The 2006 Eruption of Augustine Volcano, Alaska
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Chapter 11

Characterizing Pyroclastic-Flow Interactions with Snow and Water Using Environmental Magnetism at Augustine Volcano

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Abstract

In-place measurements of environmental magnetic susceptibility of pyroclastic flows, surges and lahars emplaced during the 2006 eruption of Augustine Volcano show that primary volume magnetic susceptibilities of pyroclastic materials decreased where the flows encountered water and steam. The Rocky Point pyroclastic flow, the largest flow of the eruption sequence, encountered a small pond near the north coast of Augustine Island where local interactions with water and steam caused susceptibilities to decrease from $1,084\pm128\times10^{-5}$ SI to $615\pm114\times10^{-5}$ SI. Ash produced during phreatic explosions and pyroclastic surges that crossed snow also produced deposits with reduced susceptibilities, while lahar deposits derived from pyroclastic flows showed even greater reductions in susceptibility ($430\pm129\times10^{-5}$ SI). The susceptibility reductions are probably largely attributable to oxidation of iron in magnetite and other minerals within the pyroclastic flows, although other physiochemical processes may play a role. Measurements of the magnetic properties of pyroclastic flows, surges, and lahar deposits can be a useful tool in understanding the processes that occur when pyroclastic flows encounter ice, snow, and water and interact with water and steam on the slopes of active volcanoes.

Introduction

The interactions that occur between pyroclastic flows and snow, ice, and water are of considerable interest to volcanologists because these processes sometimes generate floods and lahars that cause destruction and fatalities in areas far beyond the maximum extent of the pyroclastic flows themselves. For instance, the 1985 eruption at Nevado del Ruiz Volcano in the Andes Mountains of Colombia generated pyroclastic flows and surges that were restricted to the upper reaches of the volcano, far from any human habitation. However, the pyroclastic eruption melted snow and ice over part of the summit ice cap and generated devastating mudflows that traveled as far as 100 kilometers down stream valleys. These lahars traveled down the Río Lagunillas and caused an estimated 23,000 fatalities at the town of Armero, where local people had had little comprehension of the risks from the Ruiz eruption (Pierson and others, 1990).

The lahar and flood deposits produced by interactions between pyroclastic flows and glaciers, snowfields, and bodies of water have attracted much attention since the catastrophic Ruiz eruption. For instance, during the eruptions of Ruapehu Volcano in New Zealand in 1994–95 and 2005–6, interactions of pyroclastic material and snow became a focus of concern. Lahars that traveled downslope after explosive events at the summit were observed during emplacement, and their deposits were intensively studied (Cronin and others, 1997). Unfortunately, once again it proved difficult to observe and study active surges and pyroclastic flows and the processes that occur during their encounters with snow and ice, because the active vents are extremely hazardous to approach during eruptions, and because these kinds of eruptions and processes typically produce large clouds of ash, gas, and steam that hide the ground-level interactions. As a result, the processes involved in the generation of lahars and floods by pyroclastic flows are still poorly understood.

The 2006 eruption of Augustine Volcano provided an excellent opportunity to study pyroclastic-flow and surge deposits that had encountered ice, snow, and water, as well as associated lahar deposits resulting from those interactions. Comprehensive sedimentological and stratigraphic studies of the pyroclastic-flow and lahar deposits produced in 2006 at Augustine Volcano showed that such interactions were complex and varied. Some pyroclastic flows traveled across snowfields with little obvious effect on the sedimentology of

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the pyroclastic flow deposits, while others crossed areas of snow and were locally modified and transformed into mixed rock-and-snow avalanches, lahars, and water-rich floods (Vallance and others, this volume).

In this paper, we present tests of a new geophysical technique that we believe has great promise as a means to identify and characterize pyroclastic-flow and surge deposits that have interacted with snow, ice, and water. Environmental magnetism is the study of interactions between environmental processes and the magnetic properties of sediments (Evans and Heller, 2003). Studies of environmental magnetism often focus on changes in magnetic susceptibility, because this geophysical characteristic of sediments is relatively easily measured and has been shown to undergo significant changes in response to various environmental factors and depositional processes (Maher and Thompson, 1999). We have followed this approach and focused on magnetic susceptibility in this study.

Pyroclastic-flow deposits that have interacted with snow, ice, and water are good candidates for this kind of study, because the initial magnetic susceptibility of volcanic rocks and volcanic ash deposits produced by explosive eruptions elsewhere in Alaska have been shown to be relatively high, indicating the presence of abundant susceptible iron-bearing minerals (Begét and others, 1994). However, to our knowledge, no prior studies of the changes in magnetic susceptibility of pyroclastic deposits due to interactions with water and steam have ever been undertaken. Searches on Google Scholar and GeoRef found no record of scientific papers on this subject, and recent academic textbooks on environmental magnetism (Evans and Heller, 2003) and volcanology (Schmincke, 2004) contain no references to this kind of investigation.

This paper presents the results of several hundred measurements of magnetic susceptibility on fresh, in place, deposits of the 2006 pyroclastic flows on the flanks of Augustine Volcano, as well as measurements on more areally restricted surge and lahar deposits. The purpose of this paper is not to descriptively characterize the magnetic mineralogy and magnetic characteristics of the 2006 deposits, but to report on the initial development and field-testing of a new geophysical approach that can quickly and quantitatively characterize a key geophysical property of pyroclastic-flow deposits that records evidence of past interactions with water and snow.

2006 Pyroclastic Flows and Related Deposits on the North Flank of Augustine Island

The 3-month-long eruption at Augustine Volcano in 2006 involved a variety of different eruptive mechanisms and produced a wide array of pyroclastic and secondary deposits (Coombs and others, this volume; Vallance and others, this volume). Explosive activity began on January 11, 2006, and more than a dozen discrete Vulcanian blasts occurred in the next 20 days, generating ash fall, pyroclastic flows, mixed avalanches of snow, ice, and rock, and lahars. On January 28, the eruption moved into a more continuous eruptive phase as rapid effusion of lava led to vigorous block-and-ash-flows. A summit lava dome began to form in early February, and, after a pause from February 10 to March 2, two short, blocky lava flows were emplaced by late March. The initial period of explosions, lasting from January 11 to January 28, is referred to as the explosive phase, while eruptive events occurring from January 28 to February 10 are considered to be part of the continuous phase, and all subsequent activity is part of the effusive phase (Power and others, 2006; Coombs and others, this volume).

On January 27, 2006, near the end of the explosive phase, a discrete several-minute-long explosive event (event 10 in the nomenclature of Vallance and others, this volume) deposited the Rocky Point pyroclastic flow on the north flank of the volcano (fig. 1). This flow is the most voluminous of any single flow produced during the eruptive sequence, totalling 17 million m^3 (Coombs and others, this volume). It traveled almost to sea level on the north side of Augustine Island and buried earlier 2006 pyroclastic flows on the north flank of the volcano (fig. 2).

The distal portion of the Rocky Point pyroclastic flow nearly reached the coast, traveling over a small pond of water. The pond lay at 25 m above sea level (asl) and was approximately 50 m in diameter. The pond is partly surrounded by hummocks of the late 19th century Burr Point debris-avalanche deposit and the older Rocky Point debris-avalanche deposit (Begét and Kienle, 1992; Siebert and others, 1995) and likely was formed during one of these events. The 2006 Rocky Point pyroclastic flow completely filled the lake basin with pyroclastic debris. This pyroclastic flow also generated small, relatively dilute ash-cloud surges that traveled short distances beyond the lateral margins of the pyroclastic flow and singed alders and other vegetation around the former shoreline of the pond, leaving well-sorted sandy ash deposits.

The initial magmatic explosive events early in January that marked the beginning of the explosive phase occurred when Augustine Volcano was completely covered with winter snow. These explosions generated pumiceous pyroclastic flows, snow avalanches, and lahars that moved down all sides of the volcano (Vallance and others, this volume). By the time the Rocky Point pyroclastic flow was emplaced on January 28, much of the winter snowpack on the volcano had been removed or buried by the earlier pyroclastic flows. The snow was almost completely gone when block-and-ash flows, emplaced during the later continuous phase, subsequently buried the uppermost parts of the Rocky Point pyroclastic flow (Coombs and others, this volume).

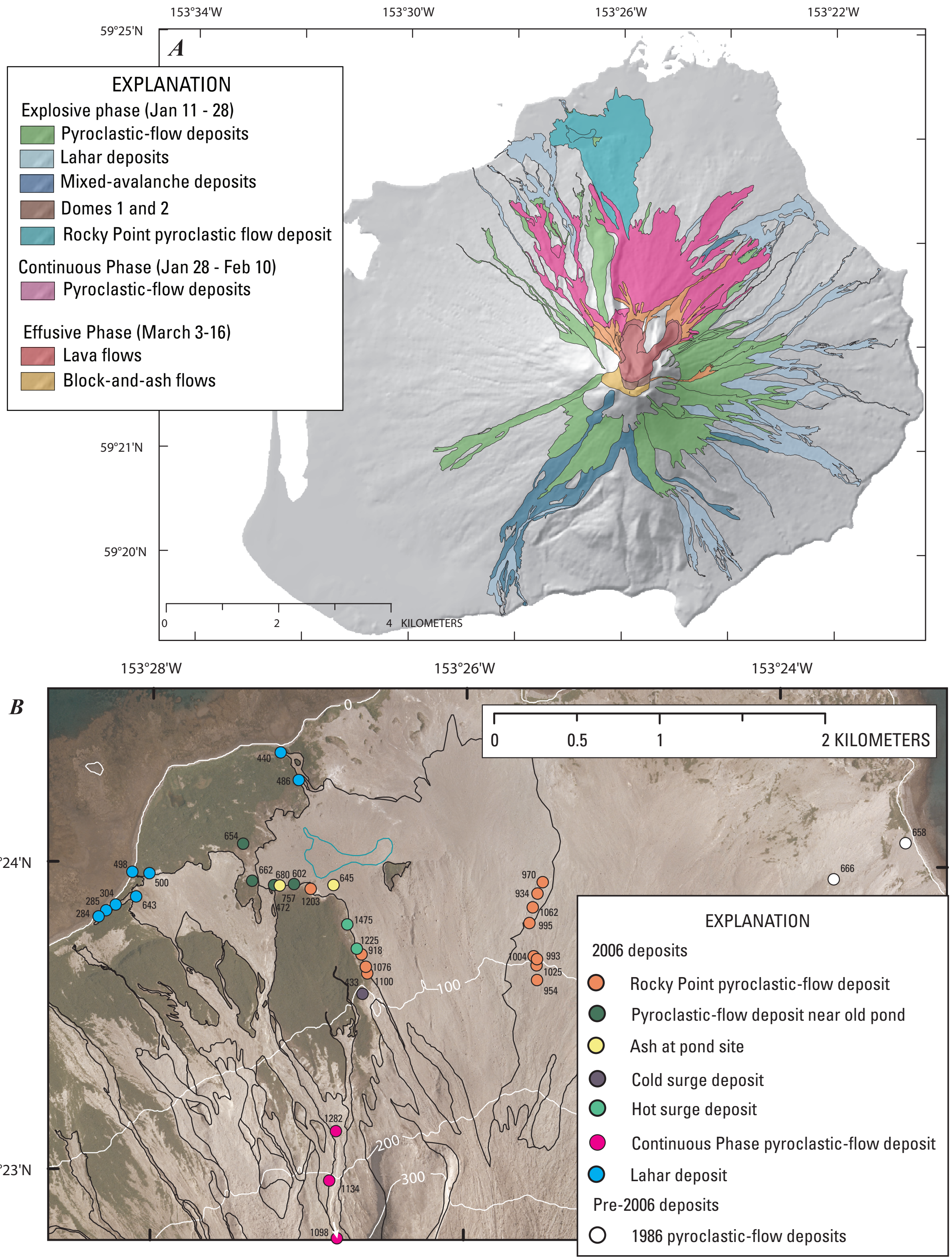
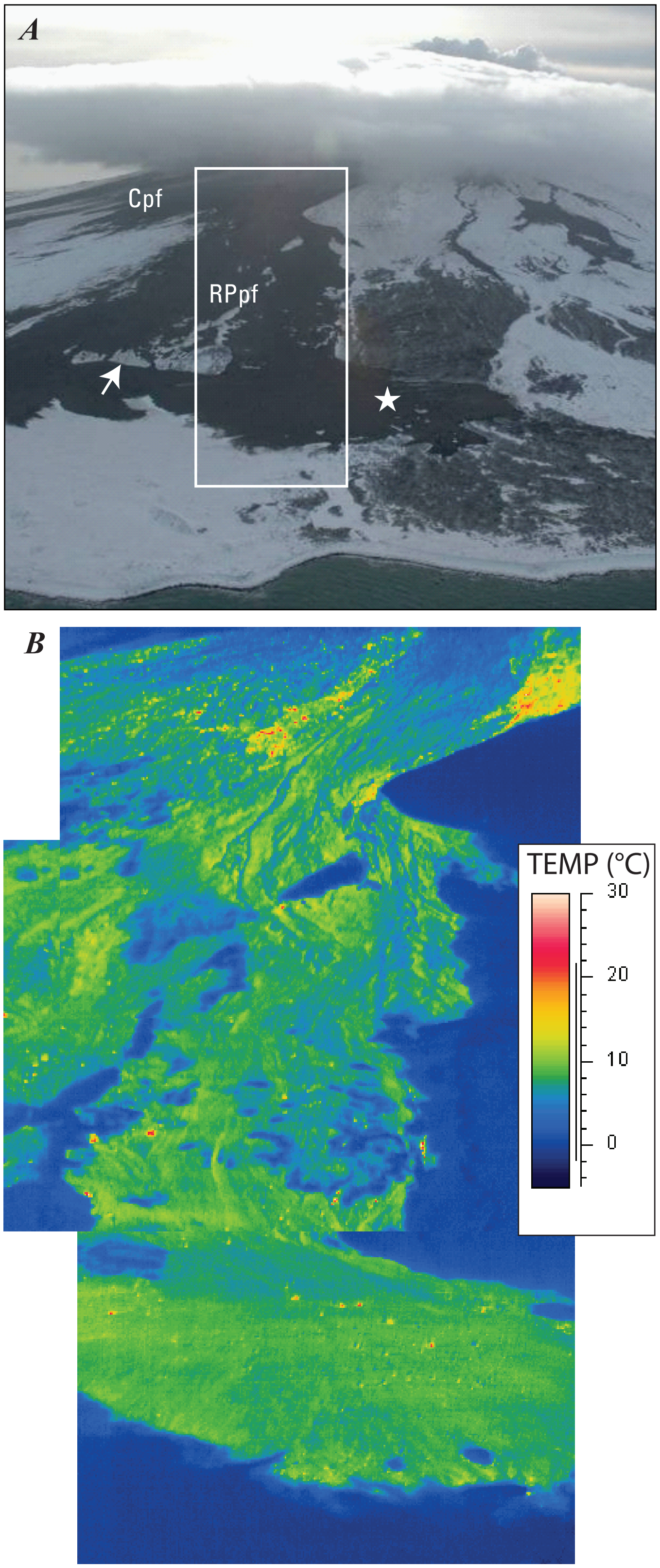


Figure 1. Generalized maps showing deposits from the 2006 eruption of Augustine Volcano on Augustine Island. *A,* Distribution of deposits from the 2006 eruption draped over shaded-relief map of Augustine Island, modified from Coombs and others (this volume). *B,* Sample locations for this study on the north flank of Augustine Volcano, overlain on an orthophoto taken July 12, 2006. Outlines of contiguous 2006 deposits are shown in black. The general outline of the small pond buried by the Rocky Point pyroclastic flow, as mapped in July 2006 by Begét, is shown in light blue, and100-m contours shown in white. Some 2006 deposits were sampled in fresh exposures in a small channel 170 m east of the region of contiguous flows and a few sites were sampled on 1986 pyroclastic flows (see text for detailed discussion).

Magnetic Susceptibility of Pyroclastic Flows, Surges and Lahars at Augustine Volcano



Augustine Volcano produced a wide range of pyroclastic deposits during the 2006 eruption. This study targets the Rocky Point pyroclastic flow deposit because it provides an almost ideal opportunity to test the hypothesis that measurements of magnetic susceptibility can provide a quantitative tool for identifying and characterizing pyroclastic deposits that have been in contact with snow, ice, and water. We also present some results from lahars, from pyroclastic flows on the north flank that were produced during the later continuous phase of the eruption and from 1986 Augustine pyroclastic flow deposits.

Magnetic susceptibility is a basic geophysical property of all rocks and sediments. Magnetic susceptibility can be measured on a mass, molar, or volume basis. It is determined by measuring the effect of an applied magnetic field of known strength on a sample. The ease of magnetization of the sample is a complex function of the concentration, size, shape, and mineralogy of magnetizable material in the sample. Most of the susceptibility signal in volcanic rocks typically reflects the presence of common ferromagnetic minerals, such as magnetite, hematite, and iron-titanium oxides, with a minor contribution from other ferromagnesian minerals that contain relatively small amounts of Fe^{2+}, Fe^{3+}, or Mn^{2+} such as olivine, amphiboles, and pyroxenes.

Field measurements of volume magnetic susceptibility of the 2006 deposits at Augustine Volcano were made with a Bartington MS2 susceptibility meter and an MS2F microprobe. A small amount of sample preparation, including the excavation of small pits, was done in this study to standardize the sampling process, but the volume magnetic susceptibility measurements themselves are nondestructive. When measuring volume susceptibility, the MS2 meter has a sensitivity of 2×10^{-6} SI, with a range from $1–9999\times10^{-5}$ SI, and a resolution of 2×10^{-6} SI in standard mode. The Bartington instrument has become an international standard for environmental susceptibility measurements and records data in dimensionless volume susceptibility units, which are multiplied by 10^{-5} to convert susceptibilities into SI units (Bartington Corporation, 2004).

◄**Figure 2.** Views of recently emplaced pyroclastic flow deposits, February 8, 2006. *A,* Oblique aerial photograph of Augustine's north flank, showing the Rocky Point pyroclastic flow (RPpf) and the overlying Continuous Phase pyroclastic flow fan (Cpf). The Rocky Point flow was bifurcated by a low ridge (white arrow). Westernmost lobe of the Rocky Point flow crossed and filled in a small lake (star). Box shows approximate area of panel B. Photo by M. Coombs, USGS. *B,* Thermal infrared image mosaic showing close up of Rocky Point deposit. Images by D.J. Schneider, AVO.

The Bartington M2SF microprobe is designed for use in geologic studies. The probe has a diameter of 15 mm and measures volume susceptibility in a small region of the sample immediately beneath the probe. In order to take a measurement the probe is placed on the sample and activated. The instrument then applies a magnetic field and measures the sample response, with about 90 percent of the susceptibility signal coming from the upper few millimeters of the sample, where the magnetic field projected by the probe is strongest (fig. 3). The MS2F microprobe proved to be ideal for field studies of the pyroclastic-flow deposits because the knowledge that 90 percent of the susceptibility response is obtained from a restricted area within a few millimeters of the MS2F probe allows the operator to precisely control what the instrument is measuring, even in field settings. For this study the goal was to effectively measure the susceptibility of the matrix of pyroclastic-flow deposits, so the probe was placed directly on exposures of the well-sorted and finer grained pyroclastic flow matrix visible between clasts in the pyroclastic flow deposits. Voids or lithic clasts hidden beneath the surface of the area chosen for the matrix sampling have a negligible influence on volume susceptibility measurements, as long as they were buried more than approximately 2 cm below the surface, or if they were more than 1 cm away from the outside edges of the MS2F microprobe (fig. 3).

Several different sampling methods were tested during this study. Initially, shallow pits and trenches approximately 50 cm deep were excavated into the tops of pyroclastic flow deposits and into the sides of associated levees, and the MS2F microprobe was then inserted into the pit for the measurement. Subsequent measurements were taken on smoothed surfaces cut only a few centimeters into the surface of massive pyroclastic flow deposits and levees to expose the matrix of the deposits, and in some cases directly on the hardpan surface of indurated pyroclastic flow deposits. After each measurement, the surface was excavated to check if voids or blocks were present just below the surface of the prepared site. No significant differences in susceptibility were observed among any of the various sampling strategies as long as the excavations and natural surfaces measured were flat and smooth.

Component analysis of the 2006 pyroclastic flow deposits revealed that they contain several different lithologies and that the relative percentages of the different lithologies changed through the course of the 2006 eruption (Vallance and others, this volume). All of the magnetic susceptibility values discussed in this paper, unless specifically noted otherwise, are from the Rocky Point pyroclastic flow, which was erupted during a short time interval and has broadly similar proportions of lithic components throughout its extent (Vallance and others, this volume). The susceptibility of the two major lithic components in the Rocky Point pyroclastic-flow deposit was measured directly on representative lithic blocks and showed that different rock types produced during the 2006 eruption have dramatically different susceptibilities (table 1). Low-silica andesite scoria and dense clasts have susceptibilities between 1,200–1,700×10^{-5} SI, while friable and moderately vesicular

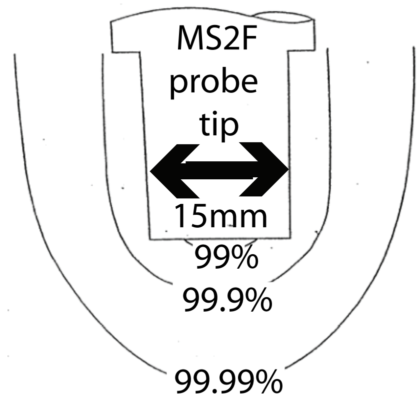


Figure 3. An isomagnetic field plot showing the rapid decrease in sensitivity of the M2SF field probe with distance from the tip of the instrument. The probe tip is 15 mm in diameter and has a maximum sensing distance of 15-20 mm, but the instrument is highly sensitive to the magnetic susceptibility of sample material just below and within a few millimeters of the center of the probe tip, so that 99% of the measured signal comes from material directly beneath the probe, and 99.9% of the signal is measured within a few millimeters of the probe. This property of the instrument makes it feasible to accurately measure the volume susceptibility of pyroclastic flow deposit matrices, as long as no voids or large lithic clasts are present within a few millimeters of the base of the probe. Figure modified from the Bartington M2S system operating manual (Bartington Corporation, 2004).

high-silica andesite "cinderblock" clasts (Vallance and others, this volume) have volume susceptibilities of 700–1,200×10^{-5} SI. The Rocky Point pyroclastic flow deposit consists mainly of high-silica andesite, with clasts of low-silica andesite being present as a secondary component. The large difference in the susceptibility measured between the two principal lithologies suggests that the volume susceptibility of the pyroclastic flow will be strongly influenced by the relative proportion of these two major components within the deposit. Component analysis of different size fractions of the Rocky Point pyroclastic flow found that similar percentages of the major components were present from the coarsest to the finest grain sizes of the pyroclastic flow (Vallance and others, this volume), suggesting that susceptibility measurements of the matrix of the pyroclastic flow deposit are a good approximation of the susceptibility of the entire pyroclastic flow deposit.

The Rocky Point pyroclastic flow traveled down the volcano's north flank, where previous explosive events had deposited pyroclastic flows and cleared the surface of snow (Coombs and others, this volume; Vallance and others, this volume). Measurements taken from different places on the Rocky Point deposit yielded generally similar magnetic susceptibilities of 900–1,400×10^{-5} SI. The repeatability of the susceptibility measurements taken at each site was good, with values of one standard deviation from the mean typically falling no more then 10–20 percent from the average value for the entire group of susceptibility measurements. The

Table 1. Magnetic susceptibility measurements of the Rocky Point pyroclastic flow and associated deposits from the 2006 eruption of Augustine Volcano.

Station Number	Elevation (meters)	Latitude (north)	Longitude (west)	Magnetic suscepti-bility[1]	1σ[2]	N[3]	Deposit type
Rocky Point pyroclastic-flow deposit							
06AUJEB45	84	59.394	153.444	1100	63	10	PF[4] 1evee ridge with pink top
06AUJEB46	79	59.394	153.444	1076	82	9	PF body
06AUJEB47	76	59.395	153.444	918	83	5	Pink top in PF body
06AUJEB40	52	59.398	153.426	1062	83	4	PF body matrix
06AUJEB41	40	59.398	153.426	934	42	3	PF matrix
06AUJEB42	34	59.399	153.425	970	49	4	Flow terminus lobe
06AUJEB35	116	59.394	153.426	954	91	4	PF matrix
06AUJEB36	91	59.395	153.426	1025	1	5	PF matrix
06AUJEB37	88	59.395	153.426	1004	211	4	PF matrix
06AUJEB38	85	59.395	153.426	993	9	5	PF matrix
06AUJEB39	61	59.397	153.427	995	49	5	PF matrix
06AUJEB52	23	59.399	153.450	1203	30	6	PF matrix upslope of pond
06AUJEB40A	49	59.401	153.429	1240	119	6	Fines-depleted matrix
Rocky Point pyroclastic-flow deposit, in or adjacent to pond							
06AUJEBJA	30	59.399	153.454	472	43	5	Pink oxidized phreatic ash
06AUJEBJ	23	59.399	153.454	757	35	6	Pink oxidized PF matrix
06AUJEB51	23	59.399	153.448	645	84	6	Fine pink ash in collapse pit
06AUJEB51A	23	--	--	443	95	4	Fine pink ash in pond phreatic explosion pits
06AUJEB51B	23	59.399	153.456	662	49	8	PF matrix
06AUJEB51C	23	59.401	153.457	654	19	11	PF matrix, thin in bushes
06AlJ.JEB88	21	59.399	153.452	802	50	5	Pinkish PF in pond
06AUJEB89	19	59.399	153.452	602	37	7	Reddish oxidized PF in pond
06AUJEB90	14	59.399	153.453	680	24	5	Pink phreatic ash in pond
06AUJEB40B	46	59.3995	153.453[5]	907	55	6	Lower PF beside pond
06AUJEB40C	46	59.3995	153.453[5]	1200	14	2	PF around burned spruce
06AUJEB42A	30	--	59.399[5]	1299	25	5	PF 100 m from pond
Surge deposits associated with Rocky Point pyroclastic flow							
06AUJEB44	109	59.393	153.444	433	41	7	Cold surge
06AUJEB44A	101	59.3935	153.444[5]	1025	94	3	Distal ash cloud
06AUJEB44B	87	59.3935	153.444[5]	1166	127	6	Intermediate surge depos
06AUJEB48	71	59.395	153.445	1225	63	6	Proximal surge deposit
06AUJEB49	49	59.397	153.446	1475	308	4	Coarse proximal surge
06AUJEB51	23	59.399	153.448	1084	33	3	Ash cloud from surge
06AUJEB51A	14	59.3995	153.448[5]	827	45	3	Gray surge deposit
Continuous phase pyroclastic-flow deposit on northwest flank							
06AUJEB2	278	59.379	155.447	1098	8	2	PF matrix
06AUJEB2A	287	59.379	155.447	989	9	2	PF matrix
06AUJEB2B	314	59.379	155.447	1058	134	4	PF matrix
06AUJEB3	213	59.383	153.448	1134	30	2	PF matrix
06AUJEB4	170	59.385	153.447	1282	35	2	PF levee

Table 1. Magnetic susceptibility measurements of the Rocky Point pyroclastic flow and associated deposits from the 2006 eruption of Augustine Volcano.—Continued

Station Number	Elevation (meters)	Latitude (north)	Longitude (west)	Magnetic suscepti-bility[1]	1σ [2]	N[3]	Deposit type
2006 lahar deposits							
06AUJEB59	14	59.398	153.468	643	21	3	Lahar clasts
06AUJEB91	12	59.399	153.467	500	18	7	Lahar matrix
06AUJEB53	6	59.404	153.451	486	17	10	Lahar matrix
06AUJEB60	2	59.398	153.470	304	54	11	Lahar matrix
06AUJEB93	1	59.399	153.469	498	23	8	Lahar matrix
06AUJEB55	1	59.406	153.453	440	23	10	Lahar matrix
06AUJEB61	1	59.397	153.472	284	22	10	Lahar matrix
06AUJEB62	0.5	59.397	153.472	285	114	10	Lahar matrix
Individual clasts from 2006 pyroclastic-flow deposits							
06AUJEB45	84	59.394	153.444	1517	93	6	Low-silica andesite
06AUJEB35	116	59.394	153.426	1288	56	3	Low-silica andesite bomb
06AUJEB35	116	59.394	153.426	761	28	3	High-silica andesite
06AUJEB2A	287	59.379	155.447	1203	0	1	High-silica andesite
06AUJEB2A	287	59.379	155.447	989	9	2	Boulder in PF matrix
06AUJEB2B	314	59.379	155.447	1150	0	1	Prismatic boulder
1986 pyroclastic-flow deposits							
06AUJEB57	26	59.399	153.394	666	50	8	1986 PF
06AUJEB58	9	59.401	153.387	658	18	11	1986 PF matrix samples
06AUJEB58A	6	59.401	153.387	672	94	11	1986 PF matrix

[1]Reported magnetic susceptibility values are averages of N measurements.

[2]σ is the standard deviation of the averaged magnetic susceptibility measurements.

[3]N is the number of individual magnetic susceptibility measurements at each station.

[4]PF is an abbreviation for pyroclastic-flow deposit.

[5]Measurements made on traverses downhill from the first station in the series.

variation in the entire data set of susceptibility measurements for the Rocky Point pyroclastic flow deposit is somewhat larger (table 1), and is thought to reflect variations in the initial componentry of these deposits.

Susceptibility Measurements Along a Traverse at the Margin of the Rocky Point Pyroclastic Flow Deposit

The pyroclastic flow deposits emplaced in 2006 on the north side of Augustine Volcano partially buried a preexisting pyroclastic fan that has been developing since 1883 (Waitt and Begét, 2009). On the lower part of the pyroclastic fan, the Rocky Point pyroclastic flow deposit is bordered on its western edge by a much older lava flow. On its western margin against the lava flow, the Rocky Point pyroclastic flow developed flat terraces and a levee that could be traced for hundreds of meters downslope. Alder trees and soil buried by the Rocky Point pyroclastic flow were charred and incinerated, showing that the pyroclastic flow was hot in this area (fig. 4).

In order to better understand the sources of variation in magnetic susceptibility, measurements were made at eight separate sites during a 1-km-long traverse along the western margin of the Rocky Point pyroclastic flow (fig. 1). The averages of all of these measurements ranged from 937 to $1,061\times10^{-5}$ SI, indicating that much less variability in magnetic susceptibility occurs in this particular region of the pyroclastic flow than was seen in the complete data set from the Rocky Point pyroclastic flow and the subsequent flows of the continuous phase (fig. 5). The small range of susceptibilities measured from this one part of the Rocky Point pyroclastic flow supports our suggestion that the susceptibility within the lithic components of each flow strongly influences the matrix magnetic susceptibility. The greater variability within the entire set of susceptibility measurements for the Rocky Point pyroclastic flow and later pyroclastic-flow deposits is therefore thought to reflect a small amount of variability in the relative abundances of the constituent components occurring through the entire pyroclastic flow (fig. 6).

Continuous-Phase Pyroclastic Flow Deposits

Measurements of magnetic susceptibility were also made on pyroclastic flow deposits produced during the continuous phase of the 2006 eruption (Coombs and others, this volume). Numerous block-and-ash flows, erupted from January 28 to February 10, are found on the upper parts of the pyroclastic fan on the north side of Augustine volcano, where they bury the slightly older Rocky Point pyroclastic flow deposit. Magnetic susceptibility measurements were made on continuous-phase pyroclastic flow deposits on both the east and west sides of the pyroclastic fan. These values ranged between 917×10^{-5} SI and $1{,}282\times10^{-5}$ SI, similar to the susceptibility measurements made on the Rocky Point pyroclastic flow deposits. Studies of the lithic makeup of deposits of the continuous phase found mostly a mixture of high-silica andesite and intermediate andesite clasts and banded clasts, with only minor amounts of greenish porphyritic andesite. The measured susceptibilities in the continuous-phase pyroclastic flow

Figure 4. The 2006 Rocky Point pyroclastic flow traveled down the north side of Augustine Island and flowed into a small pond. Yellow rucksack is 80 cm tall.

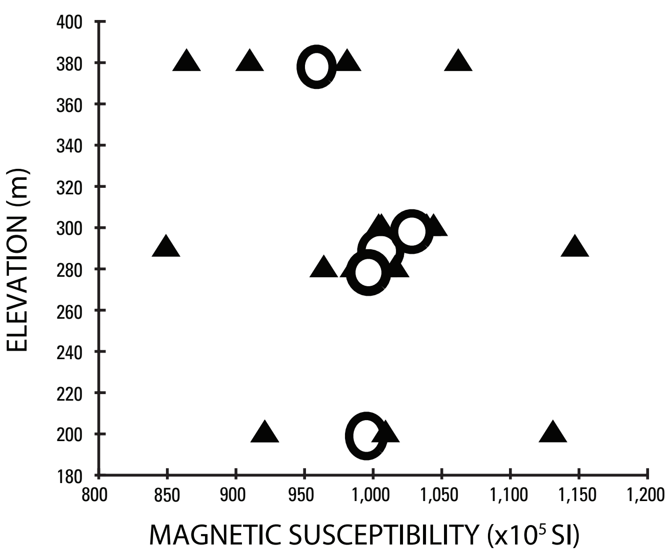


Figure 5. Magnetic susceptibility of the Rocky Point pyroclastic flow measured within a single channel along a 1.5-km-long traverse at five sites between 380 m and 200 m elevation. Multiple measurements were taken at each site. Triangles on the plot show the value of the individual magnetic susceptibility measurement, while large open circles show the mean value calculated for each site. The average susceptibilities were nearly identical at all sites along the traverse.

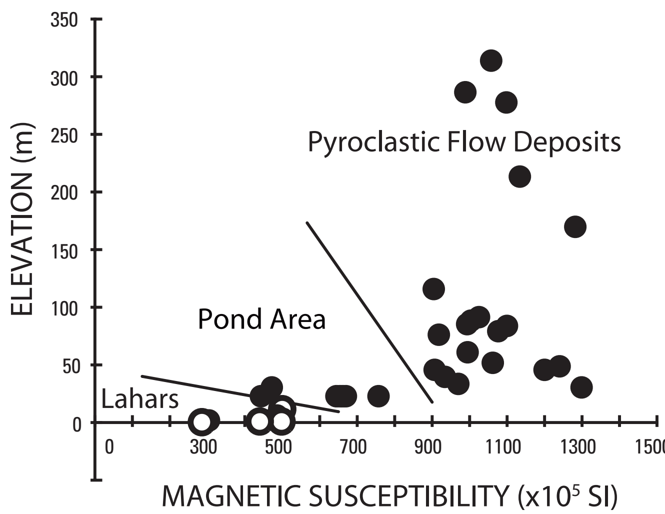


Figure 6. Average volume magnetic susceptibilities of 2006 Rocky Point pyroclastic flow deposits (solid circles), measured on the slopes above the pond site and at the pond site, and lahar deposits (open circles) measured in stream channels. The susceptibilities of the pyroclastic flow deposits in the former pond area were notably lower than those of other pyroclastic flow deposits, and lahar deposits were characterized by similarly low or even lower magnetic susceptibilities.

deposits probably reflect variations in the componentry of the deposits at different localities, just as was seen in the Rocky Point pyroclastic flow deposits.

Interaction of Rocky Point Pyroclastic-Flow Deposits with Water and Steam

The volume magnetic susceptibility of Rocky Point pyroclastic flow deposits decreased significantly where the Rocky Point flow encountered a small pond on the north side of Augustine Volcano (figs. 1, 2). As discussed above, the magnetic susceptibility of pyroclastic flow deposits determined at numerous sites above the pond ranged from ca. 900×10^{-5} SI to 1300×10^{-5} SI. A virtually identical range of susceptibility values was obtained from measurements on the Rocky Point pyroclastic flow deposits in areas immediately adjacent to the pond (table 1). For instance, at a site just 25 m from the pond, where the flow had partially buried alders and burned them (fig. 7), the averaged volume susceptibility of the Rocky Point pyroclastic flow deposit was 1203×10^{-5} SI. This value is indistinguishable from susceptibility measurements taken farther upslope and demonstrates that no significant changes were observed in the susceptibility of the pyroclastic flows as a result of travel distance or elevation loss anywhere throughout the Rocky Point pyroclastic flow deposit above the pond area (fig. 6).

The susceptibility of the Rocky Point pyroclastic flow deposit decreases abruptly where it encountered water at the pond site. During fieldwork in August 2006, the former pond site was found to be filled with the Rocky Point pyroclastic flow deposits but was still easily recognizable as a round, flat local depression in the deposit surface. While rootless fumaroles were rare within the Rocky Point pyroclastic deposit at lower elevations, several small rootless fumaroles were still active in this area, suggesting some moisture might still be present below the former pond surface (fig. 8).

The susceptibility values measured on the flow-deposit matrix around the pond basin ranged from 756×10^{-5} SI to 802×10^{-5} SI, or about 10 to 40 percent lower than the susceptibility of Rocky Point pyroclastic flow deposits or the later, continuous-phase pyroclastic flow deposits found higher on the north side of Augustine Volcano (table 1). The abrupt decrease in magnetic susceptibility observed in Rocky Point pyroclastic flow deposits filling the pond basin suggests that interactions between the hot pyroclastic flow and water and steam produced significant reductions in the initial susceptibility of the pyroclastic flow deposit.

Phreatic Ash and Other Deposits near the Pond

Multiple small craters in the surface of the pyroclastic flow deposits within the pond area, ranging from approximately 1 to 3 m in diameter (fig. 8), show that small phreatic explosions occurred in this area during or soon after the pyroclastic flows entered the pond. These explosion craters are mantled with as much as 10 cm of pink, silt-size ash derived from material elutriated from the 2006 pyroclastic flow

Figure 7. Photograph showing Rocky Point pyroclastic flow deposit on the north flank of Augustine Volcano. The presence of charred alders and soil in a lateral levee of the Rocky Point pyroclastic flow deposit 50 m from the pond area indicates that the flow was still hot when it reached the pond area. Rucksack in photo (indicated by arrow) is 0.8 m in length.

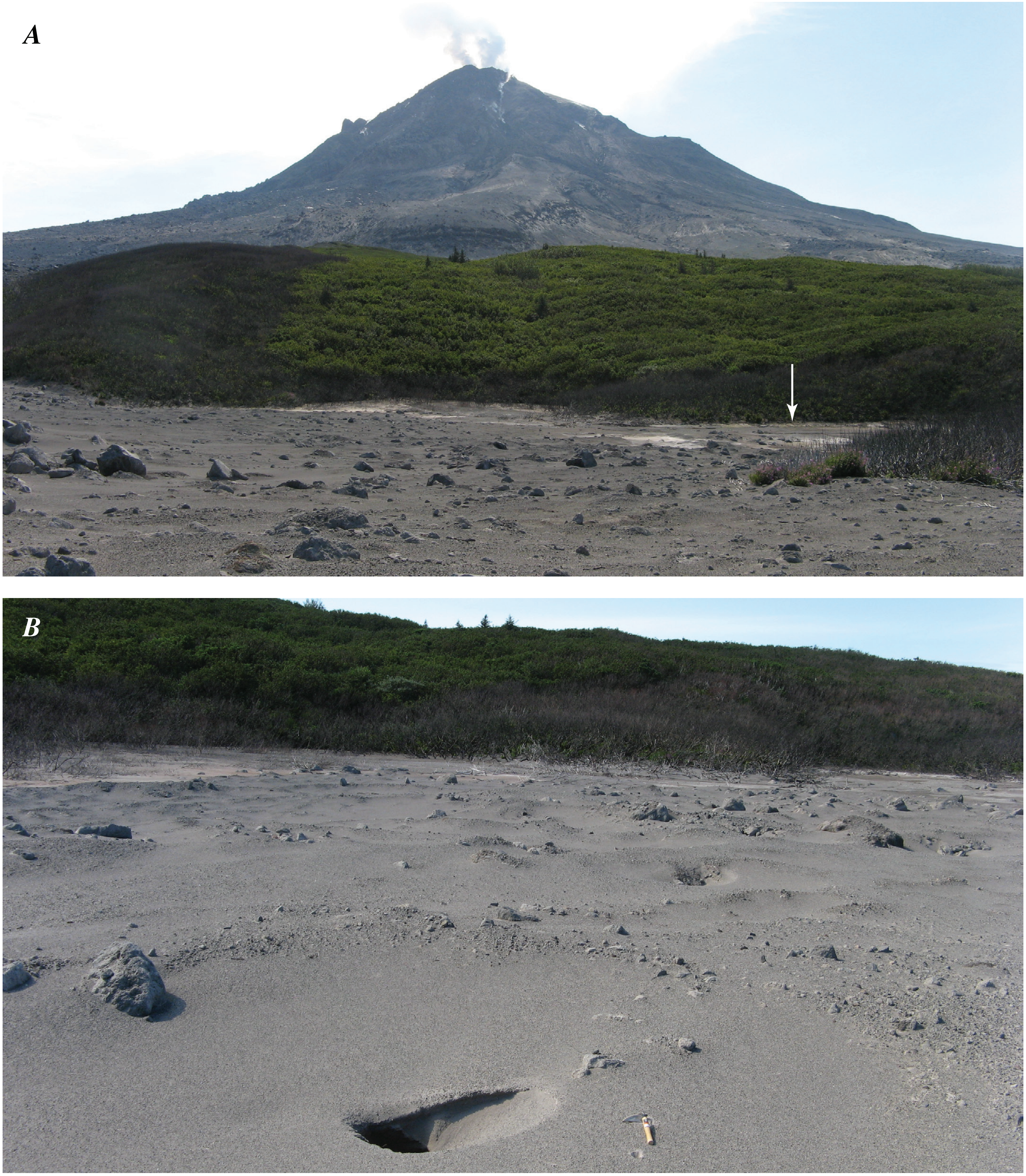


Figure. 8. Photographs of the Rocky Point pyroclastic flow. *A,* View looking south at the area of the pond filled by deposits of the 2006 Rocky Point pyroclastic flow. The Rocky Point pyroclastic flow traveled downslope alongside the ridge at the left of the image, and filled a pond (arrow) at the base of the ridge. Note the area of dead alders along the ridge caused by ash-cloud surges from the pyroclastic flows. Two traverses through the deposits left by the ash-cloud surges were made about 800 m upslope. *B,* Small phreatic explosion craters (pseudocraters) and rootless fumaroles within the pond area. The tool next to the rootless fumarole in the foreground is 28 cm long.

deposits. The magnetic susceptibility of this ash is 482×10^{-5} SI, a value 50 to 70 percent lower than that of the unaltered Rocky Point pyroclastic flow deposits outside the pond area. The low magnetic susceptibility of the phreatic ash deposits in the pond area provides additional evidence that interaction with water and steam can produce significant reductions in the magnetic susceptibility of pyroclastic flow deposits.

The secondary phreatic explosion craters probably formed during very shallow explosions caused by rapid superheating of steam that produced locally overpressured conditions (Shepherd and Sigurdsson, 1982; Sheridan and Wohletz, 1983; Schmincke, 2004). The phreatic ash generated in these explosions was probably originally part of the matrix of the pyroclastic flow that interacted with water and steam as the pyroclastic flow travelled into the pond. The ash underwent an additional period of interaction with steam during the phreatic explosion as local pockets of water flashed to steam and blasted out the small craters. The additional interaction with steam during the phreatic explosions may account for the markedly lower susceptibility of the phreatic ash when compared to the matrix of the Rocky Point pyroclastic flow deposits in the same area.

Vertical Profiles Cut into the 1986 Pyroclastic Flow Deposits

Magnetic susceptibility measurements reported on 2006 pyroclastic flow deposits are from the upper parts of flows and the top and flanks of flow levees. These pyroclastic flow deposits, even in distal areas, were at least 1 m thick and were still hot 4–7 months after the eruption, so that it was not possible to safely excavate a trench completely through a 2006 pyroclastic flow deposit during this study in order to make susceptibility measurements from the top to the bottom of a pyroclastic flow deposit.

Eroded sections through 1986 pyroclastic flow deposits were found in three places beyond the limits of the 2006 pyroclastic flow deposits. Susceptibility measurements were made at 10-cm intervals from the top to the bottom through the three different 1986 pyroclastic flow deposits in order to investigate the possible variations in susceptibility with depth within pyroclastic flows (fig. 1). No significant variations in susceptibility with depth were found in any of the three 1986 pyroclastic flow deposits we studied (fig. 9). This suggests that the susceptibility measurements made in shallow surface trenches excavated into pyroclastic flow deposits are reasonably representative of the magnetic susceptibility of the matrix of the entire pyroclastic flow at any given site.

The 1986 pyroclastic flow deposits were characterized by significantly lower susceptibilities than all the 2006 pyroclastic flow deposits above the pond area.The field setting of the 1986 pyroclastic flow deposits indicated they had not interacted with water (table 1). Light gray dacite clasts make up the main variety of lithic blocks found in the 1986 pyroclastic flows (Waitt and Begét, 2009; Roman and others, 2006), and susceptibility measurements showed that these blocks were characterized by lower susceptibilities than either of the major lithic components of the 2006 Rocky Point pyroclastic flow deposits. This finding is consistent with the hypothesis presented above that the volume susceptibility of a pyroclastic flow deposit matrix primarily reflects the susceptibility and relative abundance of its major lithic components.Because component analyses of the 2006 Augustine pyroclastic flow deposits showed that their fine-grained matrix material consisted of comminuted rock material derived from the major coarse-grained components (Vallance and others, this volume), the susceptibility measurements on the 1986 deposits comprise a rapid proxy measurement of their componentry. Therefore, the significant differences in susceptibility found between the 1986 and 2006 deposits are an indication that susceptibility data can be used to map and differentiate separate groups of pyroclastic flow deposits.

2006 Rocky Point Pyroclastic Surge Deposits

Magnetic susceptibility measurements of surge deposits that had decoupled from the Rocky Point pyroclastic flow and traveled up a slope adjacent to the main pyroclastic fan were made along two traverses spaced about 50 m apart at a site ca. 800 m inland and 175 m higher than the pond area. At this locality the surge had singed alders within a few meters of the western margin of the Rocky Point pyroclastic fan, but it was unable to burn alders after traveling 100 m and 20–30 m

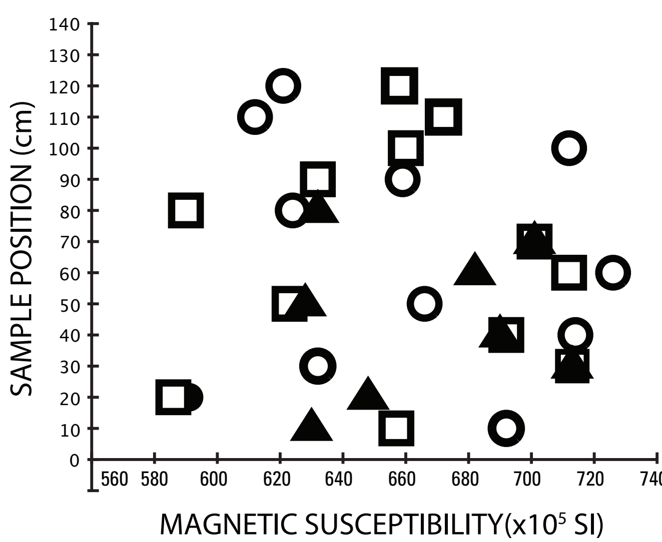


Figure 9. Vertical magnetic susceptibility profiles measured though three 1986 pyroclastic flow deposits.The measurements were taken at 10-cm intervals from the bottom to the top, with two flows (open circle and open square symbols) being ca. 1.3 m thick and one flow (solid triangle symbol) being ca. 1 m thick. No progressive changes or systematic pattern of susceptibility was noted in any of the three measured vertical profiles.Note that although the susceptibility measurements from each pyroclastic flow deposit showed small variations through the sections, the average susceptibilities (658 ×10^{-5} SI, 665 ×10^{-5} SI, and 671×10^{-5} SI) of the three 1986 flows were essentially identical.

higher up the slopes (table 1).These slopes were not affected by pyroclastic flows or floods before the Rocky Point eruptive event, and snow was probably present on these slopes and interacted with the pyroclastic surge as it traversed this slope up into the alder grove (Coombs and others, this volume). The ash-cloud surge deposits consisted of weakly bedded coarse sandy beds as much as 10 cm thick that thinned quickly and disappeared within 100 m of the western margin of the Rocky Point pyroclastic flow.

The susceptibility of the surge deposits immediately adjacent to the Rocky Point pyroclastic fan, in an area where the surge had burned alders, averaged $1,166\times10^{-5}$ SI, while the average volume susceptibility of deposits from the same surge at higher elevations, where they had cooled enough to not singe alders, was only 433×10^{-5} SI. The observed decrease in susceptibility is greater then 60 percent, i.e. much larger than the decrease in susceptibility observed downslope, where the Rocky Point pyroclastic flow traveled into the pond. The rapid and significant decrease in susceptibility measured over short distances in the ash cloud surge deposits adjacent to the Rocky Point pyroclastic flow deposit shows that the magnetic characteristics of pyroclastic surge deposits can change very rapidly. This contrasts strongly with the susceptibility data from the pyroclastic flows themselves, which showed no progressive changes with travel distance.

2006 Lahar Deposits

Lahar deposits were preserved in several small stream channels downstream from the pyroclastic flow deposits on the north flank (figs. 1, 10). Repeat photography and field observations during the 2006 eruption indicate that these lahars formed during the earliest explosive phase, when low-silica andesite-rich pyroclastic flows produced widespread flooding and lahars that reached the north coast of Augustine Island (Coombs and others, this volume).

The thin lahar deposits are composed of silt- and sand-rich diamictons that form flat terraces along narrow stream channels that are often no more than 2 to 10 m wide. The deposits are all less than 1 m thick, and often only 20–30 cm thick, with porphyritic greenish andesite boulders and rounded cobbles being the primary coarse lithic component (fig. 10). The greenish andesite boulders in pyroclastic flows had high susceptibilities (table 1), but volume susceptibility measurements on the matrix of the lahar deposits were much lower, with values ranging from 284×10^{-5} SI to 643×10^{-5} SI (fig. 6). These susceptibility values measured on lahars are lower than those measured on any of the pyroclastic flow deposits except those deposited within the pond basin.There is some overlap between highest susceptibility values measured on the lahar deposits and the susceptibility values measured for Rocky Point pyroclastic flow and phreatic ash deposits at the pond, but the lowest susceptibility values for the lahars are notably lower than any of the pyroclastic flow deposits from the 2006 eruption.

Interpretation of the Magnetic Susceptibility Data

Magnetic susceptibility is a measure of the relative amounts of different kinds of magnetic minerals present in samples. The changes in magnetic susceptibility documented in this study where pyroclastic flows encountered water and snow therefore record changes in the characteristics of the magnetic minerals in the pyroclastic flow deposits (Evans and Heller, 2003). It is well known that environmental factors, such as soil development or hydrothermal activity, can cause the alteration

Figure 10. Photograph of thin, fine-grained lahar deposits preserved in small stream channels just downslope from the terminal zone of the Rocky Point pyroclastic flow deposits. Also shown is the Bartington MS2F microprobe used in this study. Entrenching tool handle is 40 cm long.

or destruction of the existing magnetic minerals and the generation of new magnetic minerals (Liu and others, 1999). An important finding of this study is that the magnetic susceptibility of pyroclastic flow and surge deposits erupted by Augustine Volcano in 2006 were reduced in areas where encounters with water, snow, and steam occurred. Water-mediated lahar deposits derived from the pyroclastic flows had still lower susceptibilities. Our finding that interactions with water caused susceptibility variations in 2006 pyroclastic flow and lahar deposits at Augustine Island suggest that measurement of magnetic susceptibility variations can provide a new tool for evaluating interactions between pyroclastic flows and water.

Pyroclastic flows typically contain collections of different lithologies or components. Our data show that the susceptibilities of pyroclastic flow deposits erupted at Augustine Volcano in 2006 are somewhat variable but are all higher than pyroclastic flow deposits erupted in 1986. This reflects the higher susceptibilities of the major lithologic components of the 2006 pyroclastic flows and demonstrates that different assemblages of pyroclastic flow deposits produced during separate eruptive events can be differentiated by their magnetic susceptibility. This finding suggests that magnetic susceptibility data may be a useful tool for differentiating and mapping pyroclastic deposits at active volcanoes.

The magnetic susceptibility of the 2006 pyroclastic flow deposits showed significant changes in two key areas. At the northwest margin of the 2006 pyroclastic fan, Rocky Point pyroclastic flows filled a small pond basin. The magnetic susceptibilities of the pyroclastic flow deposits were significantly lower within the infilled pond basin, where the flows encountered water and steam, than they were anywhere else in the pyroclastic fan. Similar reductions in susceptibility were also found in ash cloud surge deposits that had traveled across an area where snow covered the ground. Lahar deposits in stream channels downstream from the pyroclastic flow deposits showed even lower volume susceptibility values.

The observed reductions in magnetic susceptibility in these 2006 Augustine deposits may reflect several different geochemical processes, but most of the change is probably attributable to oxidation of the iron-bearing minerals caused by interactions between the hot pyroclastic flows and water and steam. Oxidation is an inevitable consequence of the exposure of hot pyroclastic rocks to water and steam. Generations of volcanologists have noted the creation of oxidized, hematite-rich zones at the tops of pyroclastic flows, known as “pink tops,” and applied this classic criterion to infer the past presence of heat and water (Ross and Smith, 1961; Hildreth, 1983; Tait and others, 1998). Oxidation of iron-bearing minerals from the ferrous to ferric state characteristically results in the production of mineral phases with lower magnetic susceptibility, and we believe this is the main cause of the susceptibility changes we have observed in the 2006 Augustine pyroclastic flow, surge, and lahar deposits that formed by interactions with water, snow, and steam. Other geochemical processes may also be playing a role, including partial disruptions and dislocations of the atomic structure of the ferro-magnesium minerals (Ishikawa, 1958).

Over long periods of time, weathering and soil development can also cause changes in the original susceptibility of sediments (Maher and Thompson, 1999; Singer and others, 1992), but the 2006 pyroclastic deposits at Augustine were only a few months old when this study was made, and so were far too young for weathering to have greatly affected them.

Did Density Fractionation Occur in the 2006 Augustine Pyroclastic Flows, Surges, and Lahars?

In addition to the effect of geochemical processes on magnetic susceptibility, some physical processes produce sorting of sediments and can alter magnetic susceptibility. For instance, the higher density of magnetic minerals causes them to preferentially settle out of wind-blown sediment and water-transported sediment (Begét, 2001; Oldfield, 1991, 1992; Begét and others, 1990; Begét and Hawkins, 1989).

Could pyroclastic flow processes play a role in creating the observed variations in magnetic susceptiblity at Augustine Volcano?As noted above, the highest group of susceptibility values measured on any of the volcaniclastic deposits came from the 2006 pyroclastic flow deposits. The volume susceptibility measurements from the matrix of these flow deposits showed some variability from flow to flow, probably reflecting differences in the mix of the initial lithic components of the numerous pyroclastic flows produced during this part of the eruption. However, when the susceptibility of one area of the Rocky Point pyroclastic flow deposit was measured at multiple sites along its western margin, the susceptibility of the deposit showed little change for hundreds of meters downslope, suggesting that the processes involved in the lateral transit and emplacement of the Rocky Point pyroclastic flow did not produce progressive susceptibility changes along its flow path.

The prevailing modern view is that pyroclastic flows are dominantly turbulent, although locally they may be characterized by laminar or even plug flow (Schmincke, 2004). The finding here that density sorting and depletion by fractionation of heavy magnetic minerals did not occur to any significant degree as the 2006 pyroclastic flows traveled downslope suggests that the flows were sufficiently turbulent during emplacement to suspend all of the fine-grained components and minimize the loss of heavy Fe-bearing minerals. This was true for samples measured in pyroclastic flow deposit channels, recording sedimentation from the base of flow deposits, from pyroclastic flow levees formed by “freezing” of marginal parts of the pyroclastic flows, and also from flat-surfaced pyroclastic fans and terminal lobes that may have undergone plug flow as they decelerated and stopped.

Regeneration and formation of new matrix material by clast-to-clast collisions as the pyroclastic flow travels downslope and produces a deposit along its path probably plays an important role in modulating downslope changes in magnetic susceptibilities in the 2006 pyroclastic flow deposits. The absence of any progressive change in susceptibility in the Rocky Point pyroclastic flow from the upper slopes to the lower slopes strongly suggests that either density fractionation of the heavier magnetic minerals did not occur to a significant extent during flow, or new magnetic minerals were continually being added to the matrix of the flows by comminution of larger particles.

In contrast, significant reductions in magnetic susceptibility were observed in 2006 surge deposits that traveled only about 100 m beyond the margin of the Rocky Point pyroclastic flow deposit. Surges are typically highly inflated and have much lower particle concentrations than block-and-ash flows, and they would be more likely to be affected by density fractionation. The rapid decrease in susceptibility observed in the local surge deposits formed in 2006 at Augustine Volcano likely reflects some oxidation and alteration of the ferromagnetic minerals produced as the heat of the surge produced water and steam from the underlying snow, but we also suspect that some significant amount of the reduction in susceptibility seen in the distal surge deposits reflects progressive fractionation and removal of the denser magnetic minerals from the turbulent and dilute surge ash cloud as it traveled away from its source in the main Rocky Point pyroclastic flow deposit.

The magnetic susceptibility of lahars found downslope from the Rocky Point pyroclastic flow deposits is lower than that of the hot pyroclastic deposits from which they were derived. Lahars generated during the 2006 Augustine eruption appear to have been mainly produced by interactions between pyroclastic flows and surges and the winter snowpack (Vallance and others, this volume). The sediment in the lahars was in direct and prolonged contact with water, and the low susceptibility of the lahars is thought to reflect sustained geochemical alteration and oxidation of the ferromagnetic minerals. It is possible that some loss of heavy minerals by density fractionation may also have occurred during lahar deposition, but we do not see any progressive evolution in the susceptibility of the lahar deposits with distance away from the pyroclastic flow margin, as occurred in the surge deposits. For this reason, we do not think that density fractionation was an important factor in the evolution of the magnetic susceptibility of the lahar deposits, and we attribute the lower magnetic susceptibility that characterizes these deposits to water-rock interaction as the pyroclastic flows encountered snow and water and transformed into lahars that traveled to the lower flanks of the volcano.

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