KECK GEOLOGY CONSORTIUM
PROCEEDINGS OF THE TWENTY-THIRD ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

ISSN# 1528-7491

April 2010

Andrew P. de Wet
Editor & Keck Director
Franklin & Marshall College

Keck Geology Consortium
Franklin & Marshall College
PO Box 3003, Lanc. Pa, 17604

Lara Heister
Symposium Convenor
ExxonMobil Corp.

Keck Geology Consortium Member Institutions:
Amherst College, Beloit College, Carleton College, Colgate University, The College of Wooster, The Colorado College
Franklin & Marshall College, Macalester College, Mt Holyoke College, Oberlin College, Pomona College, Smith College, Trinity University
Union College, Washington & Lee University, Wesleyan University, Whitman College, Williams College

---

2009-2010 PROJECTS

SE ALASKA - EXHUMATION OF THE COAST MOUNTAINS BATHOLITH DURING THE GREENHOUSE TO ICEHOUSE TRANSITION IN SOUTHEAST ALASKA: A MULTIDISCIPLINARY STUDY OF THE PALEOGENE KOOTZNAHOO FM.
Faculty: Cameron Davidson (Carleton College), Karl Wirth (Macalester College), Tim White (Penn State University)
Students: Lenny Ancuta, Jordan Epstein, Nathan Evenson, Samantha Falcon, Alexander Gonzalez, Tiffany Henderson, Conor McNally, Julia Nave, Maria Princen

COLORADO – INTERDISCIPLINARY STUDIES IN THE CRITICAL ZONE, BOULDER CREEK CATCHMENT, FRONT RANGE, COLORADO.
Faculty: David Dethier (Williams) *Students: Elizabeth Dengler, Evan Riddle, James Trotta*

WISCONSIN - THE GEOLOGY AND ECOHYDROLOGY OF SPRINGS IN THE DRIFTLESS AREA OF SOUTHWEST WISCONSIN.
Faculty: Sue Swanson (Beloit) and Maureen Muldoon (UW-Oshkosh)
Students: Hannah Doherty, Elizabeth Forbes, Ashley Krutko, Mary Liang, Ethan Mamer, Miles Reed

OREGON - SOURCE TO SINK – WEATHERING OF VOLCANIC ROCKS AND THEIR INFLUENCE ON SOIL AND WATER CHEMISTRY IN CENTRAL OREGON.
Faculty: Holli Frey (Union) and Kathryn Szramek (Drake U.)
Students: Livia Capaldi, Matthew Harward, Matthew Kissane, Ashley Melendez, Julia Schwarz, Lauren Werckenthien

MONGOLIA - PALEOZOIC PALEOENVIRONMENTAL RECONSTRUCTION OF THE GOBI-ALTAI TERRANE, MONGOLIA.
Faculty: Connie Soja (Colgate), Paul Myrow (Colorado College), Jeff Over (SUNY-Geneseo), Chuluun Minjin (Mongolian University of Science and Technology)
Students: Uyanga Bold, Bilguun Dalaibaatar, Timothy Gibson, Badral Khurelbaatar, Madelyn Mette, Sara Oser, Adam Pellegrini, Jennifer Peteya, Munkh-Od Purevtseren, Nadine Reitman, Nicholas Sullivan, Zoe Vulgaropulos

KENAI - THE GEOMORPHOLOGY AND DATING OF HOLOCENE HIGH-WATER LEVELS ON THE KENAI PENINSULA, ALASKA
Faculty: Greg Wiles (The College of Wooster), Tom Lowell, (U. Cincinnati), Ed Berg (Kenai National Wildlife Refuge, Soldotna AK)
Students: Alena Giesche, Jessa Moser, Terry Workman

SVALBARD - HOLOCENE AND MODERN CLIMATE CHANGE IN THE HIGH ARCTIC, SVALBARD, NORWAY.
Faculty: Al Werner (Mount Holyoke College), Steve Roof (Hampshire College), Mike Retelle (Bates College)
Students: Travis Brown, Chris Coleman, Franklin Dekker, Jacalyn Gorczynski, Alice Nelson, Alexander Nereson, David Vallencourt

UNALASKA - LATE CENOZOIC VOLCANISM IN THE ALEUTIAN ARC: EXAMINING THE PRE-HOLOCENE RECORD ON UNALASKA ISLAND, AK.
Faculty: Kirsten Nicolaysen (Whitman College) and Rick Hazlett (Pomona College)
Students: Adam Curry, Allison Goldberg, Lauren Idleman, Allan Lerner, Max Siegrist, Clare Tochilin

Funding Provided by: Keck Geology Consortium Member Institutions and NSF (NSF-REU: 0648782) and ExxonMobil

Keck Geology Consortium: Projects 2009-2010
Short Contributions – UNALASKA

LATE CENOZOIC VOLCANISM IN THE ALEUTIAN ARC: EXAMINING THE PRE-HOLOCENE RECORD ON UNALASKA ISLAND

Project Faculty: ***KIRSTEN NICOLAYSEN***: Whitman College
RICHARD HAZLETT: Pomona College

GEOCHEMICAL INVESTIGATION OF THE RED CINDER PEAK AREA OF MAKUSHIN VOLCANO, UNALASKA, ALASKA

ADAM CURRY: Pomona College
Research Advisors: Jade Star Lackey and Richard Hazlett

PETROLOGIC AND VOLCANIC HISTORY OF POINT TEBENKOF IGNIMBRITE, UNALASKA, ALASKA

ALLISON R. GOLDBERG: Williams College
Research Advisor: Reinhard A. Wobus

^{40}Ar/^{39}Ar DATING OF LAVAS FROM MAKUSHIN VOLCANO, ALASKA: EVIDENCE FOR XENOCRYST CONTAMINATION

LAUREN M. IDLEMAN: Colgate University
Research Advisor: Martin S. Wong

ERUPTION DYNAMICS OF THE 7.7 KA DRIFTWOOD PUMICE-FALL, MAKUSHIN VOLCANO, ALASKA

ALLAN H. LERNER: Amherst College
Research Advisor: Peter D. Crowley, Amherst College

GEOCHEMICAL VARIATION IN PRE-CALDERA AND HOLOCENE LAVAS FROM MAKUSHIN VOLCANO, UNALASKA ISLAND, ALASKA

MAX T. SIEGRIST: Beloit College
Research Advisor: Jim Rougvie

PALEOMAGNETIC EVIDENCE AND IMPLICATIONS FOR STRUCTURAL BLOCK ROTATION ON UNALASKA ISLAND

CLARE TOCHILIN: Whitman College
Research Advisors: Kirsten Nicolaysen and Robert Varga

Funding provided by: Keck Geology Consortium Member Institutions and NSF (NSF-REU: 0648782)

Keck Geology Consortium
Franklin & Marshall College
PO Box 3003, Lancaster Pa, 17603
Keckgeology.org

PETROLOGIC AND VOLCANIC HISTORY OF POINT TEBENKOF IGNIMBRITE, UNALASKA, ALASKA

ALLISON R. GOLDBERG
Williams College
Research Advisor: Reinhard A. Wobus

INTRODUCTION

A previously undescribed 40-m thick mafic ignimbrite exposure at Point Tebenkof on the western side of Driftwood Bay provides evidence for a significant pyroclastic eruption from Makushin Volcano on Unalaska Island in the Aleutians. Previous studies of the area have focused primarily on the Holocene satellite vents and Makushin lavas thus the role of the Point Tebenkof ignimbrite in Makushin's history is unexplored.

Makushin erupted Plinian deposits at least twice during the Holocene (Begét et al., 2000). The most recent geologic map of Unalaska Island (McConnell et al., 1997) groups Point Tebenkof within Qom Older Makushin lavas and work of Idleman (this volume) indicates that the Point Tebenkof ignimbrite is likely Pleistocene in age. The Qom formation contains basalt and andesite lavas and pyroclastic deposits of varying compositions. Although mafic lava flows are generally far more common than mafic pyroclastic deposits, mafic ignimbrites like the one at Point Tebenkof are possible results of water-fueled, Plinian eruptions, which create hot avalanches of poorly-sorted pumice, lithic fragments, and ash (Lockwood and Hazlett, 2010). Many ignimbrites are welded, but non-welded ignimbrites like the one at Point Tebenkof (Fig. 1) are considered lower grade and the magma may have been cooled by water during the eruption (Walker, 1983).

This study focuses on the petrography and mineral chemistry of rocks from Point Tebenkof. Electron microprobe analyses provide data for thermobarometric calculations based on Putirka (2008) and these results elucidate the pre-eruption conditions in the magma chamber. These are important results for comparing this deposit to the two Holocene caldera-forming eruptions of Makushin.

FIELD SITES

Methods

Sample collection took place while camping near Driftwood Bay in July 2009. Field work included determining stratigraphic relationships and studying outcrop characteristics such as grain size, sorting, and grading. Adam Curry of Pomona College (contribution in this volume) and I focused on the western side of Driftwood Bay and in this report I will discuss the lava flows and pyroclastic deposits at Point Tebenkof.

Stratigraphic Relationships

The Point Tebenkof ignimbrite (BCF and BCB samples) is the oldest known Makushin pyroclastic deposit and it forms the base of the exposure at the beach cliff on the western side of Driftwood Bay (Fig. 2 of Nicolaysen and Hazlett, this volume). With the exception of the basal contact, which is buried beneath the beach deposits, the entire section is well exposed in two vertical sections along the coast. Samples discussed in this volume are from the north exposure. At the southernmost exposure, blocky basaltic andesite (BCA) overlies the ignimbrite but laterally to the north above BCF, BCA appears either to pinch out or to become baked by an overlying lava flow (BCC). In either case, the red BCE oxidized layer overlies much of the BCF exposure of the ignimbrite (Fig. 1 of Curry, this volume). Although the layers above BCA are covered by vegetation at the southern beach cliff exposure, a massive basalt (BCC) and a columnar

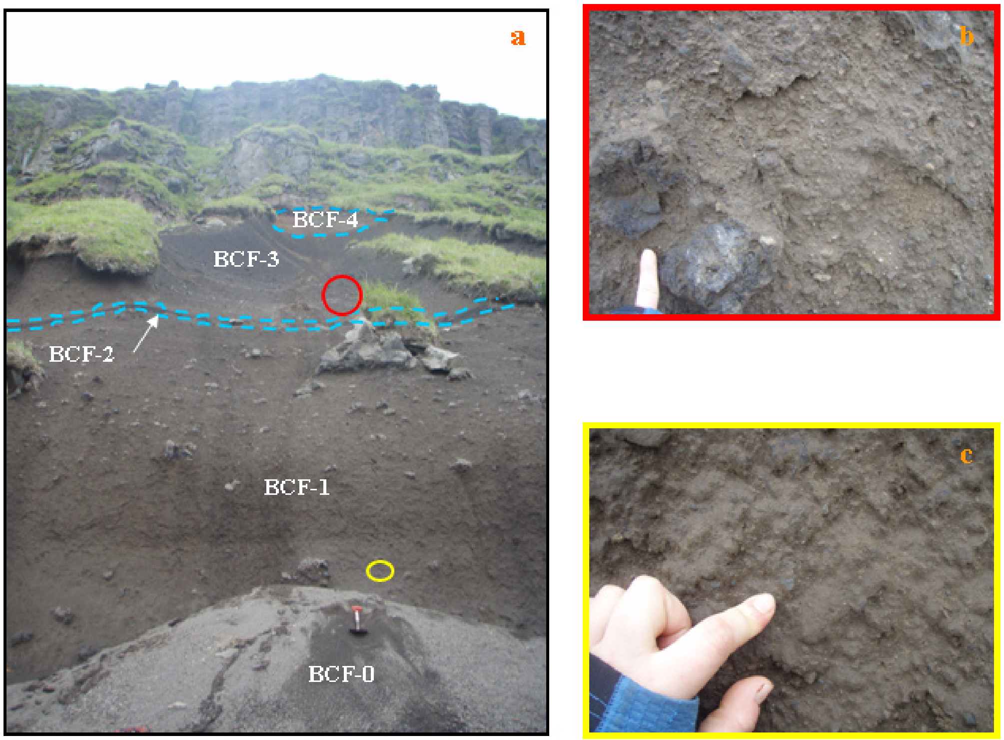

Figure 1. a) Photo of Point Tebenkof ignimbrite with shovel for scale. Circles indicate locations of photos b and c; b) shows mafic scoria in BCF-3S while c) highlights the finer grained matrix in BCF-1S.

andesite (BCD) overlie the red BCE layer above the BCF ignimbrite. A pile of scoria, BCF-0S5, slumped from the BCF ignimbrite (Fig. 1). The ability to see the entire thickness of the ignimbrite in one outcrop led me to focus on the north exposure. Importantly, new $^{40}Ar/^{39}Ar$ dating by Idleman (this volume) indicates that this ignimbrite is older than 139 ka so the Makushin volcanic center was a locus for strongly explosive eruptions even in the Pleistocene.

Within the BCF ignimbrite exposure, there are four distinct layers (Fig. 1; Fig. 1 of Curry, this volume). Layer 1 (BCF-1) refers to the lowest 8.5 m of coarse, dark brown, well-indurated ash, scoria, and lithic fragments with particle size ranging from sand to 60 cm. Clasts are subangular and poorly sorted without a clear grading trend but they do appear to be more concentrated towards the middle and upper sections of the layer. Layer 2 (BCF-2) is only 0.69 m thick, but its dark black color makes it stand out as a distinct band. Within Layer 2, there are three thin reddish brown tephra bands separated by clast-supported layers of dark, gravel-sized lithic clasts. Although the maximum grain size in Layer 2 is smaller than in Layer 1, the predominance of gravel and small cobbles makes the darker layer appear more clast supported. Layer 3 (BCF-3), the main ignimbrite sheet, is dark brown, poorly-sorted, and approximately 27 m thick. Discontinuous tan bands in the upper portion of the layer appear to be due to weathering. Although it has the highest proportion of clasts (sizes from 2-30 cm), Layer 3 lacks the induration of the other layers and it is not graded or sorted. The top 5 m of the exposure, Layer 4, consist of tannish orange matrix that fines upward to rich red, well-sorted co-ignimbrite ash. Due to difficulty accessing this layer, we were unable to collect any samples of it. Here it is also important to note that Layer 0 (BCF-0S5) refers to a pile of scoria in front of the ignimbrite outcrop at its base with clasts approximately 2-40 cm in diameter (most are 5-10 cm).

PETROGRAPHY

This analysis focuses on the compositions of phenocrysts within the BCF scoria of the Point Tebenkof Ignimbrite. Scoria from all layers contains plagio-

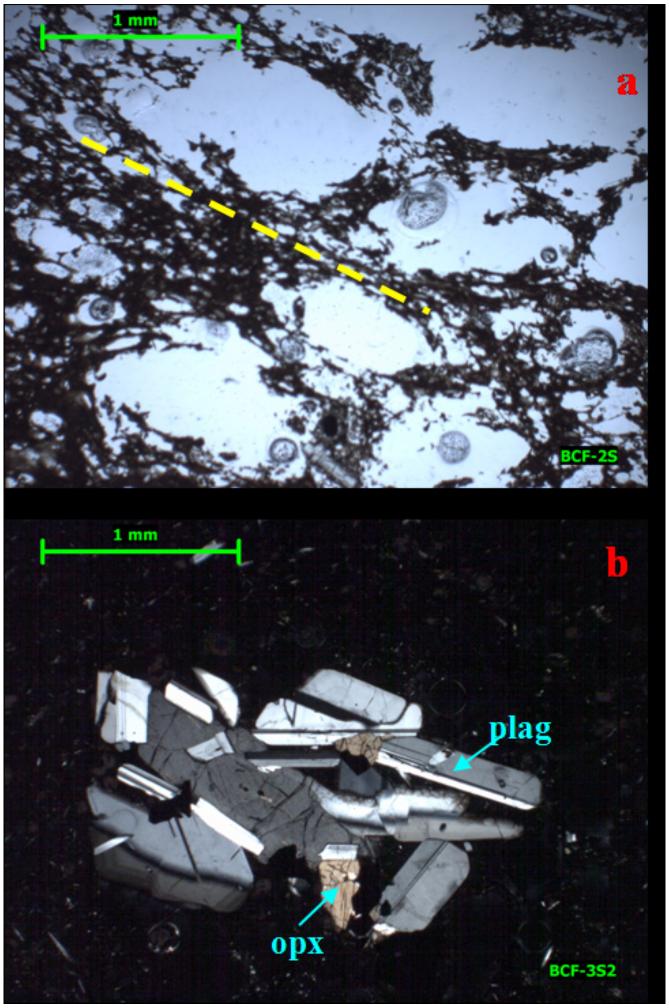

Figure 2. Photomicrographs of a) aligned vesicles in BCF-2S with yellow dashed line highlighting vesicle trend; uncrossed polars and b) crystal clot in a glassy matrix from BCF-3S2; crossed polars.

clase (An_{45-55}), titanomagnetite, ilmenite, clinopyroxene, and orthopyroxene in a glassy groundmass. Small, euhedral grains of apatite occur in most samples. Texturally, the scorias are highly vesicular (50-60%) with vesicle sizes typically ranging from 1-5 mm but rare vesicular patches may be up to 1 cm across. There does not appear to be any dominant alignment direction and the edges of the vesicles are often irregular due to the sharp, fibrous nature of the glass. Phenocrysts tend to be larger than the vesicles and they often occur in clots with subhedral to euhedral grains growing around each other for an intergranular texture.

Sample BCF-0S5 from Layer 0 has the highest amount of plagioclase (mode: 15-20%) compared to the other ignimbrite scoria due to the silicic pockets that contain aligned plagioclase needles. Sample BCF-1S from Layer 1 is notable due to a greater alignment of microlites in the glass. It rarely contains clinopyroxene crystals. Subhedral and euhedral orthopyroxene crystals are often bladed and some contain inclusions. Sample BCF-2S from Layer 2 is by far the darkest scoria due to the abundance of oxides and the paucity of plagioclase microlites. Tabular plagioclase grains show zoning and occur in intergranular masses with pyroxene. Orthopyroxene phenocrysts occur as both laths and small equant grains, whereas clinopyroxenes tend to be more tabular. In this sample vesicles do show a squashed alignment (Fig. 2a). Finally, sample BCF-3S2 from Layer 3 has euhedral plagioclase laths and blades, tiny square ilmenite crystals, fractured orthopyroxene plates, and very rare clinopyroxene blades (Fig. 2b).

THERMOBAROMETRY

Electron Microprobe Data

I obtained polished thin sections of BCF-0S5, BCF-1S, BCF-2S, BCF-3S2 (all scoria), and BCD-2 (an overlying Point Tebenkof columnar andesite flow for comparison purposes) and analyzed them at the UMass-Amherst electron microprobe lab with help from Mike Jercinovic. The Cameca SX50 Electron Microprobe was calibrated using known standards before sample analysis. Phenocrysts were analyzed with a 20.4 nA beam and an acceleration voltage of 15.0 kV wheras a 15.0 kV, 10.0 nA targeted the glass. I performed ten glass analyses for each sample and targeted up to five euhedral, clean grains of each mineral. For each phenocryst, I first analyzed the core and then 1-2 points along the rim. Although some concentric plagioclase zoning was visible under the petrographic microscope, transects across two grains in sample BCF-3S2 did not show any clear pattern of compositional zoning. All plagioclase compositions are in the An_{40-60} range and >90% of the phenocrysts are An_{45-55}.

Because thermobarometry equations from Putirka (2008) rely on equilibrium pyroxene compositions, it is important to plot compositions on a Rhodes di-

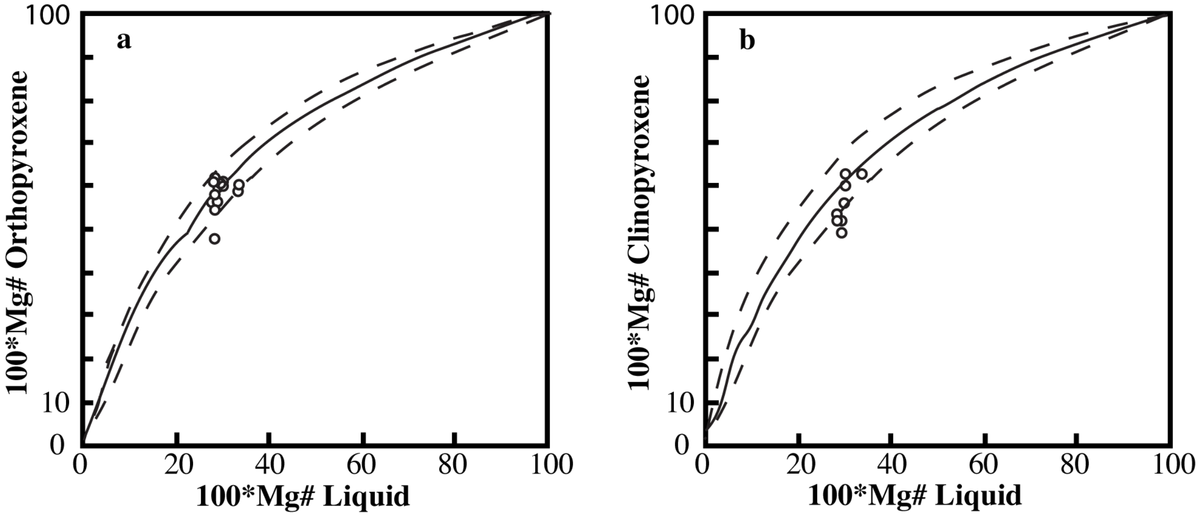

Figure 3. Diagram (after Rhodes et al., 1979) showing equilibrium for Fe-Mg mineral-glass pairs in a) orthopyroxene analyses with a partition coefficient of 0.29±0.06 and b) clinopyroxene analyses with a partition coefficient of 0.28±0.08. Analyses that do not fit within these bounds are not included in any further calculations.

agram (Rhodes et al., 1979) to determine if analyzed Fe-Mg mineral-glass pairs fit within equilibrium bounds for each analyzed pyroxene (Fig. 3). Analyses that are not within one standard deviation of the equilibrium lines based on the partition coefficient of 0.29±0.06 for orthopyroxene and 0.28±0.08 for clinopyroxene (Putirka, 2008) were not included in the thermobarometry calculations. Similarly, analyses whose summed oxides yield totals outside the 98.5-101.5% range were not included in the calculations.

Geothermometry Calculations

Following the methods of Putirka (2008), I compared pyroxene rim compositions with glass (liquid) compositions using experimentally derived equations to obtain values for the temperature at the time of crystal formation. Clinopyroxene-liquid calculations were performed according to Equation 33 (Putirka, 2008) which is calibrated against experiments at pressures less than 70 kbar to produce temperatures accurate to 10-20°C. For orthopyroxene-liquid geothermometry, Equation 28a (Putirka, 2008) rectifies past overestimates for the temperature of hydrous samples and is applicable for samples with temperatures from 750-1600°C, pressures below 11 GPa, SiO_2 weight percents from 33-77%, and H_2O less than 14.2 weight percent. Based on petrography, major element compositions, and the calculated temperatures, these assumptions are valid for the Point Tebenkof samples. Figure 4 shows the results of these calculations and Putirka (2008) suggests the accuracy of the calculated temperatures is ±26°C. Ignimbrite Layers 1-3 do not have any significant difference in temperature and these data suggest that, at the time of eruption, the magma chamber temperature was 950-1040°C and most likely 970-1015°C. The wider range and generally lower temperatures obtained from the sample from the scoria pile at the base of the outcrop (BCF-0S5) suggests that this is from an unsampled portion of the ignimbrite or that the sample is not derived from the Point Tebenkof ignimbrite outcrop.

Fe-Ti oxide geothermometry calculations (Ghiorso and Evans, 2008) for oxides analyzed in the same samples as the pyroxene thermometry show similarly consistent temperatures for each of the three sampled layers of the ignimbrite. The oxide geothermometer gives calculated temperatures lower than those calculated from the pyroxene geothermometers, from 865-930°C. This is expected because Fe-Mg exchange between oxides and melt is believed to close at lower temperatures than for pyroxenes (Ghiorso, 1997). This raises an important point; although thermobarometry results are often generalized to describe the pre-eruption temperature of

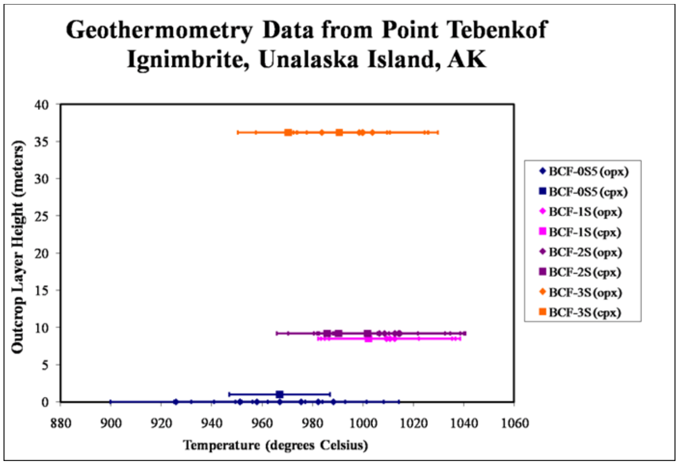

Figure 4. Geothermometry calculation results using equations from Putirka, 2008 for opx-liquid (diamonds) and cpx-liquid (squares) weight percent oxide data.

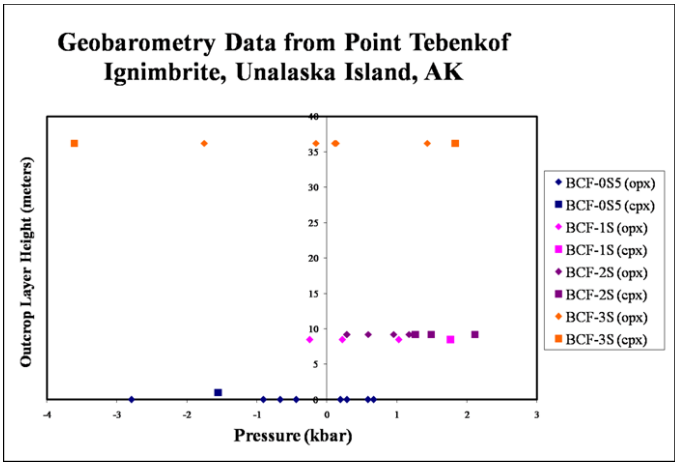

Figure 5. Geobarometry calculation results using equations from Putirka, 2008 for opx-liquid (diamonds) and cpx-liquid (squares) weight percent oxide data.

magma, they are recording the temperature at which the individual minerals close to cation exchange as the lava or ignimbrite solidifies.

Geobarometry Calculations

Putirka (2008) presented experimentally derived equations for pressure. Clinopyroxene-liquid barometers often struggle with hydrous samples, and the Point Tebenkof magma likely had significant volatile content, but Putirka's (2008) Equation 31 used a global regression of water-saturated clinopyroxene experiments for calibration. The ignimbrite scoria data show a large range in calculated pressure with the most consistency around 1.26-2.12 kbar for Layers 1 and 2 and all but one of the Layer 3 samples (Fig. 5). Note the reported standard error of the estimate (SEE) is ±1.5 kbar for the clinopyroxene-liquid barometer (Putrika, 2008). The orthopyroxene-liquid barometer in Equation 29a (Putirka, 2008) provides more accurate pressures for hydrous data but it does tend to underestimate low pressures. Because Putirka (2008) suggests the possibility a 1 kbar underestimate for these equations and an SEE of 2.6 kbar, the very low (and negative) pressures for the ignimbrite scoria based on the orthopyroxene-liquid barometer are consistent within error with the clinopyroxene-liquid constraints on crystallization pressures of the pyroxene phenocrysts. Overall, the pressure data suggest that the magma chamber was close to the surface when phenocrysts began to form.

INTERPRETATION

Based on the thermobarometric data, it appears that the entire ignimbrite deposit at Point Tebenkof came from one magma chamber with a constant temperature and pressure at the time of phenocryst formation. Moreover, because there is only one size population of phenocrysts suspended in glass (i.e. no microlites), it is likely that eruption occurred soon after the phenocrysts formed. There is no evidence for pyroxene-liquid reequilibrium at temperatures between 950°C and surface temperature. Stratigraphically the differences in the layers are not significant enough to suggest more than one event, and the contacts do not show any evidence of unconformities.

The pressure data show that given an average pressure gradient of 0.3 kbar/km, the magma chamber was 4.2-7.1 km below the surface. Considering the error on the calibration of the geobarometer; however, the magma may have stalled as shallowly as within a km of the surface. The maximum possible crystallization depth recorded by the pyroxene phenocrysts overlaps with an estimate of the crustal depth (~7 km) for a magmatic intrusion event in 1995 (Lu et al., 2002).

Along with the one large eruption that formed Layers 1-3 of the Point Tebenkof ignimbrite, there may have been a later eruption that occurred from a shallower magma chamber with a lower temperature that formed “Layer 0”, the scoria pile in front of the main ignimbrite. More investigation into the progenitor of the BCF-0 deposit could prove interesting, especially because of the evidence for magma mingling which could have served as a possible eruption trigger. However, in order to reliably study these scoria, it would be necessary to find them in an in situ deposit, and such an exposure was not accessible. Still, this study does provide clear conclusions about the eruption that formed Layers 1-4 of the Point Tebenkof Ignimbrite. Of note, this mafic ignimbrite formed from a phreatomagmatic Pleistocene eruption of a low temperature (~1000°C), relatively shallow magma chamber.

ACKNOWLEDGEMENTS

In addition to the acknowledgments already stated in the project introduction, I would like to thank Bud Wobus for all of his helpful comments about this paper as well as for his encouragement and support regarding my thesis in general. Kirsten Nicolaysen and Rick Hazlett provided great advice in the field and useful edits for this paper. Mike Jercinovic at UMass Amherst taught me how to use the microprobe and I appreciate his patience and assistance with data collection. I’d also like to acknowledge Adam, Clare, Lauren, Allan, and Max for being wonderful field partners!

REFERENCES

Begét, J.E., Nye, C.J., and Bean, K.W., 2000, Preliminary volcano-hazard assessment for Makushin Volcano, Alaska: Alaska Department of Natural Resources Division of Geological & Geophysical Surveys, Report of Investigations 2000-4, p. 1-22.

Ghiorso, M.S., 1997, Thermodynamic analysis of the effect of magnetic ordering on miscibility gaps in the FeTi cubic and rhombohedral oxide minerals and the FeTi oxide geothermometer: Physics and Chemistry of Minerals, v. 25, p. 28-38.

Ghiorso, M.S. and Evans, B.W., 2008, Thermodynamics of rhombohedral oxide solid solutions and a revision of the Fe-Ti two-oxide geothermometer and oxygen-barometer. American Journal of Science, v. 208, p. 957-1039.

Lockwood, J.P., and Hazlett, R.W., 2010, Volcanoes: A Global Perspective, Wiley-Blackwell Publishing, 600 p.

Lu, Z., Power, J.A., McConnell, V.S., Wicks, Jr., C., and Dzurisin, D., 2002, Preeruptive inflation and surface interferometric coherence characteristics revealed by satellite radar interferometry at Makushin Volcano, Alaska: 1993-2000, Journal of Geophysical Research, v. 107, p. 1-13.

McConnell, V.S., Begét, J.E., Roach, A.L., Bean, K.W., and Nye, C.J., 1997, Geologic map of the Makushin volcanic field, Unalaska Island, Alaska, Report of Investigations – Alaska Division of Geological & Geophysical Surveys, scale 1:63,360.

Putirka, K.D., 2008, Thermometers and barometers for volcanic systems. In: Putirka,. K. D., and Tepley, F. eds., Minerals, Inclusions, and Volcanic Processes, Reviews in Mineral and Geochemistry Geochemistry, MSA, v. 69, p. 61-120.

Rhodes, J.M., Dungan, M.A., Blanchard, D.P., Long, P.E., 1979, Magma mixing at mid-ocean ridges: evidence from basalts drilled near 22°N on the mid-Atlantic ridge. Tectonophysics, v. 55, p. 35-61.

Walker, G.P.L., 1983, Ignimbrite types and ignimbrite problems. In: M.F. Sheriden and F. Barberi eds., Explosive Volcanism. Journal of Volcanolology and Geothermal Research, v. 17, p. 65-88.