. a) location map with key geographic features; b) Late Wisconsin Iliamna stade glacial advance; c) Windy Creek ashflow eruption ca. 19,240 RC yr B.P.; d) Newhalen stade glacial advance; e) Iliuk stade glacial advance dams glacial lake in lower Windy Creek; f) Lethe volcanic eruption ca. 14,000-16,000 RC yr B.P.; g) Ukak glacial readvance dams small lake in Overlook valley ca. 10,000-12,000 RC yr B.P.; h) Katolinat glacial readvance dams small lake in Overlook valley ca. 8,500-10,000 RC yr B.P.; i) 1912 cataclysmic eruption forms Valley of Ten Thousand Smokes.

AGE	DATE	EVENT	DEPOSIT
Recent	1912 A.D.	Volcanic eruption	Katmai ashflow deposit
Late Holocene	ca. 1,700 RC yr B.P.	Volcanic eruption	Augustine volcano ash
Middle Holocene	ca. 3,400 RC yr B.P.	Volcanic eruption	Aniakchak ash
Middle Holocene	ca. 4,000 RC yr B.P.	Volcanic eruption	Three Forks ash
Early Holocene	8,500 - 10,000 RC yr B.P.	Glacial advance	Katolinat drift
Latest Wisconsin	10,000 - 12,000 RC yr B.P.	Glacial advance	Ukak drift
Latest Wisconsin	13,700 - 16,000 RC yr B.P.	Volcanic eruption	Lethe volcaniclastic deposits
Late Wisconsin	>13,700 - < 19,240 RC yr B.P.	Glacial advance	Iliuk drift
Late Wisconsin	>13,700 - < 19,240 RC yr B.P.	Glacial advance	Newhalen drift
Late Wisconsin	ca. 19,240 RC yr B.P.	Volcanic eruption	Windy Creek ashflow deposit
Late Wisconsin (?)	> 19,240 RC yr B.P.	Glacial advance	Iliamna drift (?)

Figure 7. Summary of Late Quaternary Geologic History of the Windy Creek Area. Dates shown as radiocarbon years before present (RC yr B.P.).

REFERENCES

Detterman, R.L. 1986.
Glaciation of the Alaska Peninsula. In *Glaciation in Alaska: The geologic record*, edited by T.D. Hamilton, K.M. Reed, and R.M. Thorson, pp. 151-170. Alaska Geological Society.

Detterman, R.L., and B.L. Reed. 1973.
Surficial deposits of the Iliamna quadrangle, Alaska. U.S. Geological Survey Bulletin. 1368-A: A1-A64

Hildreth, Wes, Judy Fierstein, J.E. Robinson, D.W. Ramsey, and T.J. Feldger. 2003.
Geologic map of the Katmai volcanic cluster, Katmai National Park, Alaska. U.S. Geological Survey Geologic Investigations 2778.

Kaufman, D.S., and K.B. Stilwell. 1997.
Preliminary evaluation of emergent postglacial shorelines, Naknek and Iliamna lakes, Southwestern Alaska. In Geologic studies in Alaska by the U.S. Geological Survey, 1995, edited by J.A. Dumoulin and J.E. Gray, pp. 73-81. U.S. Geological Survey Professional Paper 1574.

Muller, E.H. 1952.
Glacial history of the Naknek District, Alaska Peninsula, Alaska [abstract]. Geological Society of America Bulletin 63: 1284.

Muller, E.H. 1953.
Northern Alaska Peninsula and eastern Kilbuck Mountains, Alaska. In *Multiple glaciation in Alaska: A progress report*, edited by T.L. Péwé, pp. 2-3. U.S. Geological Survey Circular 289.

Péwé, T.L. 1975.
Quaternary geology of Alaska. U.S. Geological Survey Professional Paper 835: 145.

Pinney, D.S. 1993.
Late Quaternary glacial and volcanic stratigraphy near Windy Creek, Katmai National Park, Alaska. M.S. thesis. University of Alaska Fairbanks.

Pinney, D.S., and J.E. Begét. 1990.
Quaternary tephrochronology near the Valley of Ten Thousand Smokes, Katmai National Park, Alaska [abstract]. EOS, Transactions, American Geophysical Union 71(43): 1721.

Pinney, D.S., and Begét, J.E. 1991a.
Deglaciation and latest Pleistocene and early Holocene glacier readvances on the Alaska Peninsula: Records of rapid climate change due to transient changes in solar intensity and atmospheric CO2 content? Proceedings of International Conference on the Role of the Polar Regions in G1obal Change. Pp. 634-640.

Pinney, D.S., and Begét, J.E. 1991b.
Late Pleistocene Volcanic deposits near the Valley of Ten Thousand Smokes, Katmai National Park, Alaska. In *Short Notes on Alaskan Geology*, edited by R.D. Reger, pp. 45-53. Alaska Division of Geological & Geophysical Surveys Professional Report 111.

Reger, R.D., D.S. Pinney, R.M. Burke, and M.A. Wiltse. 1996.
Catalog and initial analyses of geologic data related to Middle to Late Quaternary deposits, Cook Inlet region, Alaska. Alaska Division of Geological & Geophysical Surveys Report of Investigation 95-6.

Riehle, J.R., and R.L. Detterman. 1993.
Quaternary geologic map of the Mount Katmai Quadrangle and adjacent parts of the Naknek and Afognak quadrangles, Alaska. U.S. Geological Survey Miscellaneous Investigations 2032.

Riehle, J.R., T.A. Ager, R.D. Reger, D.S. Pinney, and D.S. Kaufman. 2008.
Stratigraphic and compositional complexities of the late Quaternary Lethe tephra in South-central Alaska. Quaternary International 178(1): 210-228.

Rymer, M.J., and J.D. Sims. 1982.
Lake-sediment evidence for the date of deglaciation of the Hidden Lake area, Kenai Peninsula, Alaska. Geology 10: 314-316.

Witness: Firsthand Accounts of the Largest Volcanic Eruption in the Twentieth Century

By Jeanne Schaaf

"BLA—LOOM! Like hell! It is the mountain. The mountain is doing something." Eyewitness Harry Kaiakokonok, June 6, 1912 (*Jessee 1961*).

There is a long-standing bond between Katmai's volcanoes and resident people. In the 10,000 years since the close of the last Ice Age, there have been at least seven explosive eruptions and many minor eruptions in the Katmai volcanic cluster (*Fierstein and Hildreth 2001*). These events are evident in the archaeological sites throughout the region, where volcanic ash or tephras are layered between prehistoric house floors and camp surfaces. Witnessing the explosion of a mountain in very close proximity was not a novel experience for people living on the Alaska Peninsula, when Novarupta volcano unleashed one of the five largest eruptions in recorded history on June 6, 1912. Although an eruption of this scale had not happened in their lifetime, ancestral knowledge of immeasurable antiquity instructed them through oral tradition:

And then one old man from Katmai…started hollering and telling people about their water..."Put away as much water as you can and store it, reserve it. Wherever ashes come down, there will be no water to drink anywhere…Turn your boats upside down. They will be filled up with ash." He knows everything, that old fellow (*Kaiakhvagnak 1975*).

Figure 1. Tourist party at the base of Mt. Katmai, on the way to the Crater, photograph taken by geologist Clarence N. Fenner, July 23, 1923.

NPS photograph KATM 1469

Increasingly severe earthquakes in the days preceding the June 6 eruption led to the complete abandonment of the native villages in the Katmai region (*Griggs 1922*). Most families were already in Kodiak or Naknek by late May, as men were employed as fishermen and women worked in the canneries during the salmon runs (*Davis 1961, Hussey 1971*). Remaining residents of Katmai village and the Severnovsk (Savonoski) settlements, fled to Cold Bay (Puale Bay) and to the Bristol Bay coast a few days prior to the main eruption.

Yet this was the time of year to begin to lay away stores of dried fish and meat for the winter, so some families were out on the land hunting and fishing. They experienced the eruption first hand. Two families from Katmai village, a large coastal settlement with a trading post and Russian Orthodox Church, were fishing in Kaflia Bay, a trip of 35 to 40 miles by kayak northeast of Katmai village (*Kaiakhvagnak and Kosbruk 1975*). Other families from Kaguyak, a village northeast of Kaflia, were also putting up fish in the bay. Five people employed by a commercial fishing interest were stationed in Kaflia Bay at the time. It was from the fish camp at Kaflia, about 32 miles east of Novarupta and in the direct downwind path of the ash fallout, that six-year-old Harry Kaiakokonok witnessed the eruption.

And then afternoon - sometime in the afternoon - it was just like this, bright sunshine, hot, no wind, that's when the volcano started. Started snowing like that fine pumice coming down. Make a lot of noise, the size of rice, some of it, some of it smaller, and some of it bigger, and some of it was as big as a kettle or pot. Kaflia Bay started to get white gradually. That water used to be blue, flat calm, no wind; and started to get white, white, white, and pretty soon all white and dark, dark came. Dark didn't come all of a sudden, it comes gradually. Getting darker and darker and darker and darker, and pretty soon, pitch black. So black even if you put your hand two or three inches from your face outside you can't see it 'cause it was so dark…And then the people started to gather up. (*Kaiakhvagnak 1975*).

Closer to the volcano still were residents of the interior Severnovsk (Savonoski) settlements, among them Petr Kayagvak (American Pete) who was in the process of moving his belongings from Iqkhagmiut, where his wife Pelegia was born, to Old Savonoski when the eruption started.

The Katmai mountain blew up with lots of fire and fire came down trail from Katmai with lots of smoke. We go fast Savonoski. Everybody get bidarka (skin boat). Helluva job. We come Naknek one day, dark, no could see. Hot ash fall. Work like hell (*Griggs 1922*).

The initial stages of the eruption inspired excitement not fear among the children. They began to run up the hillside near their Kaflia camp, to get a better look at the

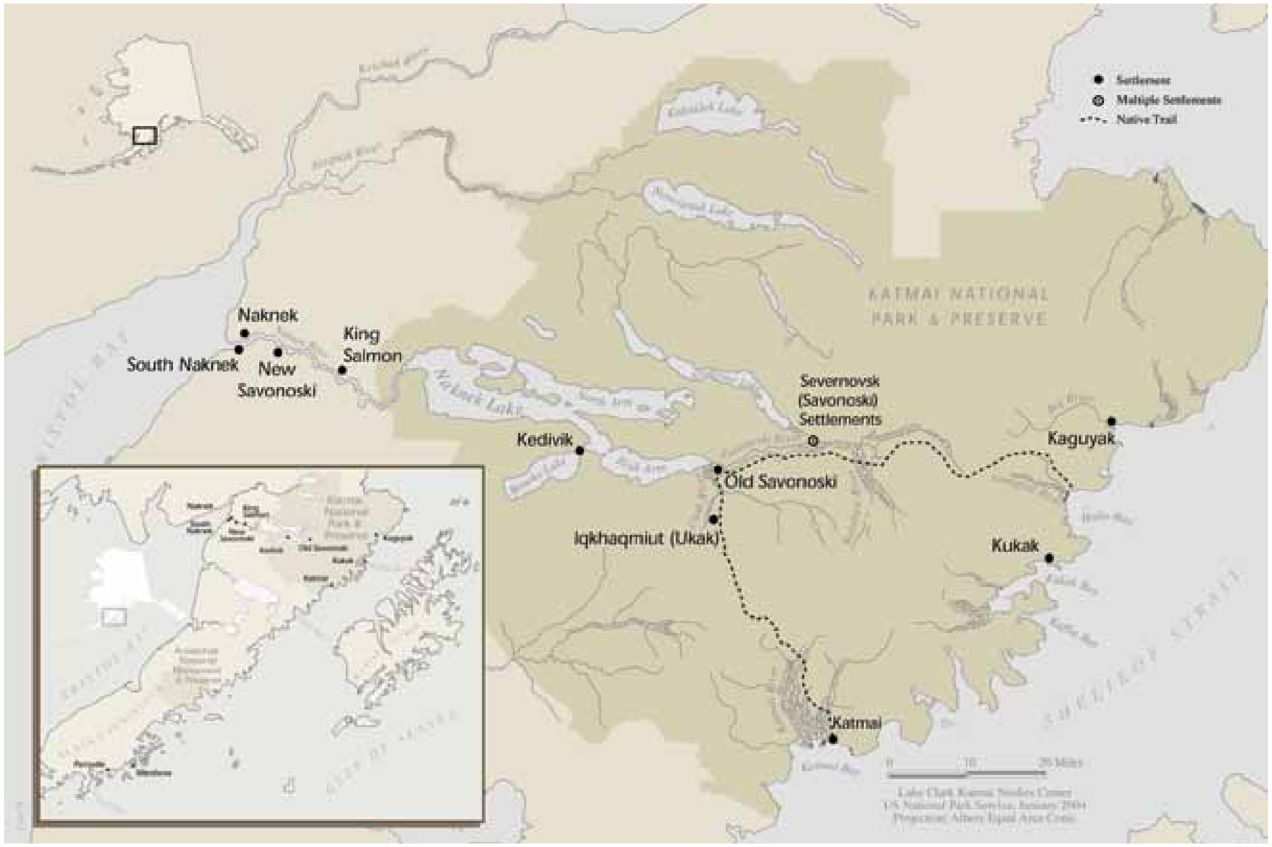


Figure 2. Kaguyak was variously known as Kayakak, Kaliak, or Naushkak and preceded the nineteenth century settlement Douglas or Ashivak, their relative locations are uncertain. Iqkhagmiut, also known as Ikak and Ukak on American maps, is last mentioned in historic records in 1909, indicating that the population had shifted to the Severnovsk settlements of Nunamiut and Kanigmiut. The location of Iqkhagmiut is unknown and is only representational on this map.

"smoky mountain," where they watched vivid lightening, a rare occurrence here, and felt the earth "never stop moving."

And we start to run as hard as we can. We don't run home. We run up the side of high hill. Everybody try to get to top of hill first. All hollering, "Let's go see the mountain." One of the childrens was blind. He blind all the time. He can't see anything. But he running right by me, and he hollering louder than anybody, "Let's go see the mountain." Then he fall down, and I help him up and put both his hands on my shoulders…He run behind me, holding onto my shoulders, hollering loud…We get to top of hill and see sky get black all over, way we looking. All full of lightnings. We don't know what those lightenings are. We don't see no lightnings before. Then our parents start hollering for us to come to our barabaras, and we run back down the hill, that blind boy still holding onto my back. (Jessee 1961).

The adults rushed to fill available containers with water, and because they had been salting and smoking fish to sell to a trader from Kodiak, as well as drying it for their own use, they were somewhat prepared to gather together and outlast the eruption in their recently built homes.

NPS photograph

Figure 3. Ash from the Valley of 10,000 Smokes clouds the air as NPS archaeologists excavate the 7,500 year sequence of human occupation surfaces and airfall tephras at the Mink Island site on the Katmai coast.

Harry Kaiakokonok's parents and uncle had built cabins at Kaflia some two years earlier and now spent winters and summers there (*Kaiakhvagnak 1975*).

This was early twentieth century America, yet for Katmai people life was a blend of strong traditional ways and modern influences. Rifles were owned, purchased with wages or from the sale of pelts, yet the bow and arrow were still used for hunting. Traditional nets and spears were preferred for fishing. Harry remembers hunting porpoise in the bay with his father, Vasilii, who could "make a noise…call them, right up to the side of the kayak." He would shoot the porpoise with a rifle, then quickly, before it could sink, he speared it with a traditional wooden spear to keep it afloat (*Kaiakhvagnak 1975*).

The ash darkened the sky for three days. Had it not been for a big whale that drifted ashore providing oil for lamps and torches, there would have been no light for the people at Kaflia, who no doubt wondered whether they might see sunlight again (*Kaiakhvagnak 1975*). The ash heated the air and it was difficult to breathe.

It get hot in those barabaras. We pull off all our clothes. We soak them in water and put them over our face. Those peoples who have mosses in their barabara pour water over *those mosses and put them over their nose and mouth so they can breathe. After a while we open the door and try to see out. All black, everywhere. A little bird fly into barabara. He can't see where he go. We childrens wash his eyes with water and he stay in barabara with us.* (*Jessee 1961*).

Eighteen year-old George Kosbruk, who was also at the Kaflia fishing camp, remembered his first glimpse of the post-eruption world. As the ash settled and light returned, people escaped the cramped and dark confines of their shelters:

...light is coming. Oh boy, just like snow. Can't see nothing. No kind of tree. All white to mountain. No kind of beach. No bluff. Nothing. All white, the big river. Filled up. No running, the water. Just like cement. That time get hard, boy. Lots of animals that time killed. Lots killed – the bear… ducks and everything (*Kosbruk and Shangin 1975*).

Porpoises, birds and fish were floating on ash and pumice several feet deep, choking the bay. There was no drinking water and little to eat. In that first light, the elders got together and chose nine young men, George Kosbruk among them, to paddle three kayaks across Shelikof Strait to Kodiak for help (*Kaiakhvagnak 1975*). On Wednesday June 12, the tug Redondo loaned to the Coast Guard by Superintendent Blodgett of the St. Paul Kodiak cannery and under the command of Second Lieutenant W.K. Thompson, anchored in Kaflia Bay at 2:30 in the morning.

Landed and found natives destitute, but apparently in normal health, and very badly frightened. Volcanic ashes had buried village to a depth of three feet on the level, closing all streams and shutting off the local water supply. Salmon were dead in the lake, and as it was apparent that the fish would not return for some time, I gathered all natives, with cooking utensils, bedding, and boats, and placed them on the Redondo. The village was comprised of natives from Cape Douglas to Katmai, seismic disturbances having caused them to abandon their usual camps and seek mutual protection at Kaflia Bay. In addition to the refugees, found five natives employed by salmon fishery located at this point. From all information gathered from the head men, I judged that all natives along the coast had been accounted for, and therefore stood out of Kaflia Bay at 10:30 p.m. … At present there are no natives on the mainland between Cape Douglas and Katmai, the region most affected by the eruption, they having been transported to Afognak by the Redondo. (USRCS 1912).

One month after the eruption, some of the Katmai refugees, 78 in number, boarded the U.S. Revenue Cutter Manning to return to the Alaska Peninsula and establish a new village (*USRCS 1913*). Senior Captain W.E. Reynolds, commander of the Bering Sea Fleet Revenue Cutter Service, decided not to resettle the villages on the Katmai coast and to "centralize" the former residents in a new place, at the head of Ivanof Bay (*Hussey 1971*). The Katmai people were not happy with this selection, citing the rainy weather and concerns about reported winter snow and ice conditions. So, three weeks later a new site was selected that had a beach suitable for landing skin boats, a plentiful supply of driftwood, abundant animal sign, fresh water nearby, and well-drained high ground for homes. Located 200 miles (320 km) southwest of Katmai

NPS photograph KATM 00236

Figure 4. Father Harry Kaiakokonok, his wife Jennie and foster son Tommy. The photograph was taken in King Salmon, April 29, 1975.

NPS photograph

Figure 5. Kaguyak (Douglas) Russian Orthodox Church and cemetery, photographed by NPS biologist Lowell Sumner in July 1952.

NPS photograph

Figure 6. Abandoned village of Savonoski, photographed by NPS biologist Lowell Sumner, July 11, 1952.

NPS photograph

Figure 7. Photograph of Katmai village in 1913 by Mel A. Horner. With William A. Hesse, U.S. Deputy Land and Mining Surveyor from Cordova, Horner from Seward was the first to see the Valley of 10,000 Smokes after the eruption.

village and neighboring the former village of Mitrofania, this new settlement was named Perry (now Perryville) after K.W. Perry, Captain of the Manning. Though now far from home, this village was in the familiar shadow of an active volcano, this time it was Mt. Veniaminof, which had last erupted 20 years earlier. Perryville is a successful community of 143 today and remains a seat of Alutiiq culture and language for people of the middle peninsula (*Morseth 2004*).

According to Pelegia Melgenak (American Pete's widow), there were two families that lived at Old Savonoski for a year after the eruption before joining others who had resettled on the lower Naknek River at New Savonoski (*Davis 1961*). She remembered especially how warm the ground and water remained for a year after the eruption; clothes were not needed for warmth, "just like they never have winter." A new chapel was built in New Savonoski, dedicated to Our Lady of Kazan as was its predecessor in Old Savonoski. New Savonoski has since been abandoned for a nearby village, South Naknek, five miles downriver at the mouth of the Naknek River.

The native villages Katmai, Kaflia, and Kaguyak on the Pacific coast, and the Severnovsk settlements were abandoned during the eruption and were never re-established (*Black 1984, Dumond 2010*). These villages had been closely knit culturally through language, kinship, shared hunting territories, and trade for untold generations. Recent archeological surveys along the Savonoski River documented a long-standing pattern of periodic village relocation within drainage systems beginning at least 1,700 years ago (*Hilton 2002*). This is in keeping with ethnohistoric records of changing village locations and names throughout the nineteenth century and until the eruption (*Black 1984, Dumond 1988, Davis 1954*). Harry Kaiakokonok's genealogy illustrates the close ties among these villages, with his parents, paternal and maternal grand and great-grandparents born, married and buried variously in Katmai, Kaguyak, Iqkhagmiut (Ukak) and the other Severnovsk settlements (*Arndt 2000*).

A network of trails, along waterways and over mountain passes, further articulated the relationships among these villages as well as use of this broad region as a home territory. As a young man, George Kosbruk remembers kayaking routinely from Katmai village, to Kukak and Kaflia Bays, to Kaguyak, from there to Kodiak, or south to the Chignik area (*Kosbruk and Shangin 1975*). He would also take his single-hole kayak up the Katmai River, over Katmai Pass and down into the Naknek Lake system and Brooks River (Kedivik). From there he could access the Bristol Bay coast. Another important native trail connected the inhabitants of the Severnovsk villages to Pacific coast settlements via the Savonoski and Ninagiak River watersheds.

By some accounts, the eruption did not have a significant impact on vegetation or on large terrestrial and marine mammals outside the immediate scene of the eruption, but seriously affected other subsistence resources such as small land mammals, birds and fish. Few fish were able to spawn in the ash-filled streams, and the recorded salmon catch on Kodiak showed a significant decline between 1915 and 1920. There was a return to normal numbers, and it is estimated that all areas occupied prior to the eruption may have been

National Geographic Society Katmai expeditions photographs, Archives and Special Collections, Consortium Library, University of Alaska Anchorage

Figure 8. Old Savonoski photograph by botanist Jasper Sayre of the 1917-1919 National Geographic expeditions. Courtesy of University of Alaska Anchorage, Archives and Manuscripts Department.

NPS photograph

Figure 9. Fish drying racks at the mouth of Brooks River. Photograph was taken by Victor Cahalane in September 1940.

habitable 10 to 20 years after the eruption (*Dumond 1979*). By that time, however, President Wilson had signed a proclamation establishing Katmai National Monument on September 24, 1918, inclusive of all the above-mentioned village sites. Annual, month-long bear hunts along the Savonoski by American Pete and other former residents were re-established by this time, and continued at least until 1939 (*Hussey 1971*). Salmon harvesting within the Naknek Lake system, particularly along Brooks River remained active through the 1960s and is an important interest today. But the likelihood of returning permanently to live was summarized by American Pete in 1918, "Never can go back to Savonoski to live again. Everything ash" (*Griggs 1922*).

Harry Kaiakokonok became chief of Perryville in 1930 and was a church leader for many years before becoming a priest. His early accounts of the eruption, written down some 30 years after the event, were described as "wonderfully articulate" with Harry "bounding from his chair…..to illustrate salient points with superb histrionics and graphic pantomime" (*Jessee 1961*). Interviewed by National Park Service ranger Michael Tollefson and archaeologist Harvey Shields another 30 years later, his stories had become more reflective and detailed. The birthplaces, former homes, camp sites and burial places of Harry's family and kinsmen all lie within the boundaries of what is now Katmai National Park and Preserve. When questioned about the establishment of the park, Harry asked first whether hunting would be allowed there. When told it would not be allowed in the park, he said, "That's a good way to preserve lots of animals for the future" (*Kaiakhvagnak 1975*).

Although permanent native villages in Katmai were eliminated by the eruption, strong and enduring ties to their homeland are retained by today's Katmai descendants. A regrettable consequence of village abandonment was the loss of carved wooden ceremonial masks from Old Savonoski.

On our trips back to our ancestral homeland near Brooks Camp…in what is now Katmai National Park, as far back as I can remember, our father Trefon Angasan, would look toward Old Savonoski where he was born, proclaiming, "There are masks in the caves." Anyone within hearing range would smile with contentment that the masks our ancestors carved and used in ceremonies were safely tucked away. In 1993 (we learned) that Harry Featherstone removed the masks in 1921. The news violated our sacred trust. President Wilson had declared the area a National Monument in 1918. How could this happen? (*Nielsen 2001*).

Harry Featherstone was a trapper who had built a cabin at the head of Naknek Lake. Documents indicate that Featherstone decorated the walls of his cabin with 35 masks that he had removed from an overhang near Old Savonoski (*Clemens and Norris 1999*). Fortunately, he gave seven of the masks to a Naknek schoolteacher, who in turn placed them in the Alaska Territorial Museum, now the Alaska State Museum in Juneau. The whereabouts of the others is unknown and remains one of the deepest concerns of the Katmai descendants.

Today Brooks River is the heart of a nationally significant cultural area designated a National Historic Landmark Archaeological District in 1993 (*McClenahan 1989*). Clustered on former river and lake terraces are dimples in the surface representing over 800 prehistoric house depressions, infilled by post-habitation ash fall and sedimentation. These villages and camps are as old as 4,500 years and as recent as 300 years old; some settlements were as large as Katmai village, Kaguyak and the Savonoski villages in their prime. Archaeological investigations began along Brooks River in 1952 and continue today, with NPS excavations at the "Cut Bank Site", a 500-year-old village rapidly eroding along the bank of the river below the popular bear-viewing falls. While the unique and fascinating culture history is well-known among archaeologists, few visitors to Brooks Camp are aware of it.

The great eruption of 1912 deposited over 600 feet of ash in a once verdant, resource-rich valley, effectively sealing its prehistoric record for as many more lifetimes as those already spent there. We know from coastal sites and those scattered throughout the park that this valley had been home to people as early as 8,000 years ago. On a windswept ridge near the outer edge of the Valley of 10,000 Smokes, the tiny, sharp stone blades, called microblades, remaining from a small hunting camp occupied millennia ago, attest to the story buried beneath the ash in the valley.

The flu epidemic of 1918 took a heavy toll among the Katmai people, prompting one historian to predict that "if present population trends continue, the name Savonoski may be kept alive in the future only in literature and as a historic site in Katmai National Monument" (*Hussey 1971*). To make sure that never happens, The Council of Katmai Descendants formed as a group in 1994, dedicated to the purpose of preserving their members' cultural heritage primarily through youth education. The group represents the descendants of the Katmai people scattered by the 1912 eruption and who today are represented by over 30 separate geographically-based native organizations.

NPS photograph

Figure 10. A South Naknek man holding his atlatl (throwing stick) and harpoon, circa 1915.

NPS photograph

Figure 11. Microblades, microblade cores and other tools from the Alagnak River drainage, dating from 5,000 to 9,000 years ago.

NPS photograph KATM 03:3:12:24

Figure 12. The thick layer of white ash from the 1912 eruption caps the sediments above a 500 year old house excavated by archeologists at Brooks River, Katmai National Park and Preserve, summer 2003.

REFERENCES

Arndt, K. 2000.
Letter to Jeanne Schaaf dated October 17, 2000. Katmai archives in the Alaska Regional Curatorial Center, Anchorage, Alaska.

Black, Lydia T. 1984.
Letter Report to J.W. Tanner, Alaska Regional Office, National Park Service. Review of records of the Alaska Russian Church Collection, dated July 31. Katmai archives in the Alaska Regional Curatorial Center, Anchorage, Alaska.

Clemens, J., and F. Norris. 1999.
Building in an Ashen Land: Historic Resource Study of Katmai National Park and Preserve. National Park Service, Alaska Support Office. Anchorage, Alaska.

Davis, W.S. 1954.
Archaeological Investigations of Inland and Coastal Sites of the Katmai National Monument, Alaska. Report to the National Park Service. Department of Anthropology, University of Oregon, Eugene.

Davis, W.L. 1961.
Mount Katmai, Alaska Eruption. Transcript of audio recording of interviews with Novarupta eruption survivors, including Pelegia Melgenak. Katmai archives in the Alaska Regional Curatorial Center, Anchorage, Alaska.

Dumond, D.E. 1979.
People and Pumice on the Alaska Peninsula. In Volcanic Activity and Human Ecology, edited by P.D. Sheets and D.K. Grayson, pp. 373-392. Academic Press. New York.

Dumond, D.E. 1988.
Final Report to NPS on Field and Library Work Conducted in or related to Katmai National Park and Preserve. Katmai archives in the Alaska Regional Curatorial Center, Anchorage, Alaska.

Dumond, D.E. 2010.
Alaska Peninsula Communities Displaced by Volcanism in 1912. Alaska Journal of Anthropology 8(2): 7-16.

Fierstein, J., and W. Hildreth. 2001.
Preliminary Volcano-Hazard Assessment for the Katmai Volcanic Cluster, Alaska. U.S. Geological Survey Open-File Report 00-489.

Griggs, R.F. 1922.
The Valley of Ten Thousand Smokes. National Geographic Society. Washington, D.C.

Hilton, M.R. 2002.
Results of the 2001 Interior Rivers Survey: Reconnaissance-Level Pedestrian Survey of Alagnak and Savonoski River Corridors, Katmai National Park and Preserve, Alaska. Katmai archives in the Alaska Regional Curatorial Center, Anchorage, Alaska.

Hussey, J.A. 1971.
Embattled Katmai; Katmai National Monument Historic Resource Study. National Park Service, San Francisco.

Jessee, T. 1961.
Letter from Tom Jessee to Dr. Luther Cressman, June 12, 1961. Katmai archives in the Alaska Regional Curatorial Center, Anchorage, Alaska.

Kaiakhvagnak, Khariton [Hariton] (Harry Kaiakokonok). 1975.
Interview with Michael Tollefson, April 29, 1975. Katmai archives in the Alaska Regional Curatorial Center, Anchorage, Alaska.

Kaiakhvagnak, K., and G. Kosbruk. 1975.
Interview with Michael Tollefson and Harvey Shields, October 22, 1975. Katmai archives in the Alaska Regional Curatorial Center, Anchorage, Alaska.

Kosbruk, G., and F. Shangin. 1975.
Interview with Michael Tollefson and Harvey Shields, October 21, 1975. Katmai archives in the Alaska Regional Curatorial Center, Anchorage, Alaska.

McClenahan, P. 1989.
Brooks River Archeological District National Historic Landmark Nomination. Katmai archives in the Alaska Regional Curatorial Center, Anchorage, Alaska.

Morseth, M. 2004.
Puyulek Pu'irtuq! The People of the Volcanoes: Aniakchak National Monument and Preserve Ethnographic Overview and Assessment. National Park Service, Anchorage, Alaska.

Nielsen, M.J. 2001.
The Missing Masks of Savonoski, Katmai Country, May 11, 2001. Katmai archives in the Alaska Regional Curatorial Center, Anchorage, Alaska.

USRCS (United States Revenue Cutter Service). 1912.
Annual Report of the United States Revenue Cutter Service for the Fiscal Year ending June 30, 1912. Washington Government Printing Office.

USRCS (United States Revenue Cutter Service). 1913.
Annual Report of the United States Revenue Cutter Service for the Fiscal Year ending June 30, 1913. Washington Government Printing Office.

Out of the Ashes: The Katmai Disaster

By Patricia H. Partnow

The eruption of Novarupta Volcano near Katmai on June 6, 1912 was a well-documented disaster that destroyed the villages of Katmai (*Figure 1*), Douglas, and Savonoski, as well as a number of fish camps on the Alaska Peninsula and a commercial salmon saltery at Kaflia Bay. To the inhabitants, the eruption marked an abrupt end to the old way of life. To anthropologists, actions taken in response to the eruption exposed and tested the resilience of the local culture and society.

This article discusses the explosion and its aftermath in the context of the anthropological theory of disaster. According to this theory, geological *events* happen to the earth, *disasters* to its inhabitants. The former is a natural occurrence while the latter entails destruction of human life and belongings, disruption of the social fabric, and interruption of customary commerce and government. Anthropologists Oliver-Smith and Hoffman explain:

The conjunction of a human population and a potentially destructive agent does not inevitably produce a disaster. A disaster becomes unavoidable in the context of a historically produced pattern of "vulnerability," evidenced in the location, infrastructure, sociopolitical organization, production and distribution systems, and ideology of a society (*Oliver-Smith and Hoffman 2002*).

Figure 1. Volcanic ash drifts around houses at Katmai after the eruption of Novarupta. Church in the distant background. August 13, 1912.

USGS http://libraryphoto.cr.usgs.gov/htmlorg/lpb085/land/mgc00747.jpg

The authors explain what can be gained by examining disasters:

Disaster exposes the way in which people construct or 'frame' their peril (including the denial of it), the way they perceive their environment and their subsistence, and the ways they invent explanation, constitute their morality, and project their continuity and promise into the future (*Oliver-Smith and Hoffman 2002*).

Disaster studies were first undertaken in the 1950s, then reframed in the 1990s as social scientists moved beyond descriptions of static cultures to considerations of the dynamics of culture change. The result was the theory of social vulnerability. Briefly stated, a community's vulnerability is its capacity to anticipate, cope with, resist, and recover from the impact of a cataclysmic event (*Blaikie et al. 1994*). The vulnerability profile of a community can be understood as a set of pre-adaptations, or practices and understandings that prepare people to deal with environmental disruptions.

Another outcome of disaster research has been a description of a range of predictable responses. These begin with an examination of the belief system, resulting in either a reaffirmation, with modifications to accommodate the new reality, or a recanting and replacement of the old system. Disasters unmask existing ties and cleavages in social alliances, and can instigate new ones. In complex societies, disasters are often occasions for readjusting the relationship between local people and the structures of the larger society. Finally, survivors assign meaning to disasters. A common response is to ascribe a cause related to human action or supernatural design, such as divine retribution for sins committed, or as a warning to people who have disregarded Nature's power. Another response is to consider disasters beyond understanding, acts of nature that are random, outside the realm of justice, and devoid of meaning.

This article will explore the responses of the Katmai Sugpiat as a contribution to an understanding of both this particular disaster and disaster theory in general.

Historical Context

Throughout history, the Sugpiat of the Alaska Peninsula had been a mobile people, recognizing a network of kinship with people up and down both coasts of the peninsula and Kodiak Island. Communities were formed, abandoned, and reinhabited over and over again (*Partnow 2001*). People moved about because of availability of resources, opportunities for cash income, and family dynamics such as marriage and feuds. They knew the resources of the land and sea.

The villages of Katmai and Douglas had been established as trading posts by the Russian-American Company during the nineteenth century. About ten years before Novarupta exploded, the two trading posts had closed, leaving the villages as backwaters rather than economic centers. Only a year before, the entire sea otter hunt had been halted under the International Fur Seal Treaty. The economy that had sustained the people for more than a century had suddenly collapsed. Meanwhile, salmon canneries in Chignik and Bristol Bay had drawn most of the peninsula's population south and west.
The 1910 US Census lists the following populations for

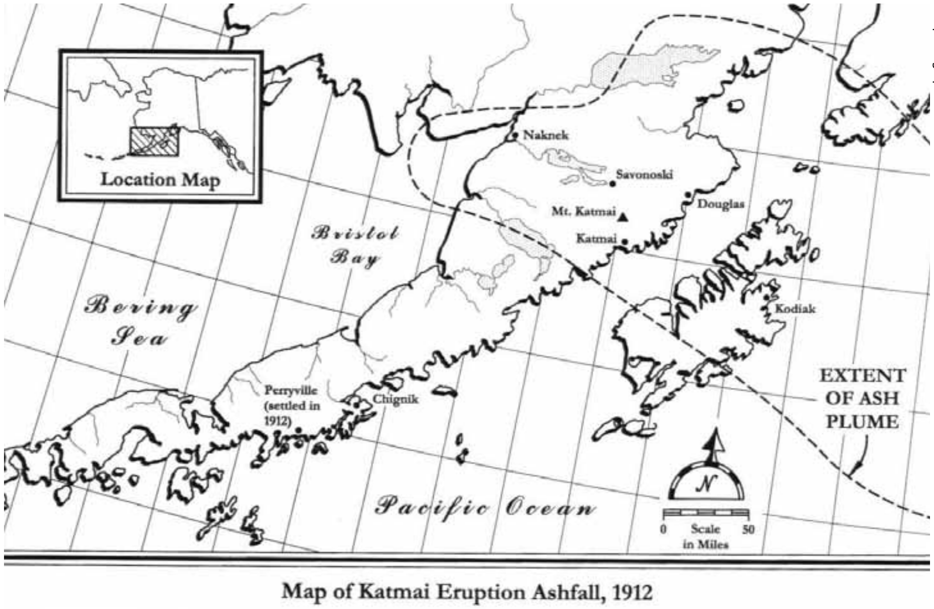


Figure 2. Map of the Alaska Peninsula with the effects of the 1912 eruption.

Alaska State Library, Flamen Ball Collection PCA 24-103

Figure 3. Two women and two children of Chignik, 1909.

Kodiak Historical Society

Figure 4. Katmai people with Reverend Alexander Petelin (with beard, center of photo on the right), 1912.

settlements on the Alaska Peninsula, a clear indication of the new importance of Chignik as a population center: Douglas - 45, Katmai - 62, Cold (Puale) Bay - 11, Kanatak - 23, Chignik - 565, Mitrofania - 27, Savonoski - 32. Much of this population growth consisted not of Sugpiat, but newly arrived Scandinavians and seasonally imported Asian workers. Alaska Native workers accounted for only a tiny proportion of the workforce, since the large canneries refused to employ Alaska Natives as late as 1910 (*cf. Porter 1893, Davis 1986*) (*Figure 3*).

The residents of Katmai and Douglas had fallen back on subsistence practices, but they were still able to find work with a commercial fishing saltery at Kaflia Bay. People had come to consider this a regular part of their seasonal round, as evidenced by the sod houses, locally called "barabaras," that they built near the saltery.

Like the economy, the social system that had held sway in Katmai and Douglas was in flux in 1912. For 100 years, these villages had been presided over by fur trading company managers who, with the cooperation of Russian Orthodox priests, had designated Sugpiaq men as village chiefs (*AOM 1902*). The system had ceased by 1902, leaving village affairs in the hands of the indigenous village leaders. By 1912 local support was an essential factor in the choice of chief (*Partnow 2001*).

Christianity had been a strong force in the two communities since the smallpox epidemic of 1838 (*cf. Partnow 2001, ARCA 1898, AOM 1898*). Everyone attended church and took part in seasonal Christian celebrations and ceremonies. Literacy was relatively high, even though neither village had a school. In Douglas, 20 years earlier, the trader had reported that someone in every household was literate (*Stafeev 1892*). The Bible and its teachings were well known and incorporated into local culture.

The Katmai Story

The story itself has been discussed in detail elsewhere (*Partnow 1995*). It is a story of rebirth and regeneration, reminiscent of both Genesis and Christ's resurrection. The story begins with Katmai as a bountiful Eden that was completely destroyed by the volcano. People were buried alive in their sod houses for three days before they could dig out and send the three most able men paddling into Shelikof Strait for help. The story casts the disaster in the role of a corrective event that forced its victims to reconstitute their communities. As often happens in cases of such disasters, the event became both a culprit and creator (*Hoffman 2002*). Eventually the group chose to resettle far down the coast in a village they named Perryville, after the captain of the ship that transported them there (*Figure 4*).

As it is told today, the saga is imbedded in two periods: the world of 1912 and the world a generation later when the story was first recorded and transmitted to the outside world. In August 1912, the Revenue Cutter Service captains who had rescued and helped relocate the people issued reports describing their pivotal role in the rescue (*USRCS 1912*). Other first-hand recollections were recorded by Afognak residents who sheltered the refugees (*Harvey 1991*). The story from the point of view of the Katmai and Douglas participants was first published in 1956, when Harry Kaiakokonok, who had been 5 years old in 1912, wrote and distributed his recollections (*Kaiakokonok 1956*). Fifteen years later, he and an older neighbor, George Kosbruk, recorded an interview with NPS rangers (*Davis 1961*). The story people tell nowadays is based on the testimony of these two men.

The story differs according to the teller's perspective. Aside from slight differences in detail, the primary contested area lies in the nexus of power. Revenue Cutter personnel believed that theirs was the central role, and that, for instance, the Sugpiat would not even have put up fish for the winter if they had not been told to do so (*USRCS 1912*). Afognak hosts saw their cousins as quaintly backward and needy. In contrast to both views, the Katmai people cited strong continuous leadership who decided where to settle, how to organize the people in the new village, and how to distribute the building materials and food provided by the government (*Kosbruk 1992*).

Magnitude of Disruptions

To what extent were the people of Katmai pre-adapted to the disaster they survived? The answer requires a consideration of the magnitude of disruptions of place, time, and people.

Place

This is an example of complete spatial disruption. The people had to abandon their homes, leave most of their belongings, and move away from the territory they had known for uncounted generations. Yet there were mitigating circumstances. The terrain, fish and game, and natural resources in the new village site were similar. The new site offered opportunities for cash income, since the commercial fishing industry had just opened up to Alaska Native workers. Perryville was both close to the fishing center of Chignik and far enough away to avoid disruptions brought by foreign workers.

The area had previously boasted a small community at Mitrofania, founded some 30 years before the settlement of Perryville. These locals helped orient the Katmai refugees to their new home and most married into the community. The fact that the refugees had been a highly mobile group, used to traveling and relocating, and familiar with a wide swath of territory long before the eruption, placed the move in the context of customary experience. The disruption was complete but not catastrophic.

Time

The ordeal itself lasted several days: three days of darkness, with thunderous noises and a deluge of ash, and several more days awaiting deliverance. Then for a month, the survivors waited in Afognak before moving to the new village site. Luckily, resettlement occurred in time for

Photograph courtesy of Patricia H. Partnow

Figure 5. Valley of Ten Thousand Smokes.

Alaska State Library PCA 222-370, Leslie Melvin Collection

Figure 6. School children at Perryville, 1939-41.

Alaska State Library, Leslie Melvin Collection

Figure 7. Perryville Bears baseball team, 1920. The Bears regularly played the Coast Guard team whenever it moored at Perryville.

Photograph courtesy of Patricia H. Partnow

Figure 8. Perryville's Russian Orthodox Church, 1990.

people to catch late runs of salmon and put up food for the winter. They were able to build houses before winter struck. They explored the terrain and learned where game could be found. And finally, the eruption occurred in a transitional period when the people were already being forced to abandon one way of life and seek another.

People

No lives were lost among the Alaska Peninsula Sugpiat. To be sure, the community was fractured, because not everyone chose to move to Perryville. However, no children were orphaned, no hunters lost. Most importantly, the community's power and social structures remained intact. The last leader of Katmai became the first leader of Perryville. In fact, during its early days, the community enjoyed a greater degree of autonomy in Perryville than it had in Katmai.

The Vulnerability Profile of the Katmai/Douglas Region

These factors add up to a series of positive pre-adaptations and a fairly low vulnerability profile that included the following:

- A local power structure, which was carried over intact to the new settlement and played a critical role in the relocation;
- A history of mobility, which meant people were knowledgeable and comfortable in a wide range of locales;
- A religion that comfortably embraced the event in its existing narrative and value system;
- The recent breakdown of an economic system, so what might have been sudden and new was actually part of a change to which people were already adjusting;
- An insularity from neighbors, which lent itself to a definition of the people of Perryville as a "chosen people" who were destined for change;
- A technologically simple infrastructure that was easily rebuilt;
- A pre-existing relationship with the federal government, which sped up assistance both in the rescue from the coast and the transportation to Perryville.

In summary, Katmai was far less vulnerable to social disruptions than might be assumed, in that its social structure persisted throughout all stages of the disaster and the people saw themselves as responsible for decisions about their future. The community was put in a dependent position only temporarily while at Afognak. Their experiences there, which were characterized by a separation due to social and cultural differences with the hosts, served to solidify the distinct identity of the Katmai and Douglas people and propelled them to seek another place to live.

Even with these mitigating factors, the huge social upheaval caused by the eruption should not be underplayed. The event brought about cataclysmic cultural change. Whereas Katmai was a village rooted in the past, Perryville was conceived from the beginning as a modern, forward-looking town. The leadership engineered and incorporated a number of changes. Within ten years, the federal government opened a school, with the result that English became the dominant European language, supplanting Russian. Since everything had been lost in the eruption, including clothing and belongings, the material culture in Perryville was strikingly different from Katmai. Most people built their new houses of wood rather than sod. People bought clothes, toys, and household goods from catalogues. The village planted foxes on a nearby island to provide regular cash flow. A baseball team, the Perryville Bears, was formed to play Revenue Cutter Service and neighboring teams (*Figure 7*).

And just before the move, cannery policies changed, allowing Native people to work there, thus solidifying involvement in the cash economy and participation in the modern era.

Katmai lives on, but primarily as a story of a distant, perfect, forever lost garden.

REFERENCES

Alaska Orthodox Messenger (AOM) (Pravoslavnyi Amerikanskii Vestnik). 1898.
Short Church Historical Description of the Kodiak Parish. Draft translation by P.H. Partnow. Vol. 2: 265-6, 508-510.

Alaska Orthodox Messenger (AOM) (Pravoslavnyi Amerikanskii Vestnik). 1902.
Report of the Voyage of Vasilii Martysh, taken in 1901. Draft translation by P. H. Partnow. Vol. 6: 431-3.

Alaskan Russian Church Archives (ARCA). 1898.
Microfilm, Reel 175. University of Alaska Anchorage Archives (originals in Library of Congress, Manuscript Division).

Blaikie, Piers, Terry Cannon, Ian Davis, and Ben Wisner. 1994.
At risk: natural hazards, people's vulnerability, and disasters. Routledge. London.

Davis, Nancy Yaw. 1986.
A Sociocultural Description of Small Communities in the Kodiak-Shumagin Region. Minerals Management Service Technical Report No. 121. US Department of the Interior, Minerals Management Service, Alaska Outer Continental Shelf Region. Anchorage.

Davis, Wilbur. 1961.
Mount Katmai, Alaska Eruption. Audio recording and transcript at the University of Oregon Archives.

Harvey, Lola. 1991.
Derevnia's Daughters: Saga of an Alaskan Village. Sunflower University Press. New York.

Hoffman, Susanna M. 2002.
The Monster and the Mother: The Symbolism of Disaster. In Catastrophe and Culture: The Anthropology of Disaster, edited by Susanna M. Hoffman and A. Oliver-Smith, pp. 113-142. School of American Research Press. Santa Fe, NM.

Kaiakokonok, Harry O. 1956.
Story. Photocopy of manuscript originally published in Island Breezes. Public Health Service. Sitka, AK.

Kosbruk, Ignatius. 1992.
Interview conducted, recorded and transcribed by Patricia Partnow. Perryville, Alaska, March 24.

Oliver-Smith, A., and S. M. Hoffman. 2002.
Introduction: Why Anthropologists Should Study Disasters. In Catastrophe and Culture: The Anthropology of Disaster, edited by Susanna M. Hoffman and A. Oliver-Smith, pp. 3-22. School of American Research Press. Santa Fe, NM.

Partnow, Patricia. 1995.
Days of Yore: Alutiiq Mythical Time. In When Our Words Return: Writing, Healing, and Remembering Oral Traditions of Alaska and the Yukon, edited by Phyllis Morrow and William Schneider, pp. 139-184. Utah State University Press. Logan, UT.

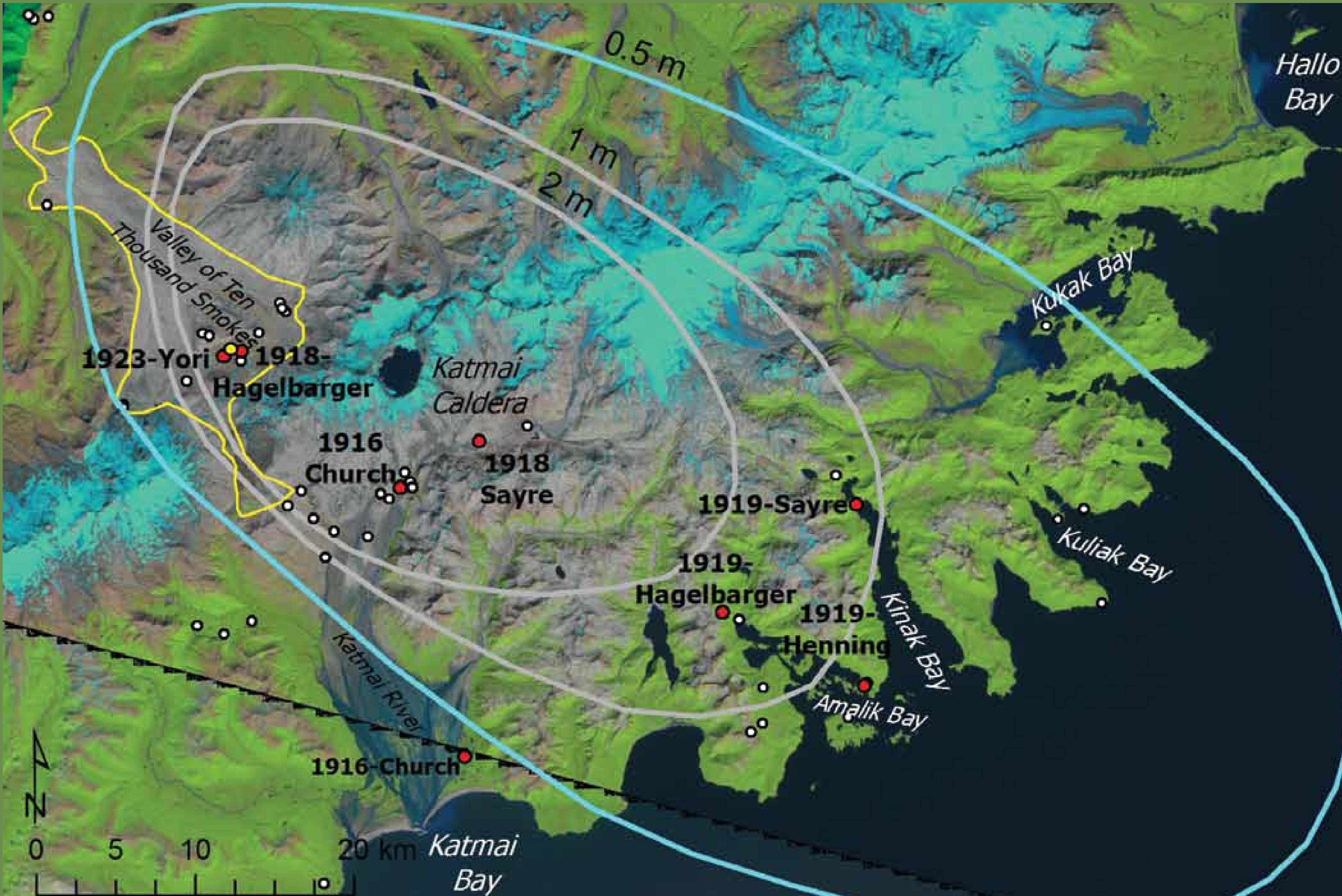
Partnow, Patricia. 2001.
Making History: Alutiiq/Sugpiaq Life on the Alaska Peninsula. University of Alaska Press. Fairbanks, AK.

Porter, Robert Percival. 1893.
Report on population and Resources of Alaska at the Eleventh Census. US Government Printing Office. Washington, D.C.

Stafeev, Vladimir. 1892.
Unpublished diary translated by Marina Ramsay, edited by Richard A. Pierce.

United States. 1910.
Census of Alaska.

United States Revenue Cutter Service (USRCS). 1912.
Annual Report. Archives 671, Roll 16. Records and Communications. US Government Printing Office. Washington, D.C.



0.5 m
1 m
2 m
Hallo Bay
Kukak Bay
Kuliak Bay
Kinak Bay
Amalik Bay
Valley of Ten Thousand Smokes
1923-Yori
1918-Hagelbarger
Katmai Caldera
1916 Church
1918 Sayre
1919-Sayre
1919-Hagelbarger
1919-Henning
Katmai River
1916-Church
N
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Katmai Bay

Ecological Recovery After the 1912 Katmai Eruption as Documented Through Repeat Photography

By M. Torre Jorgenson, Gerald V. Frost, Alan J. Bennett, Amy E. Miller

Introduction

The eruption of Novarupta in 1912 in Katmai National Park and Preserve was the largest in recent history and devastated a large mountainous and coastal region. Although scientific inquiries along the coast began almost immediately after the eruption, the sensational discovery of the center of the eruption in the Valley of 10,000 Smokes by Robert F. Griggs in 1915 catalyzed a decade of scientific expeditions in the region. The expeditions left a rich legacy of historical photographs that documented the barren landscape. The National Geographic Society (NGS) supported multiple expeditions between 1915 and 1919 to map and investigate the affected volcanic terrain (*Clemens and Norris 1999*). In 1916, Griggs led an expedition of four men, including photographer D.B. Church, that made it into the Valley of 10,000 Smokes. Subsequent NGS expeditions between 1917 and 1919 produced photographs by Church, Griggs, Paul Hagelbarger, Paul Henning, Emery Kolb, and Jasper Sayre. Additional photos were taken by Walter Smith during U.S. Geological Survey (USGS) expeditions in the early 1920s (*Smith 1925*). In 2004, the National Park Service initiated an effort to acquire, relocate, and rephotograph some of these scenes as part of a larger effort to document changes in the landscape throughout the park lands of southwestern Alaska (*Jorgenson et al. 2006*).

Figure 1. Location of all repeat photos (white dots) and a subset of repeat photos presented here (red dots) in the areas affected by the ash flow in the Valley of 10,000 Smokes (yellow line) and by the ash fall (gray isopachs show ash depth) from the eruption of Novarupta (yellow dot) in 1912.

The eruption of the Novarupta volcano took place over a 60-hour period during June 6-8, 1912 (*Martin 1913, Hildreth and Fierstein 2003*). At least 4.1 cubic miles (17 km^3) of fall deposits and 2.6 mi^3 (11 km^3) of ash-flow tuff (ignimbrite) were produced, a volume larger than that erupted by Krakatau (Indonesia) in 1883. Novarupta is known to have been exceeded by only four eruptions in the last 1,000 years: Tambora (Indonesia) in 1815, Laki (Iceland) in 1783-84, Kuwae (Vanuatu) in 1452, and Baitoushan (Korea-China) in 1050 (*Hildreth and Fierstein 2003*). The eruption caused 810 square miles (2,100 km^2) of mountainous terrain around the volcano to be covered as deep as 300 ft (91 m) in ash and pumice and created thousands of high-temperature fumaroles in the Valley of 10,000 Smokes, many of which lasted for more than 20 years.

Methods

Historical photographs were obtained from archives at the NGS, USGS Photographic Library, the Lake Clark-Katmai Studies Center of NPS, the University of Alaska Anchorage, and the University of Alaska Fairbanks. Approximately 4,800 Griggs expedition photographs were reviewed at the NGS archives, of which 344 were acquired. Additional photographs were acquired from archives at the NPS Alaska Regional Office and online sources at USGS and the Alaska Volcano Observatory.

A subset of the photographs were retaken using methods described by Hall (*2002*). In cases where the original vantage point could not be precisely triangulated, no longer existed (e.g., a river cutbank), or was obscured by vegetation, a nearby location was used. GPS coordinates, camera height, and azimuth were recorded at each site to facilitate future monitoring. Dominant plant species and estimated cover were recorded, where possible. In 2004, Gerald Frost (ABR) and Tahzay Jones (NPS) hiked to access photo points in the Valley of 10,000 Smokes, upper Knife Creek, Mageik Creek, and the middle Katmai River. In 2005, Torre Jorgenson and Alan Bennett used a helicopter to access additional photo points distributed throughout Katmai.

Results and Discussion

Recovery by Impact Zone

Repeat photographs of the Katmai landscape devastated by volcanism reveal a range of geomorphic and ecological processes affecting the recovery of the region. Photographs were sorted according to four zones of disturbance-intensity, radiating from the 1912 Novarupta eruption site (*Figure 1*).

Landsat satellite images from 2000 and 2002 (*Figure 1*) show that revegetation of the ash flow in the valley has been negligible, and in adjacent areas with heavy ash fall (>6.6 ft/2 m) only ~5% of the area has revegetated. As ash depths decrease at greater distances from the eruption site, vegetation cover increases, such that in the areas of lowest ash fall about 70% of the area shows strong vegetation recovery. Impacts from the eruption extended as far as Hallo Bay (*Jorgenson et al. 2006*) and Kodiak Island (*Griggs 1918*), and these areas have a nearly complete cover of vegetation today.

Repeat photographs taken in 2004 and 2005 provide more detailed views of vegetation recovery and are generally consistent with the Landsat imagery (*Figures 2-9*). Photos from the ash flow in the valley show very little recovery nearly 100 years after the eruption (*Figures 2-3*). In most of the area, vegetation cover, primarily willows, remained at <1% (visually estimated from photographs). In the >6.6 ft (2 m) ash fall zone, vegetation in 2004 covered 10-30% of the landscape (*Figures 4-5*). Alder has recovered in isolated patches on the valley slopes, primarily in areas where the ash had been eroded from the hillside by landslides and fluvial processes. Floodplains, however, had <1% cover in 2004 due to active channel migration and scouring (*Figure 5*). Willows were more abundant in protected drainages, but growth on thicker ash fall deposits remained negligible. In the 3.3-6.6 ft (1-2 m) zone, vegetation that survived the moderate impact covered 10-40% of the landscape soon after the eruption and then increased to cover 70-90% of the landscape by 2005 (*Figures 6-7*). In the 1.6-3.3 ft (0.5-1 m) zone along the coast, vegetation in 1919 covered 10-40% of the landscape and increased to 90-100% of the landscape by 2005 (*Figures 8-9*). In the latter two zones, present-day vegetation is dominated by alder scrub and bluejoint-herb meadows. Substantial ecological impacts also occurred beyond the 1.6 ft (0.5 m) isopach; vegetation in 1919 covered only 10-40% of the landscape and increased to nearly 100% of the landscape by 2005, with the exception of active floodplains (*Figure 9*). While meadows and shrublands have recovered in areas of moderate and low impact, trees that were once common at lower elevations, particularly cottonwood on river floodplains, have shown little recovery.

Recovery of Main Vegetation Types

Vegetation recovery was dominated mainly by four vegetation types: partially vegetated barrens, bluejoint-herb meadows, willow scrub, and alder scrub. Other uncommon vegetation types that recovered well after the eruption included Sitka spruce forests that expanded into areas disturbed by the ash fall, dwarf ericaceous scrub at higher elevations, and halophytic wet meadows on tidal flats.

Partially vegetated and barren areas (<30% vegetation cover) remained widespread in areas of ash flow and heavy ash fall. In the Valley of 10,000 Smokes, common colonizing plants included scattered willows (*Salix barclayi and S. alaxensis*), rushes (*Luzula spp*), and bluejoint grass (*Calamagrostis canadensis*). A few mosses and liverworts were found colonizing the bare soil shortly after the eruption (*Griggs 1933*) and are still present today. Sitka alder (*Alnus viridis ssp. sinuata*), however, was virtually absent from the ash flow. Near the coast, common colonizers included grasses (*Deschampsia caespitosa, Leymus mollis*) and forbs (*Chamerion angustifolium, Lupinus nootkatensis, Artemisia tilesii*).

Bluejoint-herb meadows were common on slopes interspersed with the alder thickets along the

Photograph courtesy of P. Hagelbarger, copyright NGS

Photograph courtesy of G. Frost

Figure 2. Novarupta in the Valley of 10,000 Smokes in 1918 and 2004, with only scattered vegetation comprised of willows and wood-rushes. The surficial covering of fine ash evident in 1918 is gone by 2004 due to water and wind erosion

Photograph courtesy of C. Yori

Photograph courtesy of G. Frost

Figure 3. Falling Mountain (left), Mt. Cerberus (center), and the upper Valley of 10,000 Smokes in 1923 and 2004. The parallel depressions are probably concussion fissures that formed during the eruption, followed by moderate gully erosion of the surface (foreground) and sparse willow establishment .

Figure 4. The south wall of Katmai Canyon in 1916 and 2004 shows that most of the ash has been eroded from the steep slopes, while ash remains prevalent on the lower gentle terrain. Alder was nearly absent soon after the eruption but has recovered somewhat around the margins of the ash.

coastal mountains in zones with thinner ash fall. The vegetation was dominated by bluejoint grass, umbels (*Heracleum lanatum, Angelica genuflexa*), fireweed (*Chamerion angustifolium*), and other forbs (*Geranium erianthum, Achillea borealis, Sanguisorba canadensis*).

Tall and low willow scrub was common in drainages and in the mountains near the coast. Willows were predominantly *Salix barclayi*, but included *S. sitchensis, S. alaxensis* and *S. glauca*. Numerous dwarf shrubs (*Vaccinium vitis-idaea* and *Empetrum nigrum*), bluejoint grass, and forbs (*Chamerion angustifolium, Trientalis europaea, Sanguisorba stipulata, Lupinus nootkatensis*) were common.

Alder tall scrub was abundant in the coastal mountains affected by moderate to light ash fall. Early photographs showed scattered, live tall shrub thickets on many of the steeper mountain slopes where ash cover did not persist. By 2005, Sitka alder and various willows (*Salix barclayi, S. sitchensis,* and *S. alaxensis*) up to 15 ft (4.5 m) tall were co-dominant in the overstory. Scattered Sitka spruce (*Picea sitchensis*) and black cottonwood (*Populus balsamifera* ssp. *trichocarpa*) occasionally were present. The initial survival of scattered alder patches in the coastal mountains undoubtedly aided recovery through expansion of surviving shrubs and by providing a seed source for new recruitment. The understory of alder scrub has most of the plants found in bluejoint herb meadows.

Sitka spruce woodlands appear to have expanded into new habitats in a few locations. In 1919, Sitka spruce was observed on a peninsula in Kuliak Bay and a small islet at the mouth of Amalik Bay (*Griggs 1934*). By 2005, spruce forest had increased markedly in Kukak Bay where they were not previously evident (live or dead) in 1919 (*Jorgenson et al. 2006*). Sitka spruce has also spread quickly on Kodiak Island due to the early presence of trees that provided a seed source and the occurrence of a mineral seedbed following the eruption, where plant competition at the seedling stage was minimal (*Griggs 1918*, *Tae 1997*).

At Hallo Bay, salt marshes received 4-12 in (10-30 cm) of ash and subsequently were covered by silt from tidal flooding and eolian sand. Today the coastal landscapes now support productive salt marshes on narrow tidal flats and dunegrass meadows on beaches.

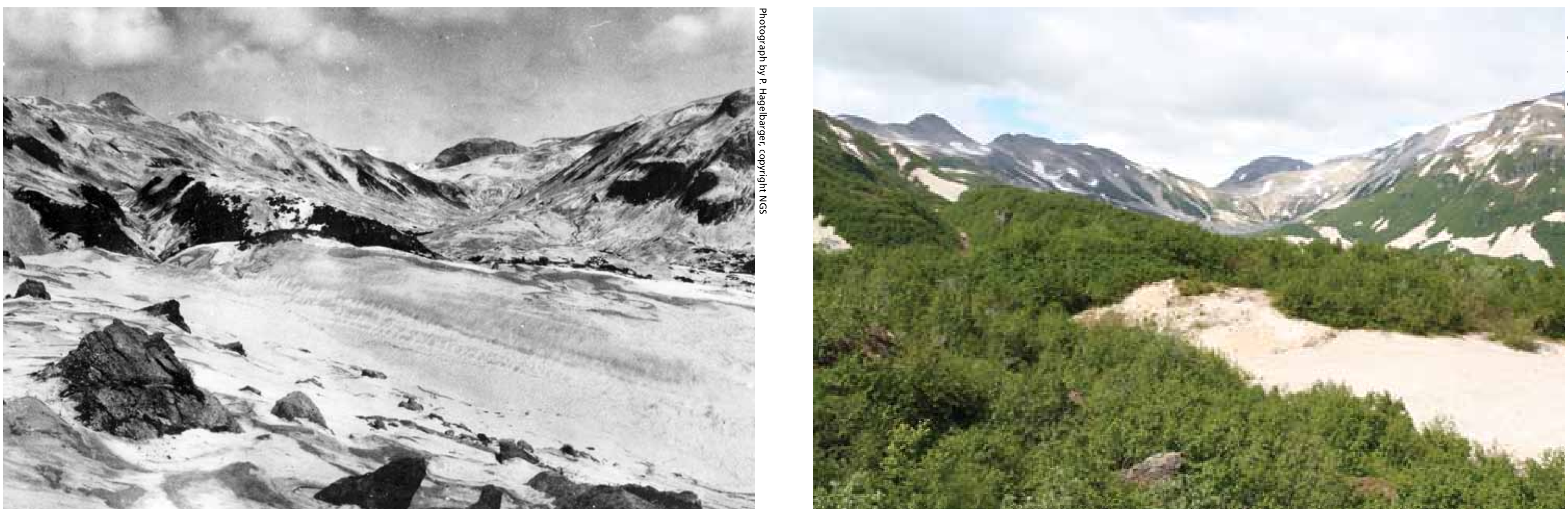
Factors Affecting Recovery

The ecological recovery of the areas disturbed by ash flow and fall has been greatly affected by geomorphic

Photograph courtesy of J. Sayre, copyright NGS

Photograph courtesy of G. Frost

Figure 5. Mt. Katmai seen from the Katmai River floodplain in 1918 and from a nearby vantage point in 2004. Channel migration has prevented vegetation from establishing on the floodplain, while vegetation has colonized the margins of the ash along the lower hillsides. Trees that were originally present remain absent across most of the landscape.



Photograph by P. Hagelbarger, copyright NGS

Photograph by T. Jorgenson

Figure 6. Mountains north of Geographic Harbor in 1919 and 2005 that received 3.3-6.6 ft (1-2 m) of ash fall. Some alders on steeper slopes survived the eruption and shrub cover later expanded across most of the area, although many thick ash deposits remain bare.

Photograph courtesy of J. Sayre, copyright NGS

Photograph courtesy of T. Jorgenson

Figure 7. Hidden Harbor, which had 3.3-6.6 ft (1-2 m) of ash fall, in 1919 and 2005. Alder and willow thickets partially survived as conspicuous as dark patches on the pale ash deposits and later recovered across most of the area.

Photograph courtesy of W. Henning, copyright NGS

Photograph courtesy of T. Jorgenson

Figure 8. Entrance of Amalik Bay in 1919 and 2005. Numerous alder patches survived the ash fall, and by 2005 alder scrub and bluejoint-herb meadows covered nearly the entire land surface.

Figure 9. Katmai village cemetery seen in 1916 and at a nearby location in 2005. Channel migration and extensive deposition of ash-rich alluvium by the braided Katmai River has left no trace of the cemetery and village. Recovery of tall alder scrub is evident on the slopes of Mt. Pedmar in the background.

processes and the chemical properties of the ash deposits (*Griggs 1919, 1922, 1933*). On slopes, much of the ash has been removed through landslides, slumping, fluvial erosion, and wind erosion (*Figure 4*). High winds that cause severe surface abrasion, particularly in the Valley of 10,000 Smokes, are common and undoubtedly retard plant establishment. Gully formation is prevalent in flat areas of the valley where the original drainage patterns were obliterated by the ash flow (*Figure 3*). Floodplain dynamics were greatly affected as heavy ash fall immediately increased suspended- and bed-loads within the channel, and heavy sediment input probably continued for many years after the eruption (*Griggs 1919*). Within a decade, the upper reaches of high-energy, braided floodplains had been mostly cleared of fine-grained cover deposits of ash (*Figure 5*), but lower reaches and deltas continue to have very active channel migration in the highly mobile sandy materials (*Figure 9*).

Soil chemistry and low nutrient-availability are major factors contributing to the slow recovery of vegetation on thick ash deposits. Katmai ash is mainly comprised of rhyolite and dacite, which are dominated by quartz and potassium- and sodium-rich feldspars (aluminum- and silica-rich). Griggs (*1933*) attributed the slow revegation to the very low nitrogen concentrations (<0.02% total nitrogen) in unmixed ash. These nutrient-limited ash deposits favor species with symbiotic nitrogen-fixing bacteria, such as alder and legumes. While alder has recovered well in areas with light to moderate ash deposits, alder has not shown much recovery on thick ash fall and especially on the ash flow in the Valley of 10,000 Smokes. Katmai ash also has very low phosphate concentrations (0.4% phosphoric acid), which also strongly limits plant growth. Finally, aluminum oxide concentrations are high (13.9% Al_2O_3) (*Griggs 1933*), which suggests high aluminum solubility, and consequent toxicity, may be a factor in acidic soils formed from rhyolite. Low soil moisture in coarse-grained pumice deposits may be a factor in limiting seedling establishment, but seedling establishment and recovery typically are rapid on other newly exposed gravelly substrates that are common in Katmai, such as landslides, glacial moraines, and riverbars. The astonishing lack of recovery of the ash deposits over much of the area after nearly 100 years warrants more detailed investigation.

Acid rain and highly corrosive sulfuric acid gasses likely affected vegetation even where ash fall was very light. Photographs of granitic outcrops west of the eruption along Lake Grosvenor in 1919 document white, barren bedrock outcrops, which have subsequently become nearly entirely covered by crustose and fruticose lichens (*Jorgenson et al. 2006*). Acid rain from the eruption was reportedly so strong that it caused clothing to disintegrate on clotheslines in Vancouver, Canada (*Geology Fieldnotes, http://www.nature.nps.gov/geology/parks/katm*). Recent investigations of widespread vegetation damage near Chiginagak Volcano on the Alaska Peninsula attributed the heavy mortality to a gaseous flow of sulfuric acid aerosols generated by catastrophic drainage of the crater lake (Schaefer et al. 2008).

In summary, the 1912 eruption at Katmai devastated a large area of southwestern Alaska through ash fall and pyroclastic flows, and its impacts extended globally. The spectacular effects of the Katmai eruption created a unique natural laboratory in which to study ecological recovery along a gradient of disturbance levels and ecosystem types, ranging from primary succession on the sterile soils of the Valley of 10,000 Smokes, to secondary succession after ash fall. Repeat photography offered an effective and highly engaging technique to monitor this recovery over a centennial time-scale. Ecological recovery occurred remarkably quickly in many areas, but the otherworldly landscape of the valley remains almost entirely barren a century after it was created. The amazing lack of revegetation in some areas that had thick pyroclastic flows and ash deposits warrants more research into what factors are limiting plant recovery.

Acknowledgements

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For additional images visit: http://science.nature.nps.gov/im/units/swan/index.cfm?theme=repeat_photos

REFERENCES

Clemens, J., and F. Norris. 1999.
Building in an ashen land: Historic Resource Study of Katmai National Park and Preserve. National Park Service. Anchorage, Alaska.

Griggs, R.F. 1918.
The recovery of vegetation at Kodiak. The Ohio Journal of Science 19: 1-57.

Griggs, R.F. 1919.
The beginnings of revegetation in Katmai Valley. The Ohio Journal of Science 19: 318-342.

Griggs, R.F. 1922.
The Valley of Ten Thousand Smokes. National Geographic Society. Washington, D.C.

Griggs, R.F. 1933.
The colonization of the Katmai ash, a new and inorganic "soil". American Journal of Botany 20: 92-113.

Griggs, R.F. 1934.
The edge of the forest in Alaska and the reasons for its position. Ecology 15(2): 80-95.

Hall, F.C. 2002.
Photo-point monitoring handbook. Pacific Northwest Research Station, U.S. Forest Service. Portland, OR. PNW-GTR-526.

Hildreth, W., and J. Fierstein. 2003.
Geologic Map of the Katmai Volcanic Cluster, Katmai National Park, Alaska. U.S. Geological Survey. Washington, D.C. Geologic Investigations Series I–2778.

Jorgenson, M.T., G.J. Frost, W. Lentz, and D. Mortenson. 2006.
Photographic monitoring of landscape change in the Southwest Alaska Network of National Parklands, 2004-2006. National Park Service. Anchorage, AK. NPS/SWAN/NRTR-2006/03.

Martin, G.C. 1913.
The recent eruption of Katmai volcano in Alaska. National Geographic Magazine 24: 131-181.

Schaefer, J.R., W.E. Scott, W.C. Evans, J. Jorgenson, R.G. McGimsey, and B. Wang. 2008.
The 2005 catastrophic acid crater lake drainage, lahar, and acidic aerosol formation at Mount Chiginagak volcano, Alaska, USA: Field observations and preliminary water and vegetation chemistry results. Geochemistry, Geophysics, Geosystems 9: Q07018.

Smith, W.R. 1925.
The Cold Bay-Katmai district, in Mineral Resources of Alaska - Report on Progress of Investigations in 1923. U.S. Geological Survey Bulletin 773: 183-207.

Tae, K.E. 1997.
Processes controlling the range expansion of Sitka Spruce on Kodiak Island, Alaska. M.S. Thesis. University of Alaska, Fairbanks.


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Effect of the Novarupta (1912) eruption on forests of southcentral Alaska: Clues from the tree ring record

By Amy E. Miller, Rosemary L. Sherriff, and Edward E. Berg

Trees represent one of the most important records of environmental change on Earth. Tree growth, as recorded in the width of annual rings, can be useful for identifying the local to global effects of volcanic eruptions, and for comparing these effects with historical records across large areas. Globally, a major eruption can lead to short-term changes in climate that can have measurable effects on tree growth. Volcanic dust and sulfur-based aerosols released into the stratosphere can absorb incoming solar radiation, resulting in cooler than average summer temperatures and warmer than average winters for one or more years following an eruption. Closer to the eruption site, strong winds, crown scorch, and heavy ash fall can cause physical injury to trees and inhibit photosynthesis for months.

When environmental conditions change abruptly, trees typically show either reduced growth ('growth suppression') or accelerated growth (a 'growth release') that is measured by changes in the width of annual rings. Tree growth rates generally decline with age, but a growth suppression is indicated by a rapid (e.g., 1-3 year) decrease in growth rate, generally in response to an unfavorable climate, or to a disturbance that temporarily inhibits growth but does not kill the tree. In contrast, growth releases can be detected in surviving trees when neighboring trees die and release the remaining trees from competition for light and nutrients. For example, a growth release could occur in understory trees if larger, over story trees were knocked down by wind or killed by insects or another type of disturbance. A growth release could also occur if conditions became more favorable for growth, e.g., due to an increase in growing-season temperature or nutrient availability.

The eruption of Novarupta on June 6-8, 1912, produced an estimated four cubic miles (17 km^3) of ash fallout (*Fierstein and Hildreth 1992*) and resulted in one of the most significant cooling events of the twentieth century (*Briffa et al. 1998*). Colder than average temperatures persisted for more than six months after the eruption (*Mass and Portman 1989*) and were reflected in reduced growth and/or frost damage ('frost rings') in tree-rings across the Northern Hemisphere (*Briffa et al. 1998, LaMarche and Hirschboeck 1984*).

Tree-ring data from white spruce (*Picea glauca*) stands in Katmai (*Figure 1*) indicate that the effects of the Novarupta eruption were two-fold. The data were collected by biologists from NPS, Humboldt State University, and the U.S. Fish and Wildlife Service as part of a larger study of forest disturbance (*Sherriff et al. 2011*). Immediately following the eruption, trees experienced an abrupt, short-term decrease in growth, consistent with records that suggest widespread cooling (*Briffa et al. 1998*). However, the growth suppression appeared only in the stands sampled in Katmai and not in other locations sampled (e.g., farther north on the Alaska Peninsula or east on the Kenai Peninsula). This suggests that localized effects, such as damage due to ash fall and/or continued seismic activity, played a greater role than climate in slowing tree growth.

A dramatic shift occurred after the Novarupta eruption, when a short-lived (less than 10 years) but significant period of rapid growth began (*Figure 2*) (*Eicher and Rounsefell 1957*). Between 20% and 80% of trees sampled in Katmai showed an increase in growth during this time, as did trees downwind from the eruption site, on Kodiak Island (*Kaiser and Kaiser-Bernhard 1987*). Similar growth releases have also been reported one to several years following the eruption of Volcán Llaima, Chile, in 1640 (*Pollman 2003*);Volcán de Fuego de Colima, Mexico, in 1913 (*Biondi et al. 2003*); and Mount St. Helens, Washington, in 1980 (*Yamaguchi and Lawrence 1993, Segura et al. 1995, Weber et al. 2006*). This 'rebound effect' indicated by an increase in growth is usually ascribed to low-level disturbance (e.g., tephra deposits or lahar flows) that opens the canopy.

The localized growth release that followed the 1912 eruption of Novarupta occurred shortly after the start of a regional-scale release that has been attributed to spruce beetle disturbance. The Katmai records, described above, were compiled by the NPS and cooperators as part of a larger, regional tree-ring dataset that spans a roughly 250-year period (*Sherriff et al. 2011*). Large-scale spruce beetle outbreaks were recorded in the 1810s, 1870s, and 1970s, as well as in the early 1900s, shortly before the 1912 eruption (*Figure 3*). The short-lived and highly synchronous growth release recorded in the Katmai tree cores after 1912 (*Figure 2*) was not observed at other sites in the study and was therefore excluded from the regional spruce beetle analysis. The short-lived suppression and subsequent growth release were, however, recorded in tree-ring records from Kodiak, compiled as part of a separate study (*Kaiser and Kaiser-Bernhard 1987*). Ash depths in Kodiak were as great as 12 inches (30 cm), whereas upwind, near

Figure 1. Ecologist Ed Berg, U.S. Fish & Wildlife Service, cores a white spruce in Katmai National Park and Preserve.
NPS photograph

Figure 2. (Map) Location of forest study sites in Katmai relative to ash fall from the 1912 eruption of Novarupta. Contours show ash depths in cm (adapted from *Williams and McBirney 1979*). (1) Valley of 10,000 Smokes Road; (2): Brooks; (3-4) Bay of Isles; (5) Coville.

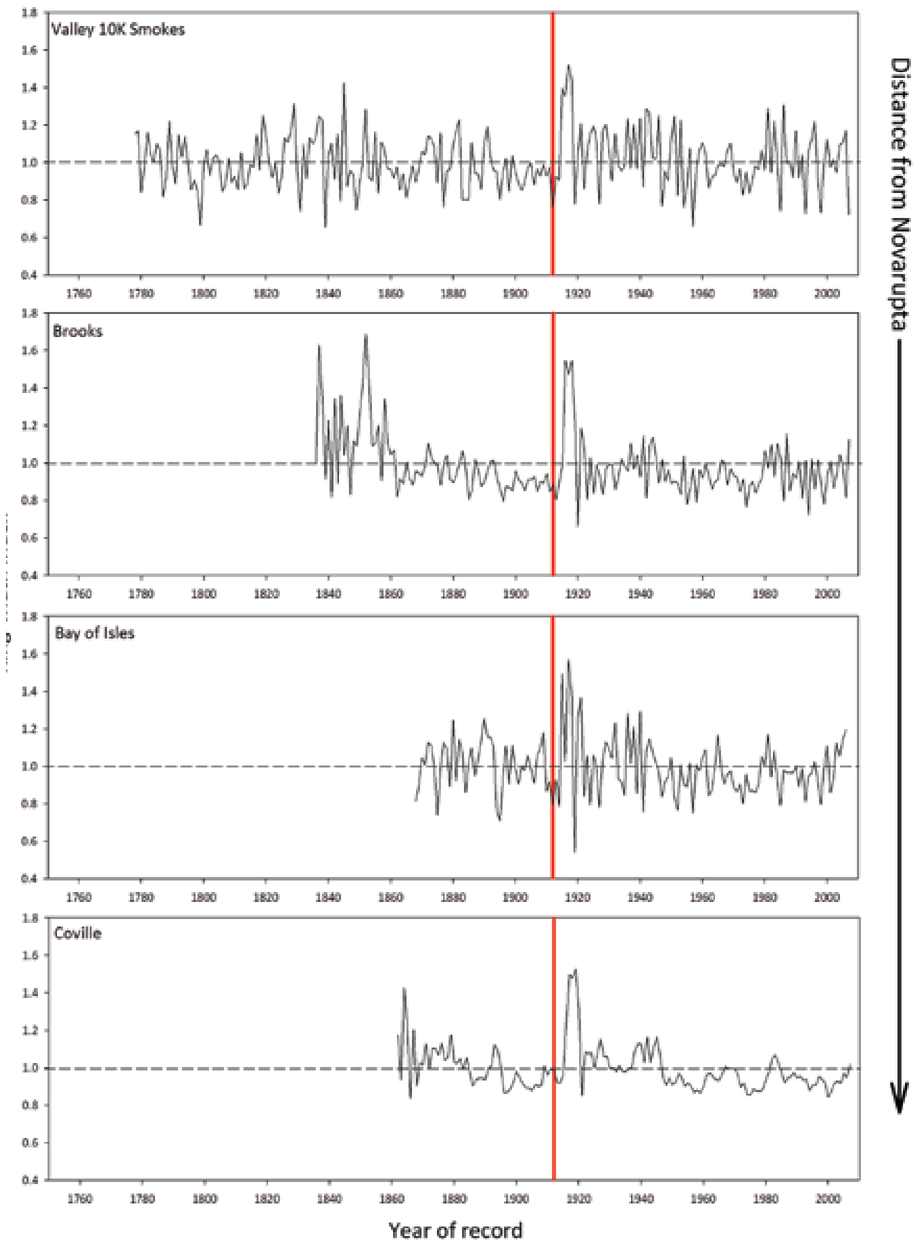


Figure 2. Tree-ring chronologies from forested sites in Katmai, sorted by increasing distance from the 1912 eruption site. Ring-width index shows growth trends averaged across all trees at a site, with values <1.0 indicating slower than average annual growth, and values >1.0 indicating greater than average growth. The 1912 eruption is indicated by the red line.

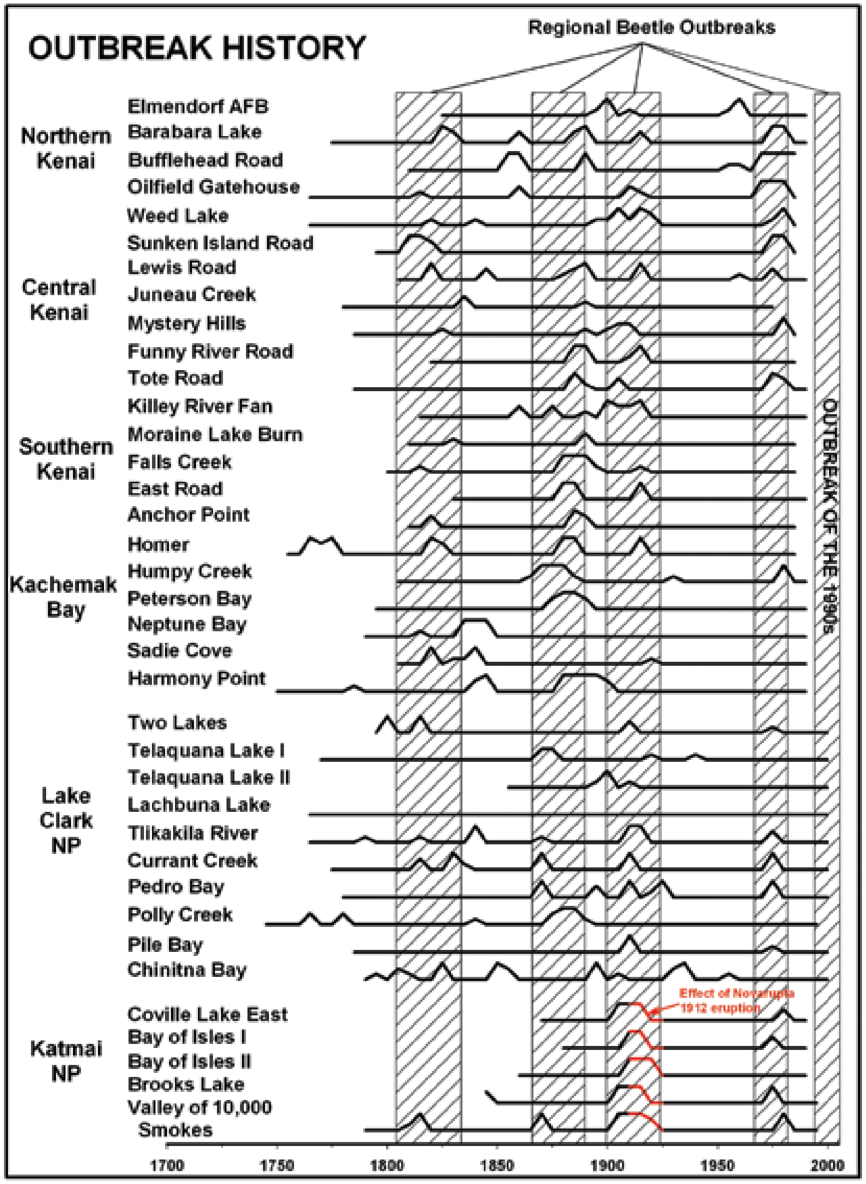


Figure 3. Regional spruce beetle outbreaks (hatched bands) recorded on the Kenai and Alaska Peninsulas. Katmai sites are shown at the bottom. Peaks in individual site chronologies (black) show significant growth releases attributed to spruce beetle disturbance. Growth releases attributed to the Novarupta eruption (red) are short-lived and highly synchronous, appearing in the Katmai chronologies between approximately 1913-1920.

Lake Brooks and several of our study sites, they ranged from 4-8 inches (10-20 cm) (*Fierstein and Hildreth 1992*).

The cause of the post-1912 release in Katmai and Kodiak is uncertain, but there are several possible explanations. Some authors have suggested that it could have resulted from a fertilization effect associated with ash fall (*Eicher and Rounsefell 1957*). This is unlikely a direct effect of ash deposition, as the silica-rich ash was extremely nutrient-poor (*Griggs 1920, Williams and McBirney 1979*), comparable in nutrient content to finely-ground glass. Instead, any increase in soil nutrient availability would have been due to soil disturbance that stimulated microbial activity, an increase in soil organic matter due to the decay of buried plants, and/or reduced competition for nutrients due to the decline and/or death of some trees.

Similarly, canopy gaps resulting from crown damage or wind throw could have increased light availability to understory and/or neighboring trees, releasing them from competition and enhancing their growth. It is also possible that moderate ash fall could provide a mulching effect (*cf. Segura et al. 1995*), enhancing soil moisture, similar to plastic sheeting on a garden. The fact that the stands in Katmai were already under attack by spruce beetles at the time of the eruption suggests that the trees were drought-stressed. Thus, an increase in soil moisture retention could have facilitated tree growth.

Trees at most of the sites in Katmai range in age from 130-170 years, having established between 1860 and 1890. However, the study site closest to the eruption site, located along the Valley of 10,000 Smokes Road, also has trees that established between 1900 and 1920, suggesting that ash fall did not adversely affect seedlings and may have in fact facilitated establishment. Living trees as old as 235 years were also found at the site, indicating an available seed source at the time of the eruption.

The interaction of spruce beetle disturbance and volcanic activity has likely affected forest structure throughout southern Katmai, with volcanism affecting the growth and expansion of spruce forests on Kodiak, as well. Tree-ring chronologies, stand age and structure, and climate data can be used in concert to understand long-term forest dynamics and to make predictions about future forest conditions. As additional tree-ring records from the region are analyzed, biologists will continue to reconstruct the influence of past eruptions on tree growth and climate, and to analyze forest responses to environmental change, both of which can provide a basis for understanding future responses to rapid changes in climate.

REFERENCES

Biondi, F., I.G. Estrada, J.C.G. Ruiz, and A.E. Torres. 2003.
Tree growth response to the 1913 eruption of Volcán de Fuego de Colima, Mexico. Quaternary Research 59: 293-299.

Briffa, K.R., F.H. Schweingruber, P.D. Jones, T.J. Osborn, S.G. Shiyatov, and E.A. Vaganov. 1998.
Reduced sensitivity of recent tree-growth to temperature at high northern latitudes. Nature 391: 678-682.

Eicher, G.J., Jr., and G.A. Rounsefell. 1957.
Effects of lake fertilization by volcanic activity on abundance of salmon. Limnology and Oceanography 2: 70-76.

Fierstein, J., and W. Hildreth. 1992.
The plinian eruptions of 1912 at Novarupta, Katmai National Park, Alaska. Bulletin of Volcanology 54: 646-684.

Griggs, R.F. 1920.
The recovery of vegetation at Kodiak. Ohio State University Bulletin 24: 1-57.

Kaiser, K.F., and C. Kaiser-Bernhard. 1987.
The Katmai eruption of 1912 and the Alaska earthquake of 1964 as reflected in the annual rings of Sitka Spruce on Kodiak Island. Dendrochronologia 5: 111-125.

LaMarche, V.C., Jr., and K.K. Hirschboeck. 1984.
Frost rings in trees as records of major volcanic eruptions. Nature 307: 121-126.

Mass, C.F., and D.A. Portman. 1989.
Major volcanic eruptions and climate: A critical evaluation. Journal of Climate 2: 566-593.

Pollman, W. 2003.
Stand structure and dendroecology of an old-growth Nothofagus forest in Conguillio National Park, south Chile. Forest Ecology and Management 176: 87-103.

Segura, G., T.M. Hinckley, and L.B. Brubaker.1995.
Variations in radial growth of declining old-growth stands of Abiesamabilis after tephra deposition from Mount St. Helens. Canadian Journal of Forest Research 25: 1484-1492.

Sherriff, R.L., E.E. Berg, and A.E. Miller. 2011.
Climate variability and spruce beetle (Dendroctonus rufipennis) outbreaks in southcentral and southwest Alaska. Ecology 92: 1459-1470.

Weber, M.H., K.S. Hadley, P.M. Frenzen, and J.F. Franklin. 2006.
Forest development following mudflow deposition, Mount St. Helens, Washington. Canadian Journal of Forest Research 36: 437-449.

Williams, H., and A.R. McBirney. 1979.
Volcanology. Freeman, Cooper and Company. San Francisco.

Yamaguchi, D.K., and D.B. Lawrence. 1993.
Tree-ring evidence for 1842-1843 eruptive activity at the Goat Rocks dome, Mount St. Helens, Washington. Bulletin of Volcanology 55: 264-272.

Possible Effects of a Volcanic Eruption on the Nearshore Marine Environment

By Heather A. Coletti

Volcanic eruptions are infrequent disturbance events that vary in magnitude and type, which effects how ecosystems respond to these disturbance events (*DeGange et al. 2010*). Southwestern Alaska has been shaped and reshaped by these events over many centuries, for it resides in the Pacific Ring of Fire, an area where the Pacific Plate of the earth's crust is slowly subducting under the North American Plate. These events also influence the biological environment of the nearshore ecosystem. Here, a brief overview of the literature and recent field accounts are summarized from three volcanic eruptions that occurred on the Alaska Peninsula. These three eruptions, which differed greatly in magnitude and type, are presented to illustrate the range of effects that these eruptions have on the nearshore marine ecosystem.

Novarupta-1912

In 1912, Novarupta erupted in what is now Katmai National Park and Preserve (NPP) and was the largest volcanic eruption of the twentieth century (*Fierstein and Hildreth 2001*). After the eruption, initial accounts on the effects to the marine environment primarily discussed the amount of ash and pumice deposited. One account described Kaflia Bay, along the coast, as being so choked with several feet thick of floating pumice that birds, fish, and marine mammals were actually floating on the surface of the ash and pumice mixture (*Schaaf 2004*). Extensive fields of floating pumice were observed in other areas as well, and witnesses claimed floating pumice mats were so thick that they could support the weight of a man (*Figure 1*) (*Martin 1913*).

Figure 1. This photograph, taken from the north end of Takli Island in August 1912, is a view of Amalik Bay showing the pumice in the water and on the beach. The dark area in the left foreground is clear water, and the white bands in the water are pumice.

Photograph courtesy of George C. Martin

Ash deposits along the shoreline most likely buried existing marine plants and were still evident a year after the eruption (*Rigg 1914*). Intertidal and subtidal canopy kelps most likely succumbed to the grinding effect of the floating pumice, exacerbated by waves and tidal action. Two kelps, *Nereocystis luetkeana* (bull kelp) and *Eualaria fistulosa* (formally *Alaria fistulosa*) (dragon kelp), were of particular importance to the livelihoods of local residents. Both of these kelps were used as navigation aids to indicate areas of shallow water and as fertilizer for gardens (*Rigg 1914*). Besides the grinding effects of floating pumice on kelps, marine plants as well as the rocks many marine plants attach to, were buried, possibly permanently altering the quantity of available kelp forest habitat.

The immediate impacts of the Novarupta eruption resulted in substantial changes in the marine ecosystem. We cannot say with certainty how these physical changes affected the complex biological balance of flora and fauna, but the loss of the kelp beds, nearshore plants and sessile invertebrates altered the complex balance for many years following the eruption and caused Alaska Natives to abandon coastal settlements (*Schaaf 2004*). However, Rigg (*1914*) noted that the effects on marine vegetation from this eruption were most likely temporary, as tide, waves, wind and other natural forces eroded ash deposits in the nearshore, allowing the ecosystem to recover.

Kasatochi-2008

Kasatochi, an island in the Aleutian chain, erupted for two days in August of 2008 (*DeGange et al. 2010, Scott et al. 2010*). Pyroclastic flows decimated the entire terrestrial portion of the island, devastated marine nearshore habitats to the 66 ft (20 m) isobath, and actually increased the size of the terrestrial portion of the island by approximately 30% (*Scott et al. 2010, Jewett et al. 2010*) (*Figure 2*). Algal and faunal communities as well as rocky substrates were buried with volcanic deposits, well into the subtidal zone. These deposits not only destroyed existing plants but also severely limited rocky habitat through burial. The loss of this rocky habitat may constrain kelp recolonization around Kasatochi. However, little information is known regarding ocean current directions and velocities that may ultimately help erode soft-sediments and expose hard substrates necessary for kelp bed recolonization (*Jewett et al. 2010*).

Higher trophic marine organisms were also affected by the eruption. Prior to eruption, Kasatochi provided foraging and breeding habitat for many species of seabirds and marine mammals (*Williams et al. 2010*). Nesting habitat for several species of auklets was covered in meters of tephra. Adults returned in 2009 to former colony areas and attempted to nest and lay eggs (*Figure 3*) (*Williams et al. 2010*). Researchers found broken, non-predated eggs scattered and in the open at these former colonies (*Figure 4*) (*Williams et al. 2010*). While post-eruption densities of adult seabird populations were similar to pre-eruption densities, the present lack of suitable nesting habitat could have negative impacts on future seabird populations on Kasatochi (*Drew et al. 2010*). This eruption has given scientists a unique opportunity to examine rates and processes of successional recovery (*DeGange et al. 2010*).

Redoubt-2009

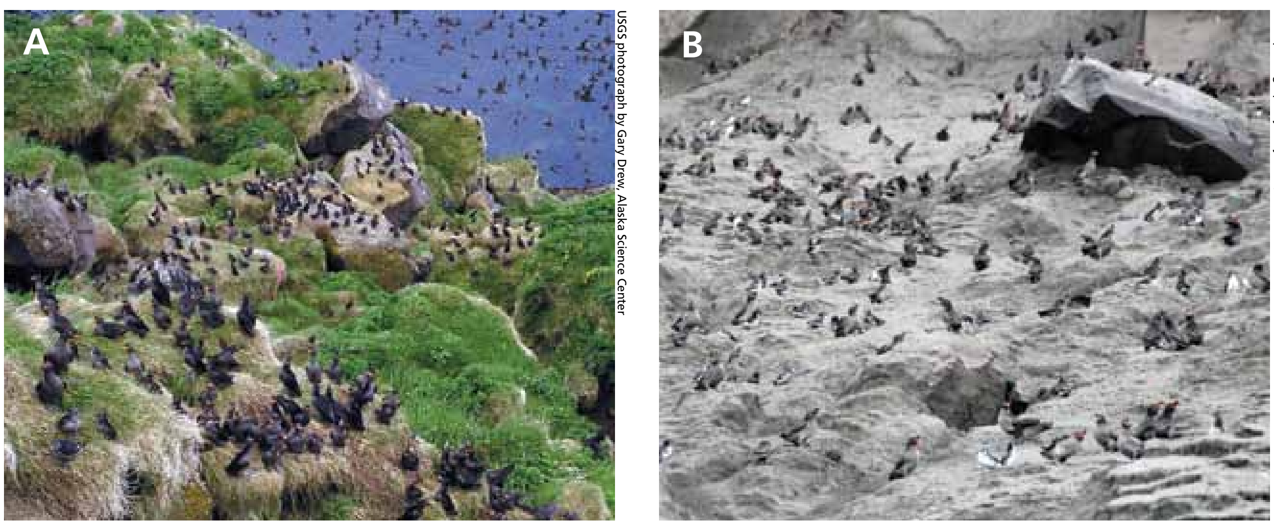
In 2009, Redoubt volcano, west of Cook Inlet in Lake Clark National Park and Preserve (NPP), erupted creating an ash cloud 30,000 - 60,000 feet above sea level (*Carlisle and Nelson 2009*). Ash deposits were visible in terrestrial upland areas, but a light coating of ash was also observed in the intertidal (*Coletti, personal observation*). Ash deposited in the nearshore environment was considered minor, resulting in short-term impacts to the flora and fauna of the nearshore marine ecosystem (*Figures 5-6*).

However, a major threat to the nearshore from the Redoubt eruption was the formation of a lahar (a flow of pyroclastic material mixed with water), that flooded the Drift River valley. The mouth of the river is home to the Drift River Oil Terminal, which has a crude oil storage capacity of several million gallons. The mouth of Drift River opens into Cook Inlet, whose waters run along shore of Lake Clark NPP and Katmai NPP. These park shorelines, as well as adjacent areas, support a variety of marine flora and fauna that interact in a complex food web—beginning with primary production from kelps and sea grasses, to primary consumers such as mussels and limpets, to apex predators such as seabirds and marine mammals (*Dean and Bodkin 2011*). Ample evidence collected over several decades since the 1989 Exxon Valdez Oil Spill in Prince William Sound, Alaska, has demonstrated that species and ecosystems immediately affected by the oil spill have not fully recovered in the twenty plus years since the spill (*Peterson 2001, Rice et al. 2007*). An oil spill along the Katmai NPP and Lake Clark NPP coastlines could exacerbate and protract the process of recovery to a system responding to natural and anthropogenic change.

The unpredictability of catastrophic events as well as anticipated changes in the nearshore ecosystem, due to natural causes or anthropogenic influences, supports the need for long-term monitoring programs to elucidate the processes of recovery and change, such as the Southwest Alaska Network (SWAN) of the National Park Service. Current marine nearshore monitoring in SWAN parks should be able to quantify changes in (1) intertidal kelp species composition and percent cover; and (2) intertidal invertebrate densities that graze on kelps; and (3) determine the effects on higher trophic level marine birds and mammals following an eruption or other disturbances. The unpredictability of eruptions and the degree to which the resulting disturbance affects coastal ecosystems highlights the need for long-term monitoring to anticipate recovery rates and track succession of key species following a catastrophic disturbance.

USGS photograph by George Esslinger, Alaska Science Center

Figure 2. Expansion of Kasatochi Island, as a result of the 2008 eruption.



USGS photograph by Gary Drew, Alaska Science Center

USGS photograph by Gary Drew, Alaska Science Center

Figure 3. Crested auklets on a colony (A) pre- and (B) post-eruption.

USGS photograph by Gary Drew, Alaska Science Center

Figure 4. An example of broken, non-predated seabird eggs found at former colony sites.

NPS photograph by Heather Coletti

Figure 5. Looking up into the mountain of Lake Clark National Park and Preserve from the coastline. Notice the ash deposits in the mountains.

Photograph by Susan Saupe, Cook Inlet Regional Citizens Advisory Council

Figure 6. A limpet leaves a track across a boulder lightly covered in ash in Lake Clark National Park and Preserve.

REFERENCES

Carlisle, J., and K. Nelson. 2009.
Redoubt Volcano eruption/ash synopsis - November 2008 - July 2009. Unpublished Federal Aviation Administration summary document.

Dean, T.A., and J.L. Bodkin. 2011.
Protocol narrative for marine nearshore ecosystem monitoring in the Southwest Alaska Network of National Parks. Natural Resource Report NPS/SWAN/NRR-2011/449. National Park Service. Fort Collins, Colorado.

DeGange, A.R., G.V. Byrd, L.R. Walker, and C.F. Waythomas. 2010.
Introduction - The impacts of the 2008 eruption of Kasatochi Volcano on the terrestrial and marine ecosystems in the Aleutian Islands, Alaska. Arctic, Antarctic, and Alpine Research 42(3): 245-249.

Drew, G.S., D.E. Dragoo, M. Renner, and J.F. Piatt. 2010.
At-sea observations of marine birds and their habitats before and after the 2008 eruption of Kasatochi Volcano, Alaska. Arctic, Antarctic, and Alpine Researc h 42(3): 325-334.

Fierstein J., and W. Hildreth. 2001.
Preliminary volcano-hazard assessment for the Katmai Volcanic Cluster, Alaska. USGS Open-File Report 00-489. Alaska Volcano Observatory. Anchorage, Alaska.

Jewett, S.C., J.L. Bodkin, H. Chenelot, G.G. Esslinger, and M.K. Hoberg. 2010.
The nearshore benthic community of Kasatochi Island, one year after the 2008 volcanic eruption. Arctic, Antarctic, and Alpine Research 42(3): 315-324.

Martin, G.C. 1913.
The Recent Eruption of Katmai Volcano in Alaska. The National Geographic Magazine 24: 131-181.

Peterson C.H. 2001.
The Exxon Valdez oil spill in Alaska: acute, indirect, and chronic effects on the ecosystem. Advances in Marine Biology 39: 1-103.

Rice S.D., J.W. Short, M.G. Carls, A. Moles, and R.B. Spies. 2007.
The Exxon Valdez oil spill. In *Long-term ecological change in the Northern Gulf of Alaska*, edited by R.B. Spies. Elsevier. Amsterdam.

Rigg, G.B. 1914.
The effects of the Katmai eruption on marine vegetation. Science: 509-513.

Schaaf, J.M. 2004.
Witness: Firsthand accounts of the largest volcanic eruption in the twentieth century. U.S. National Park Service.

Scott, W.E., C.J. Nye, C.F. Waythomas, and C.A. Neal. 2010.
August 2008 eruption of Kasatochi Volcano, Aleutian Islands, Alaska – Resetting an island landscape. Arctic, Antarctic, and Alpine Research 42(3): 250-259.

Williams, J.C., B.A. Drummond, and R.T. Buxton. 2010.
Initial effects of the August 2008 volcanic eruption on breeding birds and marine mammals at Kasatochi Island, Alaska. Arctic, Antarctic, and Alpine Research 42(3): 306-314.

Bringing the World to a Standstill: An Investigation into the Effects of a Novarupta Scale Volcanic Eruption on Today's Aviation Industry

By Rebecca Anne Welchman

Introduction

One hundred years ago the Novarupta Volcano erupted, sending ash over the globe, and was the biggest eruption of the twentieth century. The ash settled over the U.S.A., Canada and as far as Africa (*Fierstein 2007*). Today, the North Pacific is one of the busiest air corridors in the world (*Kite-Powell 2000*). The eruption of Eyjafjallajökull in April 2010 demonstrated how disruptive a volcanic eruption can be to the aviation industry, as Europe was almost brought to a standstill (*Chung and Pearce 2010*). Al Jazeera (*2010*) reported that by the third day of the eruption, 17,000 flights had been cancelled across Europe.

Europe has extensive infrastructure; not all countries are so lucky, and must rely on air travel. The relatively small eruption in Iceland raised questions about the possible effects of a larger eruption, particularly in an area where air traffic is vital, such as Alaska and northern Canada. With the Iceland eruption in mind, this project investigated the possible effects on eruption of a Novarupta-scale eruption. Its size and location below a busy air corridor made it ideal for the study.

Novarupta

Alaska has over 100 active volcanoes (*Dean et al. 2002, Topinka 1999*), and there have been at least five eruptions in Alaska per decade since 1900, with the last three decades being exceptionally active (*AVO, accessed 2010*) (*Figure 2*). Novarupta is one of nine volcanic vents in the Katmai cluster (*Fierstein and Hildreth 2001*), and the Katmai cluster has had 15 eruptive episodes in the last 10,000 years (*Fierstein and Hildreth 2001, Fierstein 2007*). The area is prone to most volcanic hazards (i.e. ash clouds, pyroclastic flows, lahars etc.) (*Fierstein and Hildreth 2001*). Although the Katmai cluster is isolated from towns and cities, it is vital that scientists, decision makers and residents understand the potential threats the cluster could pose to Alaska, America and the rest of the world.

Figure 1. DC-10 airplane offset by the weight of ash falling from the eruption of Mount Pinatubo, Philippines. Cubi Point Naval Air Station.

US Navy photograph by R.L. Rieger. June 17, 1991. T.J. Casadevall 15

The 1912 Eruption

The Novarupta eruption started on June 6, 1912, and lasted approximately 60 hours (*Fierstein and Hildreth 2001*). The ash cloud rose to over 100,000 ft (32,000 m) (*Fierstein and Hildreth 2001*), and the jet stream carried the ash eastwards. The size of the 1912 eruption is compared to others in Figure 3.

The eruption formed the Valley of 10,000 Smokes. It created and spread more ash fallout than all the other historic eruptions from Alaska volcanoes combined (*Fierstein and Hildreth 2001, Fierstein 2007*). The dust and sulphurous aerosols were detected over California, Europe and North Africa within two weeks of the eruption (*AVO, Fierstein and Hildreth 2001*). It was also reported that an ash blanket reached as far as Greece (*Fierstein and Hildreth 2001*). The ash and dust deposited has shown up in ice cores taken from Greenland (*Fierstein and Hildreth 2001*). Other recorded effects were extensive and included collapsed roofs, contaminated water supplies, a devastated fishing industry and cooler summers (*AVO, Fierstein and Hildreth 2001, NPS 2000*).

Who Is At Risk?

Fierstein and Hildreth (*2001*) believe there to be 5 main aspects of Alaskan communities that are most at risk from Katmai cluster eruptions: 1) Alaska's air corridor; 2) Regional and military bases and ports; 3) Fisheries and shipping lanes; 4) Wildlife habitats; and 5) Tourist facilities. Whilst each of these aspects is closely connected, we will focus on the first one.

Today over 200 flights per day pass in the range of Alaska's volcanoes (*Fierstein and Hildreth 2001, Kite-Powell 2000*). Air freight is the primary source of aviation commerce in Alaska, and many of the smaller communities rely on local airports for supplies (*Dean et al. 2002*). About $41 billion (5%) of all US-international air cargo passed through Ted Stevens Anchorage International Airport in 2008 (*BTS 2009*). Air traffic over the entire North Pacific, Alaska, Canada and U.S.A could be affected, interrupting both national and international air commerce (*Fierstein and Hildreth 2001*).

Methodology

Simulations were run on the Puff model (created by the Alaskan Volcano Observatory and the University of Alaska Fairbanks). The parameters used for the simulations can be seen in Figure 4, believed to be the same as those of the 1912 eruption. Simulations were run from 2005 until 2009 and imported into a Geographical Information Systems program, which allowed a visual assessment of the distribution of ash. This data was cross-referenced with the locations of major international airports.

Once all this information was collated, the number of airports directly affected by the ash clouds was counted on each simulation. The totals and mean averages were calculated per week to discover a 'worst-case' scenario. This was based on passenger and financial information, which was obtained from the respective airport websites and reports by Tuck et al. (1992) on the 1989 Mount Redoubt eruption. These costs can be seen in Figure 5.

Results

The 'worst-case' scenario turned out to be a simulation started on January 17, 2005, which directly affected 43.3 airports per day during the simulation, as well as an average of 7.6 airports per day that were close to the ash cloud path. The dispersion of this ash cloud can be seen in Figures 6-11.

Based on passenger numbers and how long the ash cloud was in the vicinity of the airport, a total loss figure was estimated for the seven days. The total cost for delayed and cancelled flights for the scenario was estimated over $322 million.

What Does This Mean For Alaska?

Although Alaska is part of the United States, it does not have the same infrastructure as the contiguous 48

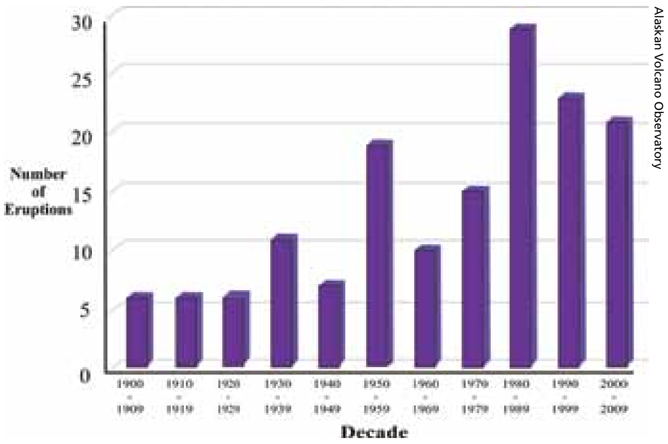


Figure 2. Number of eruptions per decade of Alaska volcanoes.

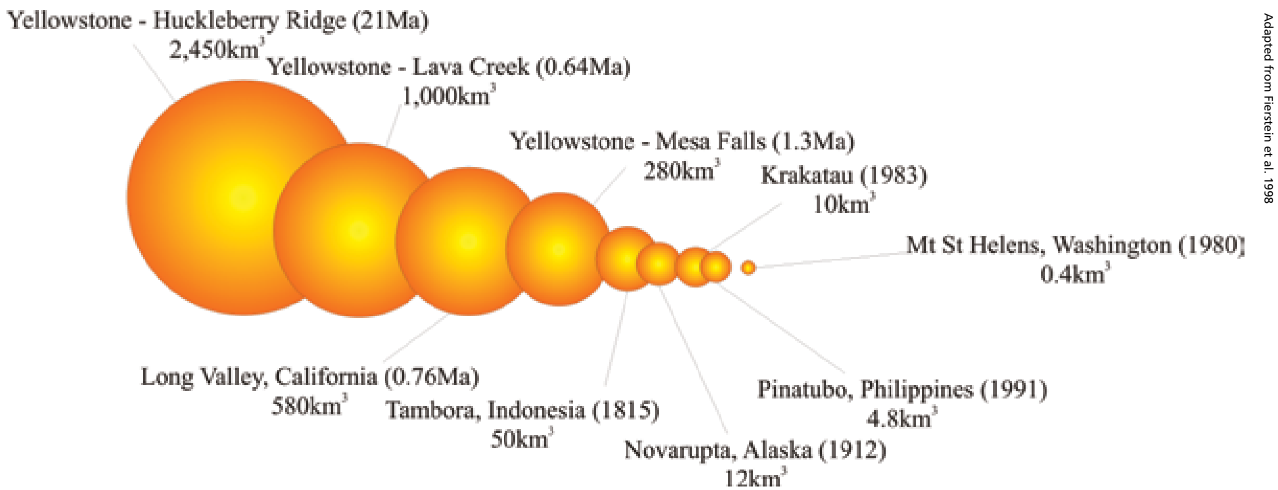


Figure 3. The relative size of the 1912 Novarupta eruption compared to several ancient and recent volcanic events.

Parameter	Input	Reason
Date	Various	Once a week every year to coincide with 6th June of that year.
Volcano	Novarupta	Inspiration for study
Simulation Hours	200	Practical simulation time for a study of this size
Save every (hrs)	24	Results can be compared per day, and produce a manageable amount of data
Plume Height (m)	32,000	Plume height during 1912 eruption
Eruption Hours	60	Total time of 1912 eruption
Particles	100,000	This number of particles will give the best result with the length of eruption and simulation
Plume Bottom	841	Altitude of vent
Wind Model	reanalysis	PUFF states this wind model is designed for high altitude ash clouds
Plume Shape	exponential	Chosen from review of literature

Figure 4. Eruption parameters for simulations.

Description	Value
Cost per loss of passenger (from cancelled incoming flights)	$46.03
Average wait (based on Mount Redoubt's most eruptive period in December 1989)	2.2
Cost per waiting time (of passengers who waited in the aiport for alternative flights)	$3.71

Tuck et al. 1992

Figure 5. Values used for calculation cost of eruption

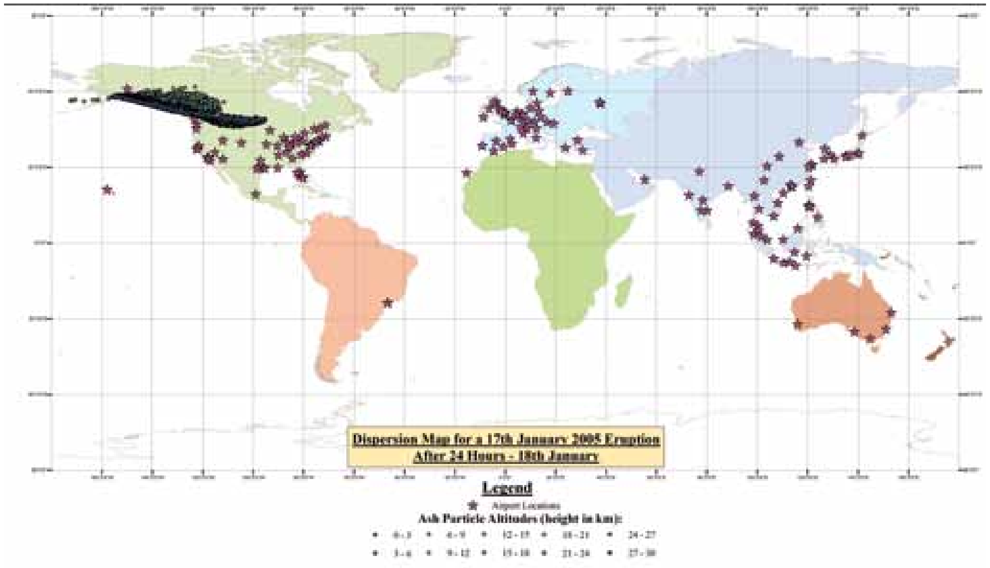


Figure 6. Dispersion of ash cloud from a simulated eruption on 17th January 2005 – after 24 hours.

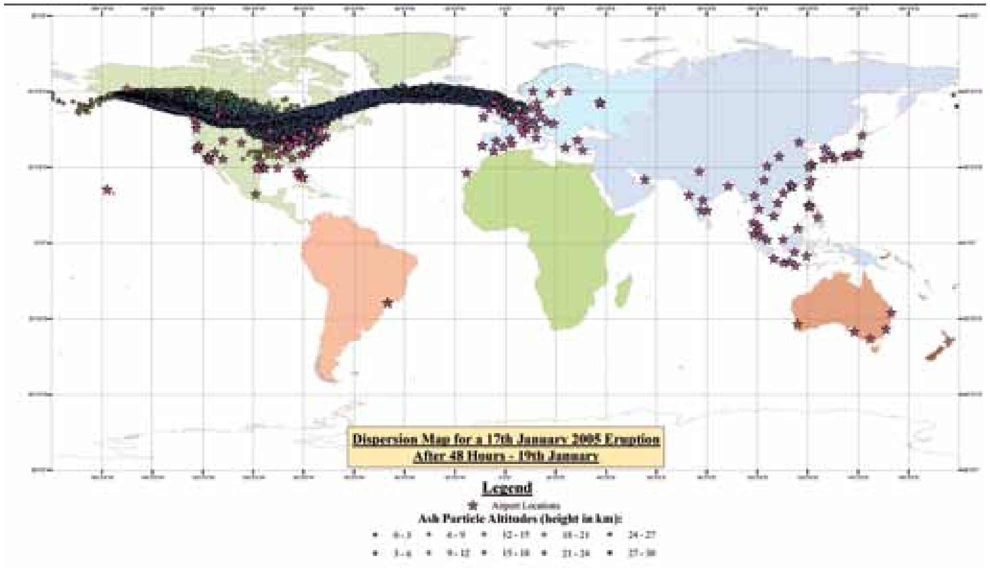


Figure 7. Dispersion of Ash Cloud from a simulated eruption on 17th January 2005 – after 48 hours.

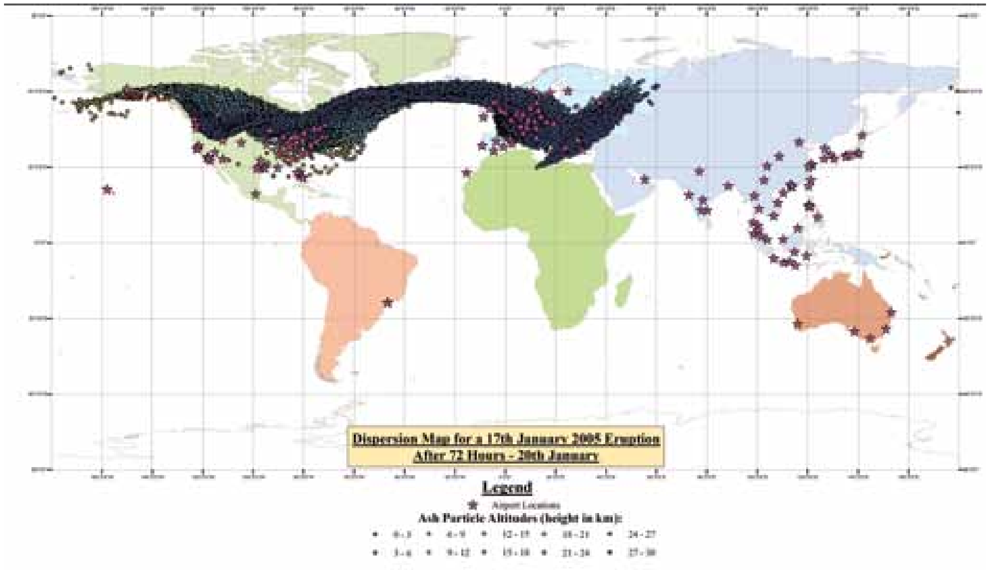


Figure 8. Dispersion of Ash Cloud from a simulated eruption on 17th January 2005 – after 72 hours.

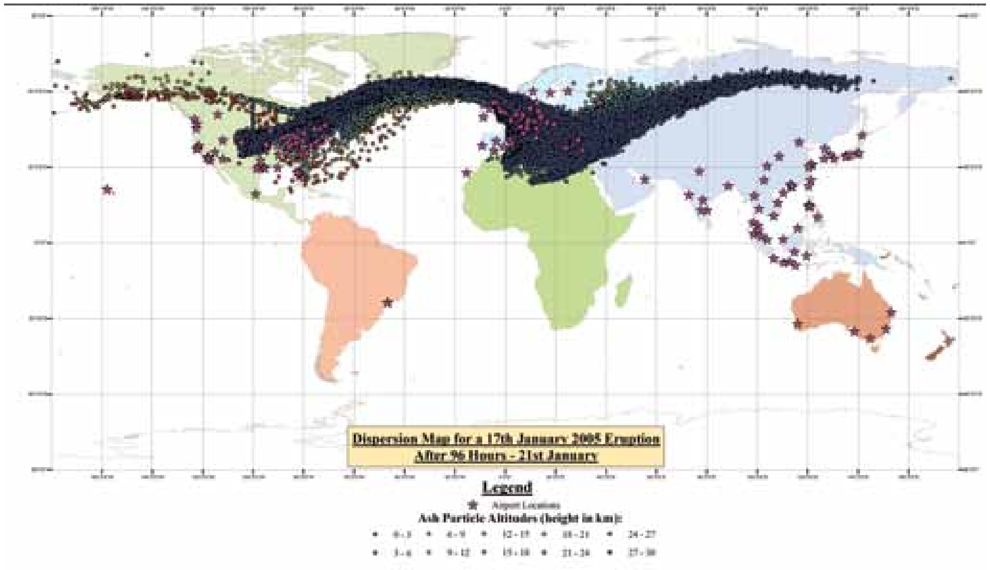


Figure 9. Dispersion of Ash Cloud from a simulated eruption on 17th January 2005 – after 96 hours.

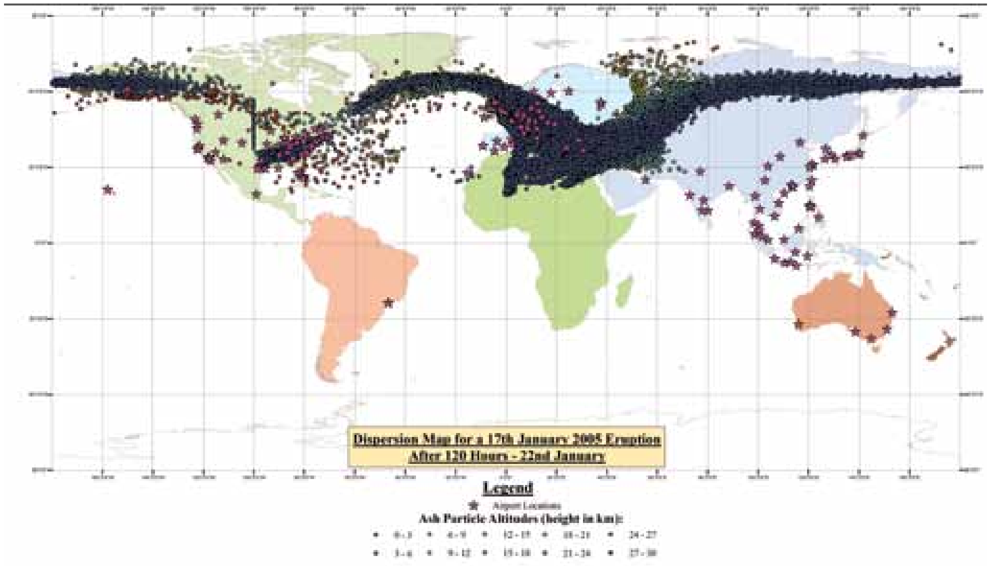


Figure 10. Dispersion of Ash Cloud from a simulated eruption on 17th January 2005 – after 120 hours.

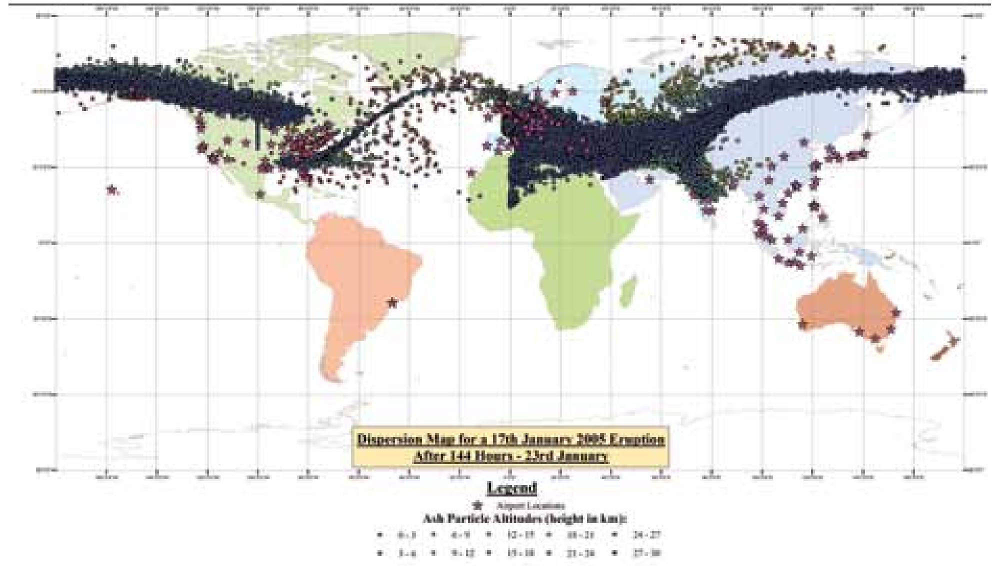


Figure 11. Dispersion of Ash Cloud from a simulated eruption on 17th January 2005 – after 144 hours.

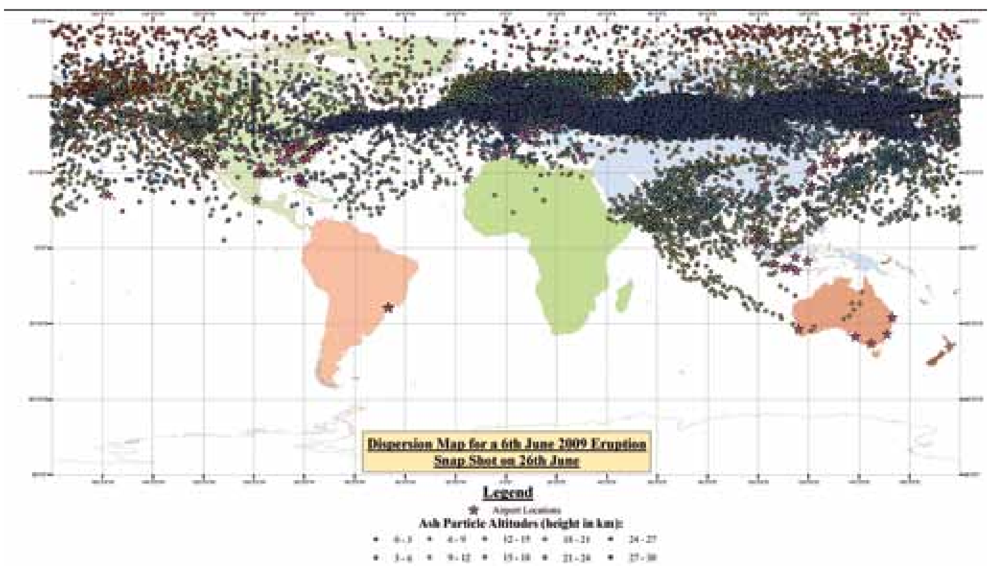


Figure 12. Ash from a simulated eruption starting 6th June 2009 after 20 days.

states. People would become stranded until the eruption deposits were cleaned up. As a state, it is reliant on food from mainland U.S.A. Alaska is dependent on aviation to supply remote villages and is not able to offer alternative transport. Aviation is particularly vital during the winter when roads are impassable due to snow. Supplies in these areas would quickly run out, causing extra health issues and putting people's lives at risk.

Alaska is used as a midway-stop for ships and aeroplanes to refuel when travelling across the Pacific or Arctic. However, with it being one of the most volcanically active areas in the world, the area is highly at risk. Having planes grounded for many days, passengers waiting at airports and the cleaning of aviation areas (runways, aircraft, and airports) would be a significant financial strain on Alaska's economy.

Alaska would suffer significantly both socially and economically from an eruption, from which it would be difficult to recover. It is likely many industries (such as the extensive fishing industry) would suffer, but the exact extent of the impact is difficult to calculate for this study.

What About the Rest of the World?

The estimated cost for this report does not include the landing fees for aircraft, the duty-free concessions, clean up and aircraft rerouting. As these figures stand, the cost of losing passengers is already three times more than that of Mount Redoubt in 1989/90, demonstrating the sheer potential impact of a large eruption. The simulations were only run for the equivalent to seven days, meaning costs are likely to be significantly higher.

All major flights from the U.S. to Asia, Australasia and some to the Middle East fly over Alaska. These areas of the world are heavily reliant on each other for commerce and consequently would be affected if an eruption of this scale occurred. The tourism industry would be heavily affected around the globe. Many industries would likely lose confidence in the reliance on aviation for the transport of goods as a result of the disruption. In this case, whilst airports would be expected to be affected all over the world, air traffic itself would likely not be possible throughout North America and Europe, making any operations very difficult as we are now so reliant on aircraft.

The Benefits of Longer Predictions

A simulation was run from June 6, 2009, to look at how the ash behaved over a longer period. In just 20 days, ash covered the whole of the northern hemisphere as well as southern India (*Figure 12*). If volcanic ash were to cross the equator, we could be in for a devastating situation. If Katmai, or even any volcano were to erupt at this magnitude again, it would cause global disruption. The simulation showed that an eruption of this size is not likely to dissipate quickly and could bring the world to a standstill.

Conclusions

Recent eruptions (in particular the April 2010 Eyjafjallajökull event) demonstrated the disruption a volcanic eruption could cause. The research demonstrated the potential devastation a bigger eruption could cause. If Novarupta erupted again today, to the same scale as in 1912, it would cripple the aviation industry in North America and possibly Europe. The minimum cost is estimated in excess of $300 million and the social implications are likely to be devastating all around the world.

The study demonstrates the need for a specific understanding of an eruption's potential impact, and its wider social implications. There is still room for many developments of the project but it gives a basic overview of what we could be dealing with, maybe in our life time, if not in Alaska, somewhere else around the world.

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REFERENCES

Al Jazeera. 2010.
Ash cloud disrupts global aviation. http://www.aljazeera.com/news/Europe/2010/04/201041692933434631.html Accessed 16th April 2010.

Alaskan Volcano Observatory (AVO).
Event Specific Information: Katmai -1912. (http://www.avo.alaska.edu/volcanoes/volcact.php?volcname=Katmai&eruptionid=494&page=basics) Accessed February 24, 2010.

Bureau of Transportation Statistics (BTS). 2009.
Ted Stevens Anchorage International Airport, Alaska-air freight gateway. Research and Innovative Technology Administration, U.S. Department of Transportation. (http://www.bts.gov/publications/americas_freight_transportation_gateways/2009/highlights_of_top_25_freight_gateways_by_shipment_value/anchorage/index.html)

Chung A., and D. Pearse. 2010.
Volcanic Ash Forces UK Flight Ban Extension. (http://news.sky.com/home/uk-news/article/15602425) Accessed April 16, 2010.

Dean, K.G., J. Dehn, K. Engle, P. Izbekov, K. Papp, and M. Patrick. 2002.
Operational Satellite Monitoring of Volcanoes at the Alaska Volcano Observatory. Advances in Environmental Monitoring and Modelling 1(1): 70-97.

Fierstein, J., W. Hildreth, J.W. Hendley, and P.H. Stauffer. 1998.
Can another Great Eruption Happen in Alaska? United States Geological Survey Fact Sheet 075-98.

Fierstein, J., and W. Hildreth. 2001.
Preliminary Volcanic-Hazard Assessment for the Katmai Volcanic Cluster, Alaska. U.S Geological Survey. Anchorage, Alaska.

Fierstein, J. 2007.
Explosive eruptive record in the Katmai Region, Alaska Peninsula: an overview. Bulletin of Volcanology 69: 469-509.

Kite-Powell, H.L. 2000.
Benefits of NPOESS for commercial-aviation – Volcanic ash avoidance. Report to the National Polar Orbiting Operational Environmental Satellite System (NPOESS) Integrated Program Office (IPO). Washington, D.C.

National Park Service (NPS). 2000.
Geology Fieldnotes –Katmai National Park and Preserve, Alaska. In *Description: 1912 Eruption of Novarupta, Alaska* (vulcan.wr.usgs.gov/Volcanoes/Alaska/description_1912_eruption_novarupta.html) Accessed 24th February 2010.

Topinka, L. 1999.
Active Volcanoes and Plate Tectonics. (Vulcan.wr.usgs.gov/Glossary/PlateTectonics/Maps/map_plate_tectonics_world2.html) Accessed September 6, 2010.

Tuck, B.H., L. Huskey, and L. Talbot. 1992.
The Economic Consequences of the 1989-190 Mt. Redoubt Eruptions. U.S. Geological Survey.

Concluding Thoughts.
Can Another Great Volcanic Eruption Happen in Alaska?

By Judy Fierstein

A Novarupta-scale eruption is almost certain to happen again in Alaska; the question is when. Although the chance of another eruption of this magnitude occurring in any given year is small, such cataclysmic volcanic events have occurred repeatedly in Alaska. Picturesque Aniakchak caldera formed during a similar, though larger, catastrophic eruption 3,500 years ago (*Neal et al. 2001*). Within 500 miles of Anchorage, volcanologists have identified at least seven deposits of volcanic ash younger than 6,000 years that approach or exceed the volume of ash ejected by Novarupta in 1912, including a thick layer of ash erupted from Hayes Volcano, only 90 miles (150 km) northwest of Anchorage (*Figure 2*). Alaska was very sparsely populated in 1912, and there were few airplanes. Now, nearly three-quarters of a million people live in the state, and aircraft carrying many thousands of passengers and millions of dollars in cargo pass near Alaska's more than 40 historically active volcanoes each day. The heavy ash fall produced by a Novarupta-scale eruption occurring today in southern Alaska would have economic and environmental impacts in Alaska and beyond.

Figure 1. Drifts of ash in village of Kodiak, June 1912. Ashfall was about one foot (30 cm) thick 100 miles (170 km) downwind from Novarupta.

Photograph courtesy of W.J. Erskine, courtesy of National Geographic Society

Volcano Hazards

A volcano hazard is any volcano-related process that potentially threatens life or property, with or without eruptive activity (*Figure 3*). Typically, several kinds of hazard will result from an eruption, the attendant risks depending upon the type and size of the eruption and location relative to the volcano. The most threatening hazards from the Katmai volcanoes include volcanic ash clouds and pyroclastic fallout, pyroclastic flows, lava domes and flows, floods and lahars, pumice rafts (large accumulations of coarse pumice floating in lakes or at sea), hydrothermal explosions, debris avalanches, volcanic gases, and phreatomagmatic eruptions through crater lakes or ice. Clearly, these dangers are initially destructive, but in many cases their lingering effects are also pronounced. Erosion and remobilization of pumice and ash deposits continue well after they are initially deposited. After the 1912 eruption, large amounts of pumice and ash were washed into creeks and rivers and quickly worked their way to the ocean. Re-vegetation can be slow on unstable, wind-blown pumice-covered surfaces, so the pumice continues to be washed into creeks for a long time. Great pumice rafts were reported still floating and clogging waterways in Shelikof Strait 22 years after the 1912 eruption (*Hubbard 1935*)! In any given area, the effects and extent of these volcano hazards will vary, depending on many factors, including (1) the size and duration of the eruption; (2) eruption type (for example, lava flow or explosive eruption), which can vary in time during an eruptive episode; (3) distance from the volcano; (4) proximity to any stream drainage that might become a pathway for any type of flow (lahar, flood, pyroclastic); (5) the amount of snow and ice that interacts with the eruption and eruptive products; and (6) wind speed and direction and general weather conditions.

Event Frequency and Risk: Katmai Volcanoes as Examples

Explosive, ash-producing eruptions pose the greatest risk to life and property in the remote Alaska wilderness, with aircraft being most at risk (*Casadevall 1994*). Fortunately, although such large eruptions are devastating, they are also infrequent. More common are those eruptions like Southwest Trident (*Figure 5*) that erupted mainly lava flows intermittently for a couple of decades (1953-74). Eruptive histories of the Katmai cluster demonstrate the variety and scales of volcanic activity we might expect from the 80-odd volcanoes in the Alaska Peninsula and the Aleutian Chain. These eruptive histories show that, of the Katmai cluster of volcanoes, Mount Katmai and (to a lesser degree) Mount Mageik are most likely to erupt explosively, conceivably on the scale of the great 1912 outburst (*Fierstein and Hildreth 2001*). Such explosive eruptions would be less likely from Martin, Griggs, Trident, or Snowy, where lava flows, dome building, and small ash-plume episodes have been the norm. Although any volcanic ash plume ejected into the atmosphere is of concern for aircraft, the scale of an eruption significantly affects the extent of its associated hazards and areas at-risk. Such eruptive histories and subsequent hazard assessments have been done for nearly 20 active Alaska volcanoes by the Alaska Volcano Observatory (*e.g., Neal et al. 2001, Coombs et al. 2008*). Examining these volcanic histories helps geologists try to predict how each volcano might behave in the future.

'Normal' Events

'Normal' eruptive events in the Katmai district, and in many places along the Alaska Peninsula and Aleutians, are characterized by the 1950s Trident eruptions, which

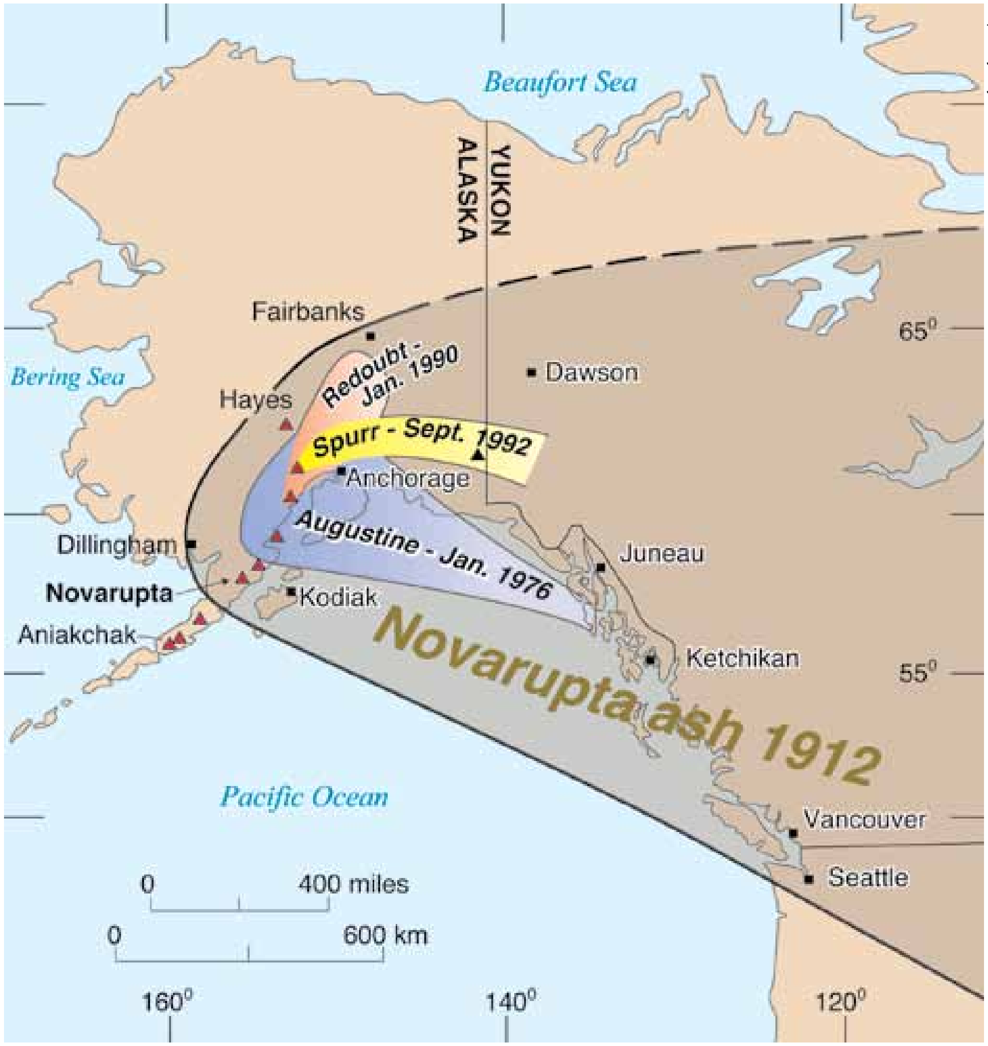


Figure 2. Alaska Peninsula map of volcanoes with Novarupta ash fall compared to that from recent eruptions. The volume of volcanic ash from Novarupta was more than from all other historical Alaska eruptions combined. Ash from seven prehistoric eruptions, all younger than 6,000 years and approaching the volume of the 1912 event, are found within 500 miles (800 km) of Anchorage, including ash from Hayes volcano.

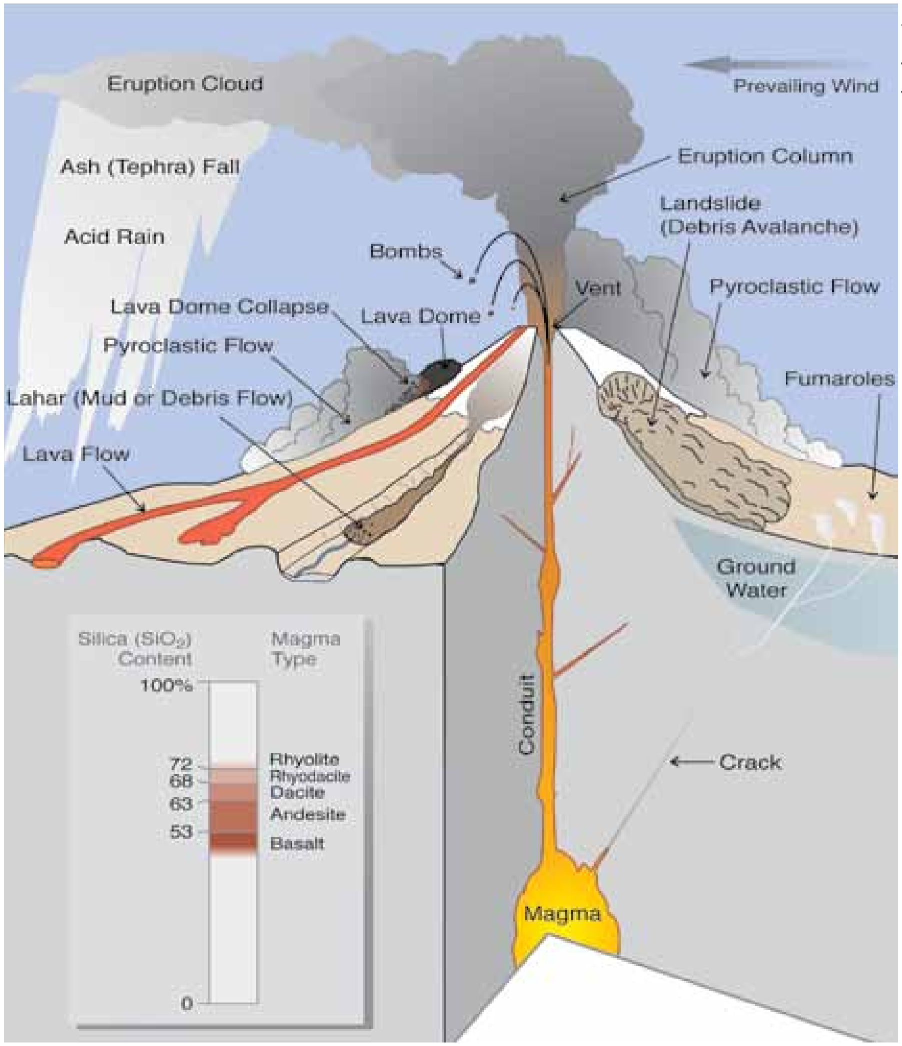


Figure 3. Hazardous phenomena associated with active volcanoes. Small eruptions typically pose hazards only within several kilometers of a volcano, whereas larger eruptions can endanger people and property at tens to hundreds of kilometers distant. Ash clouds can travel thousands of kilometers from a volcano and pose hazards to aircraft far downwind. Silicic magmas (rhyolite, rhyodacite, dacite) tend to erupt more explosively than mafic (andesite and basalt) magmas.

sent several ash columns 6,600-20,000 ft (2-6 km) into the atmosphere, and a few 30,000-40,000 ft (9-12 km) high. Prevailing winds at elevations over 3.5 miles (5.5 km) would most commonly direct ash toward the southeast, whereas lower-elevation winds are most likely to direct ash toward the northeast (*Figure 4*). Although less common, winds do sometimes come from the Pacific, blowing north and northwestward. Such were conditions that directed most of the 1953 Trident ash (*Ray 1967*). Only rarely do winds in this area at any elevation blow westward, thus it is unlikely that significant amounts of ash (even from large eruptions) would be distributed much more than a hundred miles or so (a couple of hundred kilometers) west or southwest of the erupting volcano.

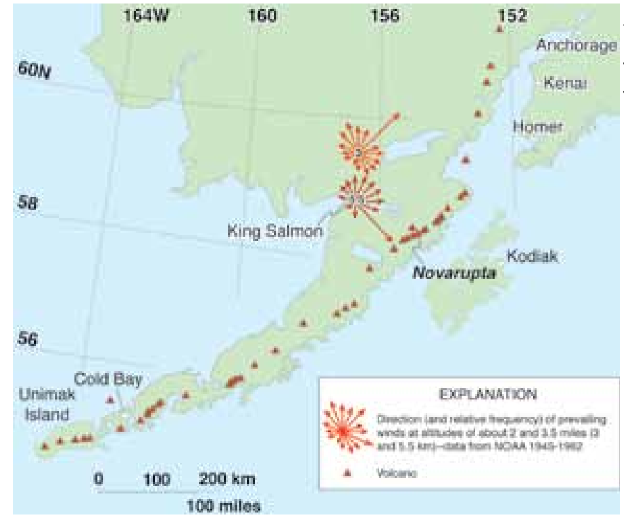
Size Matters

The size of the sector and extent of ash distribution depends mostly on the scale of an eruption; large eruptions affect much larger areas than small ones. Ash clouds from Southwest Trident would have severely affected aircraft overhead and in the immediate Katmai area. The larger (but still moderate-sized) eruptions of Redoubt (1990), Spurr (1992), and Augustine (1976 and 1986) affected considerably larger areas several hundred kilometers away (*Figure 2*). The 1912 eruption of Novarupta was exceptional; ash distribution dwarfed that of all the other historic Alaska eruptions combined. Although small to moderate-sized eruptions have been common throughout the eruptive histories of the Katmai volcanoes (no fewer than 15 such episodes in post-glacial time), there have been three 'exceptional' events from this cluster and a few moderately explosive pumice falls. Possibly the largest of all erupted ~23,000 years ago, another ~16,000 years ago (deposit is poorly preserved but eruption clearly was large), and the most recent was less than 100 years ago (Novarupta). Magma for all three originated beneath Mount Katmai.

Although exceptionally large events occur infrequently, the potential effects are far-reaching and severe. Now-populous Cook Inlet was severely blanketed with ash when Novarupta exploded (as the area also was 16,000 and 23,000 years ago). The Pacific slope of the Katmai volcanoes, too, was heavily mantled with pumice and ash (much of it remaining so today), and floating pumice rafts clogged Shelikof Strait and many of the bays along that coast. Ash was strongly wind-directed to the east-southeast in 1912, with the plight of inhabitants of Kodiak (*Figure 1*) making news headlines from San Francisco to Boston. Due to the sheer size of that eruption, significant amounts of ash fell even as far as 90 miles (150 km) upwind, to the northwest, covering what are today prime fishing and tourist areas.

Potential Impacts of Future Eruptions

A normal Trident-scale eruption (similar to the 1953-1974 episode) would affect mostly aircraft and backcountry hikers. Ash plumes, drifting ash clouds,



Graphics by Judy Fierstein

Figure 4. Direction (and relative frequency) of prevailing winds at altitudes of just under 2 and 3.5 miles (3 and 5.5 km) during year. Based on 18 years of National Oceanic and Atmospheric Administration daily data from King Salmon, Alaska.

USGS photograph by J. Fierstein

Figure 5. Aerial view looking southwestward towards Trident cones and flows. The blocky, dark young lavas, which are not covered with 1912 ash, were emplaced between 1953 and 1974. Older Trident peaks are in the background.

and occasional dustings of ash on nearby airports in King Salmon and possibly Kodiak could disrupt local and regional air traffic for days to weeks at a time. Such disruption of supplies and access by air could occur sporadically for a decade or more. Impacts of a prolonged eruption may not be entirely negative; small aircraft and local guide services might be anticipated to even take the opportunity to make such an eruption a tourist attraction! Backcountry hikers, too, could be drawn to such a phenomenon. Such intrepid adventurers would be at risk for unexpected explosions, lahars, debris avalanches, and ballistic bomb showers that accompany such eruptions.

During and after an exceptional 1912-scale eruption, we might expect a range of problems that would have severe and long-lasting economic effects for Alaska. Significant ash fall could damage or significantly disrupt operation of infrastructure (airports, electrical, water, and other critical systems) in areas of southern Alaska (*Wilson et al. 2011*). Chronic exposure to ash can adversely affect all types of motors from chainsaws to automobiles and affect cooling and ventilation systems reliant on external air (for instance: hospitals, computer systems, and bankcard machines). Ash fall would also contaminate water supplies and would be detrimental to fishing, wildlife, and tourism for years thereafter, as well as create eye and respiratory problems for many residents and animals. Clean-up may take days or weeks following small eruptions but such efforts could extend for months after a large eruption like that of 1912. Even after initial clean-up, within 100-200 miles of the volcano, normal Alaskan windstorms would remobilize loose dust from ash-covered slopes and valleys, lofting it high into the atmosphere. Such remobilization of ash can continue for decades; remobilizing of 1912 ash continues today (*Fierstein and Hildreth 2001*).

Early Warning

Volcanic eruptions cannot be prevented, but monitoring volcanoes can provide early warning of pending activity. The Alaska Volcano Observatory (AVO), a cooperative program of the U.S. Geological Survey, University of Alaska, and the Alaska State Division of Geological and Geophysical Surveys, operates a network of seismometers that detects earthquakes around the Katmai cluster of volcanoes as well as on and near many other volcanoes from Cook Inlet to the Aleutians. Volcanic earthquakes, caused by movement of magma or hydrothermal fluids beneath an edifice, are used to monitor the activity level of volcanoes, since most eruptions are typically preceded for hours to months by increased seismicity.

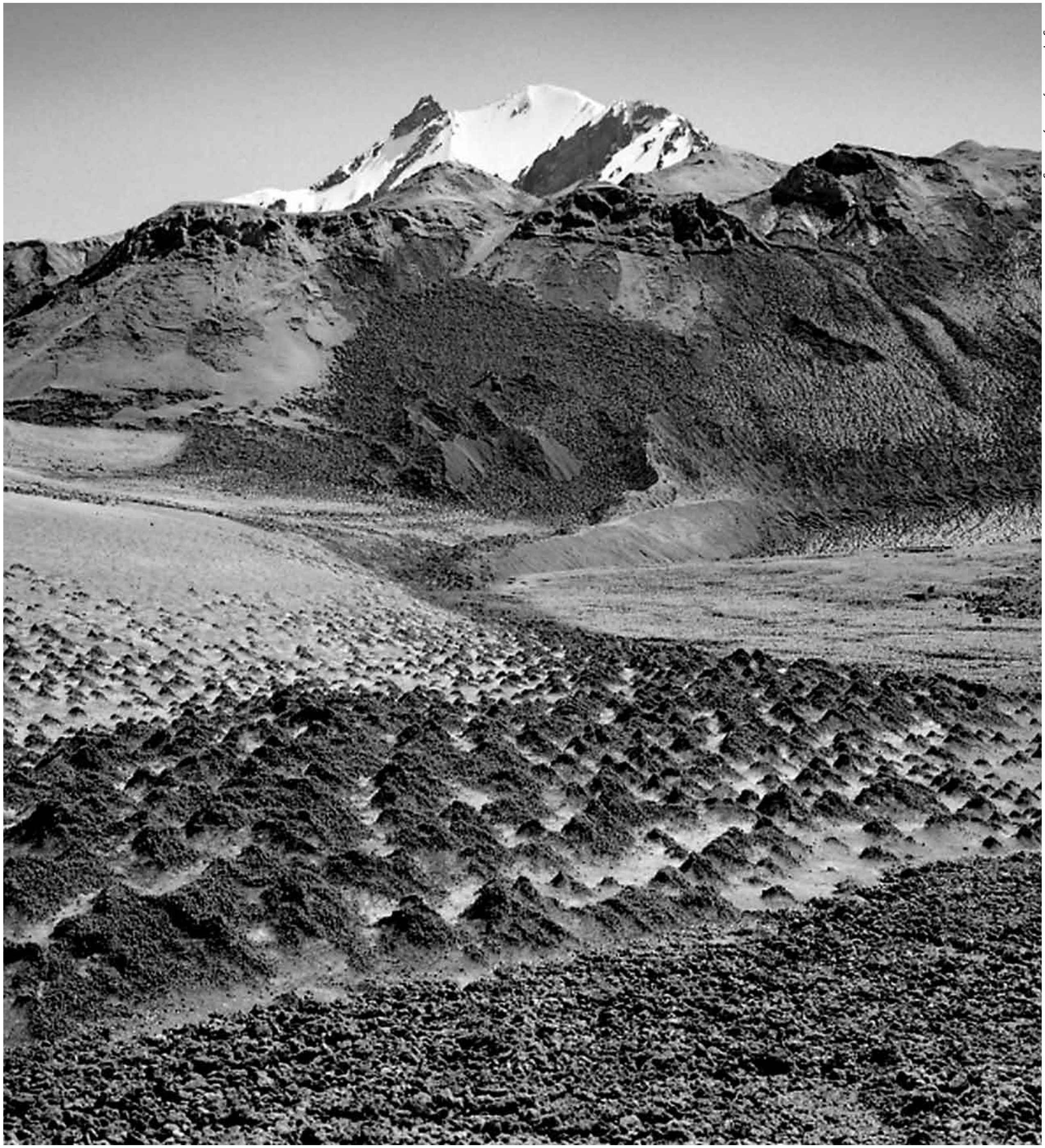
Other tools employed by AVO to monitor volcanic unrest include: daily satellite observation to look for elevated surface temperatures or the presence of ash in the atmosphere, airborne and ground-based volcanic gas measurements, lake and spring water chemistry, and surveys of ground deformation. Pilots and hikers also commonly provide AVO with observations that are used to direct further investigations of reported phenomena. Sightings of new steaming ground, increased fumarolic activity, and possible ash plumes all prompt further investigation by AVO personnel.

Early warning signs of volcanic unrest are evaluated in light of what is known about the volcano and its eruptive history. Thus, familiarity with a volcano's eruptive past can inform interpretations of data collected from monitoring instruments.

Alaska Volcanoes: Scenic Wildernesses and Natural Laboratories

Alaska volcanoes make for some of the most spectacular landscapes on earth. Adventurers, sightseers, artists and photographers are awed by this scenery and its wildness. Scientific researchers, too, are moved by the forces that have shaped these landscapes. For more than a century, Alaska volcanoes, including those preserved in national parks, have been host to cutting-edge scientific research that has shaped our thinking about how volcanoes work. Seismic data reveal the depth at which magma is stored beneath volcanoes and how quickly it rises toward the surface. Satellite images show ground deformation and ash plumes in remote areas. Geologic mapping and studies of a volcano's eruptive products provide a framework in which to interpret new volcanic activity. Examination of plant, animal and human recovery from past catastrophic eruptions gives an insight as to how modern life might be affected by a similar event. Ongoing studies continue to improve our understanding of volcanoes, magmatism, and how those interact with our society today. There is room now more than ever for enthusiastic new researchers, and Alaska's national parks provide a beautiful and dynamic natural laboratory.

For more information about volcanic ash hazards visit: http://volcanoes.usgs.gov/ash/



Photograph courtesy of Gary Freeburg

Figure 6. Conical pyramids of ash-covered snow near the base of Knife Creek Glacier, Valley of Ten Thousand Smokes.

REFERENCES

Casadevall, T.J., (ed). 1994.
Volcanic ash and aviation safety. Proceedings of the First International Symposium on Volcanic Ash and Aviation Safety. U.S. Geological Survey Bulletin 2047.

Coombs, M.L., R.G. McGimsey, and B.L. Brown. 2008.
Preliminary volcano-hazard assessment for Gareloi Volcano, Garreloi Island, Alaska. U.S. Geological Survey Scientific Investigations Report 2008-5159.

Fierstein, J., and W. Hildreth. 2001.
Preliminary volcano-hazard assessment for the Katmai Volcanic Cluster, Alaska. U.S. Geological Survey Open-File Report 00-489.

Hubbard, B.R. 1935.
Cradle of the Storms. Dodd, Mead & Co. New York.

Meyers, B., S.R. Brantley, P. Stauffer, and J.W. Hendley. 1997.
What are Volcano Hazards? U.S. Geological Survey Fact Sheet-002-97.

Neal, C.A., R.G. McGimsey, T.P. Miller, J.R. Riehle, and C.F. Waythomas. 2001.
Preliminary volcano-hazards assessment for Aniakchak Volcano, Alaska. U.S. Geological Survey Open-File Report 00-519.

Ray, D.K. 1967.
Geochemistry and Petrology of the Mt. Trident Andesites, Katmai National Monument, Alaska. Ph.D. Dissertation. University of Alaska Fairbanks.

Wilson, T.M., C. Stewart, V. Sword-Daniels, G.S. Leonard, D.M. Johnston, J.W. Cole, J. Wardman, G. Wilson, and S.T. Barnard. 2011.
Volcanic ash impacts on critical infrastructure. Journal of Physics and Chemistry of the Earth. DOI: 10.1016/j.pce.2011.06.006.

GLOSSARY

Andesite.
Volcanic rock, usually dark grey, with about 54% to 63% silica. See silica. Andesite is the predominant rock type of most volcanoes on the Alaska Peninsula.

Ash.
Fine fragments (less than 0.08 inch/2 mm across) of volcanic rock formed in an explosive volcanic eruption.

Ash cloud.
Cloud of gas, steam, ash, dust, and coarser fragments that forms during an explosive volcanic eruption and commonly gets blown long distances. Also called an eruption cloud.

Ash flow.
Mixtures of hot pumice, ash, and volcanic gas that travel along the ground.

Ballistic.
Fragments ejected explosively from a volcanic vent on an arcuate trajectory, much like a cannonball. Sometimes called a volcanic bomb. Ballistic fragments seldom land farther than a mile or two from the volcano; concurrently erupted ash clouds go much farther.

Basalt.
Volcanic rock with about 45% to 53% silica. (see silica). Basaltic lavas are more fluid than andesites or dacites, both of which contain more silica.

Caldera.
Crudely circular depression, generally larger than a crater, and typically more than 1.2 miles (2 km) across. It is formed by the collapse of a volcano during withdrawal or ejection of a large volume of magma that leaves the roof of the magma reservoir unsupported.

Crater.
Bowl-, funnel-shaped, or cylindrical depression usually near the top of a volcano, and commonly less than 1.2 miles (2 km) across. It is formed by volcanic explosions and usually involve constructive buildup of crater-rimming deposits rather than subsidence of the floor (cf. caldera).

Dacite.
Volcanic rock with about 64% to 68% silica. (see silica). Dacite lavas are viscous and tend to form thick blocky lava flows or steep-sided piles of lava called lava domes. Dacitic magmas tend to erupt explosively, thus also ejecting abundant ash and pumice.

Debris avalanche.
Rapidly moving slide masses of rock debris, sand, and silt that often form by structural collapse of a volcano. Debris avalanches can travel considerable distances from their source, and deposits are characterized by a hummocky surface.

Debris flow.
Rapidly flowing mixture of water, mud, and rock debris. A volcano-derived debris flow is commonly called a lahar. Parts of debris avalanches can transform into debris flows by mixing with the water in rivers or lakes overrun.

Effusive eruption.
An eruption that produces mainly lava flows and domes (as opposed to an explosive eruption).

Eruption cloud.
Cloud of gas, steam, ash, and other fragments that forms during an explosive volcanic eruption and travels long distances with the prevailing winds. Also called an ash cloud.

Eruption column.
The ascending, vertical mass of erupting debris and volcanic gas that rises directly above a volcanic vent. Higher in the atmosphere, columns usually spread laterally into plumes or umbrella clouds.

Ejecta.
General term for anything thrown into the air from a volcano during an eruption; synonymous with pyroclast. (cf. pyroclast).

Explosive eruption.
An energetic eruption that produces mainly ash, pumice, and fragmental ballistic debris (as opposed to an effusive eruption).

Fallout.
A general term for all the ash and debris that falls to earth from an eruption or ash cloud.

Fumarole.
A small opening, crack, or vent from which hot gases are emitted. Commonly on the floor of a volcanic crater, but sometimes also on a volcano's flanks. Short-lived fumaroles also issue from hot lava flows and pyroclastic deposits during their period of cooling.

Ignimbrite.
The deposit of a hot chaotic mixture of pumice, ash, and gas that travels rapidly (as fast as tens of meters per second) away from a volcanic vent during an explosive eruption. Ignimbrite is a pumice-rich type of pyroclastic flow that commonly accompanies plinian eruption columns. Synonymous with ash-flow tuff.

Lahar.
See debris flow. A mixture of water and volcanic debris that moves rapidly downstream. Consistency can range from that of muddy dishwater to that of wet cement, depending on ratio of water to debris.

Lava.
Molten rock that reaches the earth's surface and maintains its integrity as a fluid or viscous mass, rather than exploding into fragments (cf. magma).

Lava dome.
A steep-sided mass of viscous and often blocky lava extruded from a vent; typically has a rounded top and covers a roughly circular area. May be isolated (like Novarupta) or, alternatively, associated with lobes or flows of lava from the same vent.

Mafic magma.
Magma that contains lower amounts of silica and is generally less viscous and less gas-rich than silicic magma. Tends to erupt effusively, as lava flows. Includes andesites (54-63% SiO_2) and basalts (45-53% SiO_2).

Magma.
Molten rock beneath the earth's surface (cf. lava).

Magma chamber.
A storage area or reservoir of molten rock beneath the earth's surface.

Phreatic eruption.
An eruption that primarily involves steam explosions, usually groundwater flashed by the heat of subsurface magma.

Phreatomagmatic eruption.
An eruption that involves both magma and water, which typically interact explosively, leading to concurrent ejection of steam and pyroclasts.

Plinian eruption.
A large explosive eruption that produces a steady vertical eruption column of pumice and ash, that may reach tens of kilometers above a volcano. Results in far-traveled ash clouds, widespread fallout of pyroclastic debris, and can have accompanying pyroclastic flows and surges. (Named for Pliny, who observed and reported on the eruption that devastated Pompeii in A.D. 79).

Post-caldera.
A term used to describe the time after caldera formation.

Postglacial.
Refers to the end of the last major ice age, about 10,000 years ago. Geologically, the transition from Pleistocene (>10,000 years) to Holocene (<10,000 years) time. A loose term: The actual withdrawal of major Pleistocene ice sheets varied with location and latitude.

Pumice.
Highly vesicular volcanic ejecta, essentially magma that has been frothed up by escaping gases and solidified during eruptive cooling. Rhyolitic pumice is typically of low enough density that it floats on water.

Pyroclastic.
General term applied to volcanic products or processes that involve explosive ejection and fragmentation of erupting material. The Greek roots mean "fire" and "broken."

Pyroclastic flow.
A hot (typically >800 degrees C), chaotic mixture of rock fragments, gas, and ash that travels rapidly (tens of meters per second) away from a volcanic vent. Pyroclastic flows that form from an explosive eruption column contain a high proportion of fine ash and pumice and are sometimes called ash flows or ignimbrites. Pyroclastic flows that form by failure of the front of a cooling lava dome or flow are called block and ash flows.

Rhyodacite.
Volcanic rock with 68% to 72% silica (see silica). Rhyodacitic lavas are viscous and tend to form thick blocky lava flows or steep-sided piles of lava called lava domes. Rhyodacite magmas tend to erupt explosively, commonly also producing abundant ash and pumice.

Rhyolite.
Volcanic rock with more than 72% silica (see silica). Rhyolitic lavas are viscous and tend to form thick blocky lava flows or steep-sided piles of lava called lava domes. Rhyolite magmas tend to erupt explosively, commonly producing abundant ash and pumice.

Scoria.
Vesicular volcanic ejecta, essentially magma that has been frothed up by escaping gases. It is a textural variant of pumice, with scoria typically being less vesicular, denser, and usually andesitic or basaltic.

Silica.
Silica is SiO_2, the predominant molecular constituent of volcanic rocks and magmas. It tends to polymerize into molecular chains, increasing the viscosity of the magma. Basaltic magma having lower SiO_2 is fairly fluid, but with increasing contents of SiO_2, andesite, dacite, rhyodacite, and rhyolite magmas become progressively more viscous. The greater difficulty for dissolved gas to escape from more viscous magma makes higher-silica magmas generally more explosive.

Silicic magma.
Magma that contains more than ~63% silica and is generally viscous, gas-rich, and tends to erupt explosively. Includes rhyolite, rhyodacite, and dacite in the Katmai cluster.

Stratocone.
A steep-sided volcano, usually conical in shape if there is one central vent, built of lava flows and fragmental deposits from many periods of eruptive activity. Also called a stratovolcano or composite cone.

Tephra.
Any type and size of rock fragment that is forcibly ejected from the volcano and travels an airborne path during an eruption (ash, bombs, scoria, cinders, etc.). Generally synonymous with fallout, but sometimes used more loosely to embrace pyroclastic-flow material as well.

Tsunami.
Seismic sea waves typically initiated by sudden displacements of the sea floor during earthquakes. Collapse of oceanic volcanoes can initiate some tsunamis.

Vent.
Any opening at the earth's surface through which magma erupts or volcanic gases are emitted.

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