Sampling and **In**-situ **O**bservations of **Ok**mok (SINOOK)

Timothy Masterlark[1], John Eichelberger[2], Jeffrey Freymueller[2], Matthew Haney[3], Shaul Hurwitz[4], Pavel Izbekov[2], Jessica Larsen[2], Setsuya Nakada[5], Christina Neal[3], William Roggenthen[1], and Clifford Thurber[6].
[1] South Dakota School of Mines and Technology, Rapid City, SD 57701, USA.
[2] University of Alaska Fairbanks, Fairbanks, AK 99775, USA.
[3] Alaska Volcano Observatory, U.S. Geological Survey, Anchorage, AK 99508, USA.
[4] U.S. Geological Survey, Menlo Park, CA 94025, USA.
[5] ERI, University of Tokyo, Japan.
[6] University of Wisconsin-Madison, Madison, WI 53706, USA.

Project Summary

SINOOK will drill the caldera of Okmok volcano, Alaska (Figure 1), and collect *core and fluid samples*, *temperature measurements*, and *borehole stress measurements* to a depth of 4 kilometers. Ideally, the sampling will penetrate the transition zone between the country rock and the magma chamber and culminate with direct sampling of quenched magma. This assemblage of in situ information will provide unprecedented constraints for interdisciplinary models of deformation, stress, geothermal systems, eruption history, and caldera formation for this active volcano. SINOOK will address an array of important scientific questions for the specific example of Okmok volcano and have far-reaching interdisciplinary implications.

Scientific Questions addressed by SINOOK:

1. *How reliable are estimates and uncertainties for internal processes and structures of volcanoes, determined from geophysical surface observations?* SINOOK will verify geophysical models determined from seismic tomography, reflection, and anisotropy; gravity; and geodesy. For example, are the in situ or laboratory based rock properties (collected by SINOOK) within uncertainties of surface-based geophysical models? Results will have important implications for the reliability of geophysical models for Okmok volcano and elsewhere, as well as influence the justification and scope of major geophysical data collection initiatives for other volcanoes.
2. *What is the magma migration and storage and eruption style in space and time? What are the systematic and asystematic aspects of eruption cycles?* Results and implications may be transferrable to the general understanding of other volcanoes in island arc settings.
3. *What is the basic structure of the magma chamber?* Is it a single finite chamber, an assembly of dike and sill structures, or a multiphasic mush zone? The answer to this question has important implications for magma migration and storage, as well as understanding the conditions that lead to specific eruption styles.
4. *What is the rheologic structure of the transition zone separating the magma chamber from the country rock?* Results that combine in situ observations and laboratory experiments will have implications for understanding the magma replenishment, as determined from geodetic data.
5. *What are the characteristics and interactions of the shallow groundwater and deeper hydrothermal systems? How do these fluid systems influence the eruption style?* The 2008 hydrovolcanic eruption was very different from the effusive 1997 eruption, even though both eruptions tapped the same magma source. The answers to these questions have important implications for understanding the evolution of eruption styles for other volcanoes, as well as for unraveling the complexity volcanic geothermal systems.
6. *How does dike propagation couple to the local stress field and loading in the complex domain of a caldera?* Results have strong implications for geothermal and hydrocarbon production, as well as nuclear waste disposal strategies, and are thus aligned with Energy and Economic interests.
7. *How do eruption cycles integrate with ecological and local societal systems?* Eruption cycles present examples of stress and recovery episodes with relevance to interdisciplinary ecological, societal, and economic systems.
8. *What are the long-range ash plume or climate impacts?* Determining the frequency, scale, and style of eruptions will have important implications for major civilian and military air traffic corridors that intersect Aleutian airspace.

Although scientific drilling of Okmok's caldera is the kernel of SINOOK, the project will include both pre- and post-drilling components that span field, laboratory, remote sensing, and computational activities. While these activities are dominated by geologic and geophysical studies, the scientific questions above demonstrate great potential for interdisciplinary studies that naturally integrate Earth science with ecology, cultural studies, economics, and energy interests.

Pre-drilling geophysical surveys (e.g., gravity, MT, EM, and seismic) will sharpen our understanding of the caldera's interior and provide guidance for drilling operations. Furthermore, these high resolution 3D models, developed using state-of-the-art geophysical instruments and methods, will be confronted with in situ observations in verification analyses. Auxiliary boreholes will be drilled to collect complementary information before, during, and after the main drilling operation. Downhole geophysical instruments will be deployed in the main borehole to collect geophysical information that will leverage co-drilling measurements and provide a basis for future complementary studies of this dynamic volcano.

Okmok Volcano: An ideal target

Okmok volcano is readily accessed from the deep sea port of Dutch Harbor (Figure 1) by boat, helicopter, and amphibious aircraft. The land is privately owned and operated as a cattle ranch, and the owners have been receptive to research activities. The ranch house has long provided lodging for scientists and helicopter pilots. Drilling would entail shipping equipment to the range dock, and then airlifting a short distance by helicopter to the center of the caldera. There is abundant water within the caldera to support drilling. Existing entities, such as DOSECC, have ample expertise and appropriate equipment for this kind of operation.

Okmok is representative of an array of caldera systems (e.g., Ksudach, Aniakchak, Aso, and Santorini) characteristic of island arcs. These volcanoes are characterized by the sudden appearance of voluminous silicic magma after a protracted period of mafic volcanism. The paroxysmal eruptions are usually strongly and discontinuously chemically zoned, followed by a return to small-volume mafic eruptions, and then may repeat this cycle after a few thousand years. The apparently rapid generation of highly explosive silicic magma in a predominantly mafic arc environment is both a petrologic puzzle and an important disaster risk that will be addressed by SINOOK's probing of Okmok's thermal regime.

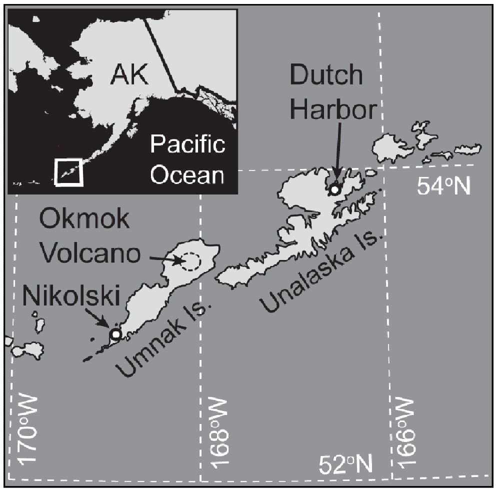

Figure 1. Target: Okmok Volcano, Alaska. Okmok occupies the northeast lobe of Umnak Island. White box in inset denotes the regional location of Okmok.

Okmok volcano is one of the largest and best studied volcanic shields of the Aleutian arc. A central caldera, having a radius of 5 km, dominates the physiography of Okmok. The existing caldera is the result of two separate caldera-forming eruptions having ages of 12,000 and 2,050 years b.p. [*Finney et al.*, 2008; *Larsen et al.*, 2007]. Post-caldera eruptions are effusive or phreatomagmatic and basaltic to andesitic [*Burgisser*, 2005]. The most recent eruption in 2008 originated from several new vents surrounding Cone D near the eastern rim of the caldera, while the three previous eruptions in 1945, 1958, and 1997 originated from Cone A near the southwest rim of the caldera [*Larsen et al.*, 2009]. Geochemical analyses of erupted materials are consistent with primitive magma from depth and brief storage in shallow reservoirs [*Finney et al.*, 2008]. Over the past decade, Okmok was instrumented with GPS instruments [*Fournier et al.*, 2009; *Miyagi et al.*, 2004] and seismic networks [*Caplan-Auerbach et al.*, 2003; *Haney*, 2010; *Johnson et al.*, 2010; *Masterlark et al.*, 2010]. Okmok also hosts a site of the Aleutian infrasound array [*Arnoult et al.*, 2010]. Remote sensing data remain essential for monitoring Okmok [*Dehn et al.*, 2000; *Lu*, 2007; *Lu et al.*, 2003; *Patrick et al.*, 2004] and future satellite radar imagery will be available from a successful proposal to JAXA 4th ALOS Research Program for ALOS-2. Okmok is an excellent target for this project because of its location, activity, and internal structure. Okmok is well instrumented and has been well studied from a variety of perspectives that used different type of geologic, geophysical, and remote sensing data. SINOOK will provide opportunities to discriminate among different conceptual configurations of Okmok's interior (Figure 2).

The assumed treatment of Okmok's weak shallow caldera materials strongly influences interpretations of Okmok's magmatic system, based on analyses of observed deformation (InSAR and GPS). For example, standard elastic half-space (EHS) analyses predict a magma chamber depth of 3 km, whereas models that account for weak caldera materials predict that the magma chamber is significantly deeper (~4 km) [*Masterlark*, 2007; *Masterlark et al.*, 2012]. Furthermore, contrasts in material properties between the weak shallow caldera versus stiff subcaldera regions fundamentally influence dike propagation that transports eruption materials from the magma chamber at depth to the surface of the volcano [*Masterlark et al.*, 2010]. These prediction differences are substantial and have important implications for our understanding of Okmok's magmatic system. Available seismic tomography models provide constraints on the distribution of material properties in the shallow caldera [*Masterlark et al.*, 2010; *Ohlendorf*, 2010] and observed VLP tremors [*Haney*, 2010] constrain active magma migration in space and time. SINOOK will provide a rare opportunity to verify these tomographic models and interpretations of seismic data. Therefore, SINOOK presents an avenue to advance our fundamental understanding of magma migration and storage within active volcanoes. No fewer than 12 publications describe investigations of geodetic data to estimate the characteristics of Okmok's subcaldera magmatic plumbing structure associated with the 1997 and 2008 eruptions, as well as various pre-, post-, and inter-eruption intervals [*Biggs et al.*, 2010; *Masterlark et al.*, 2012 (and references therein)]. All of these studies suggest the observed deformation is caused by magma migration and storage into (or out of) an isometric magma chamber that is somewhat stationary in space and time. However the specific characteristics of this geodetically-determined source vary considerably, as demonstrated for the case of Okmok's 1997 eruption:

- shallow chamber embedded in an EHS domain [*Lu et al.*, 2005, 2000; *Masterlark*, 2007; *Masterlark et al.*, 2012]
- shallow chamber + sill embedded in an EHS domain [*Mann et al.*, 2002]

- deep chamber embedded in a heterogeneous elastic domain [*Masterlark*, 2007; *Masterlark et al.*, 2012]
- deep chamber embedded in a heterogeneous viscoelastic domain [*Masterlark et al.*, 2010]

Additional proposed deformation sources include viscoelastic or poroelastic deformation of the caldera substrate caused by gravitational loading by the lava field [*Lu et al.*, 2005]. All of the preceding deformation mechanisms can be cast as formal competing hypotheses and tested with data collected by SINOOK. Such analyses can identify the most likely model, or refine the range of plausible models of Okmok's interior. Calibrated deformation models can predict the internal stress field of Okmok and account for characteristics of dike propagation that transport eruption materials from the magma chamber to the land surface. The presence of weak caldera materials accounts for co-eruption magma migration (diking) from the caldera-centered magma chamber to extrusion points near the caldera rim [*Masterlark et al.*, 2010]. However, it is unclear why extrusion shifted from Cone A (near the southwest rim of the caldera) during the 1997 basaltic eruption to Cone D (east rim of the caldera) during the 2008 basaltic/andesitic hydrovolcanic eruption. Changes in the deformation pattern after the 2008 eruption suggest that this eruption has altered the subsurface magma storage and plumbing system beneath the volcano; the post-eruption inflation seems to have occurred at a shallower depth than the post-1997 inflation. In situ stress measurements will help solve this puzzle. Likewise, an understanding of the characteristics and interactions of the shallow groundwater and deeper hydrothermal systems will reveal why the 2008 hydrovolcanic eruption style was very different from the effusive 1997 eruption, even though both eruptions presumably tapped the same magma source. While SINOOK will allow us to verify geodetic methods and provide a basis for understanding the volcanic system specifically for Okmok,

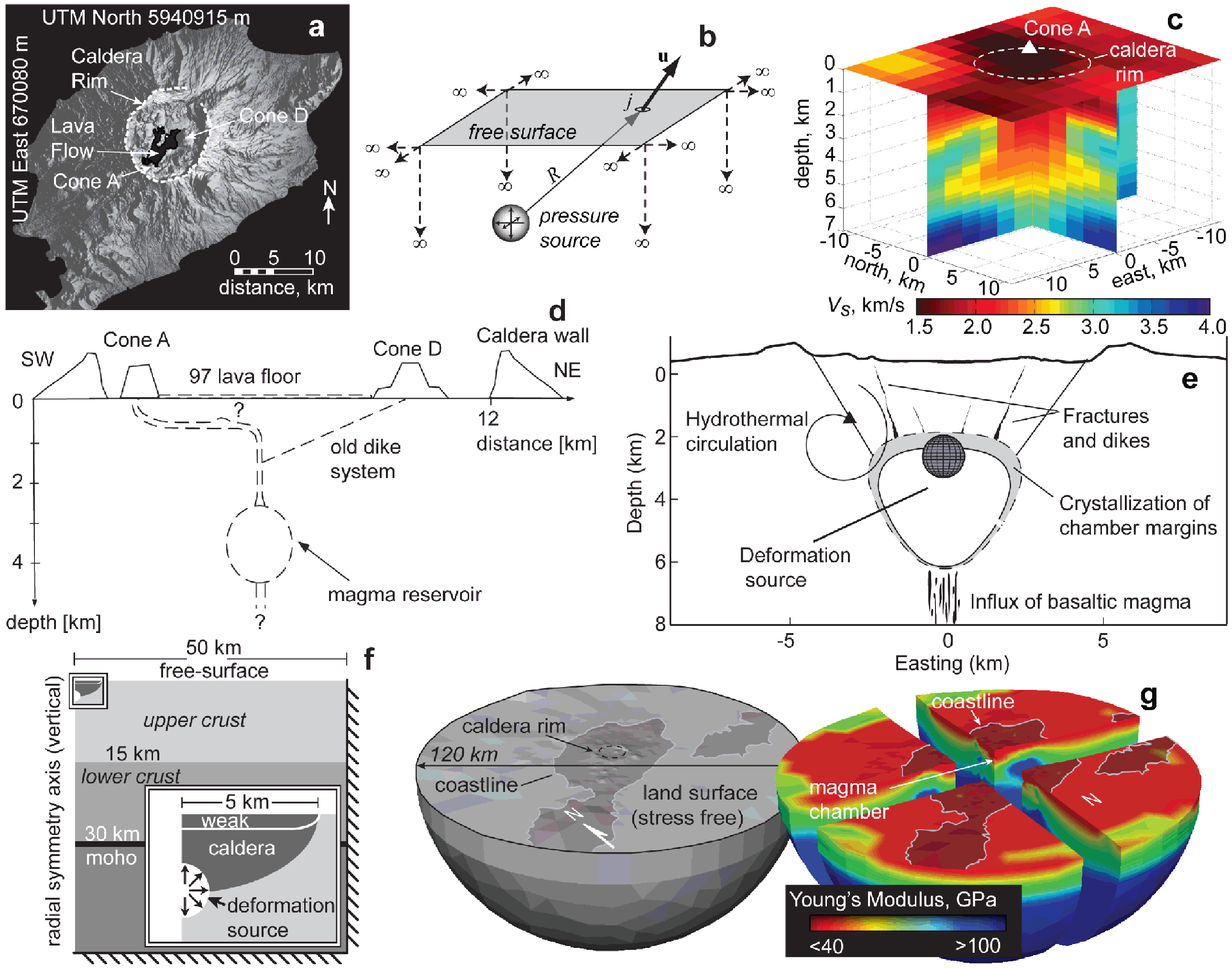

Figure 2. The interior of Okmok Volcano, Alaska. (**a**) Study site. Okmok occupies the northeast lobe of Umnak Island. See Figure 1 for regional location. (**b**) Standard elastic half-space (EHS) model (e.g., *Mogi* [1958]). (**c**) ANT images the internal structure of Okmok [*Masterlark et al.*, 2010]. (**d**) Interpretation based on InSAR and EHS models [*Mann et al.*, 2002]. (**e**) Interpretation based on GPS and EHS models [*Fournier et al.*, 2009]. (**f**) Conceptual deformation model accounting for caldera structure [*Masterlark*, 2007]. (**g**) Tomography results converted into a distribution of elastic material properties in a deformation model (FEM) domain [*Masterlark et al.*, 2012].

the results will have important implications for analyses of geophysical data that seek to estimate the characteristics of magma migration and storage for active volcanoes worldwide.

Broader Impacts and Initiatives

Seismic tomography, gravity, and EM methods are regularly employed to image subsurface structure using inverse methods and observations of the respective geophysical fields at the Earth's surface. These inverse methods provide models having precisely defined quantitative estimates, uncertainties, and resolution of internal structures (e.g., *Aster et al.*, 2005). Likewise, surface geophysical observations (e.g., deformation and gravity) are routinely analyzed using inverse methods to define internal processes, such as magma migration and fault slip distributions for earthquakes at depth. SINOOK provides rare and precious opportunities to verify (ground-truth) these geophysical models of subsurface structure and processes for the case of Okmok . These tests of routinely employed geophysical methods will have far-reaching implications for the geophysical community.

Dike propagation in the presence of a complex distribution of stress, fluid pressure, and material properties is precisely analogous to fracture propagation studies for geothermal, hydrocarbon, and nuclear waste interests. As such, studies of dike propagation in Okmok's caldera, as constrained by in situ stress measurements and material property characterizations, will have important implications for energy-related initiatives, as well as for dike propagation within volcanoes elsewhere. Similarly, hydrologic investigations of Okmok's shallow groundwater and deep geothermal systems will provide results that cut across scientific and energy interests.

The geophysical analyses of deformation and stress discussed above can be thought of as physical impulse-response experiments. By simulating the impulse and comparing predictions to the observed response, we can infer the internal structure and processes within the volcano. We can develop interdisciplinary collaborations that use the same principles to study ecological and cultural impacts of volcanic activity revealed by the drilling. One can envision studies of stress (volcanic eruption) and the time-dependent recovery (societal and ecological response). Such studies could integrate nearby Native American communities (e.g., Nikolski, Figure 1), or alternatively investigate stress and recovery of the large-scale economic fishery operations served by Dutch Harbor (Figure 1), which leads the nation in terms of amounts of fish landed [www.noaa.gov].

SINOOK spans many important scientific and societal interests and, therefore, has the potential to tap an array of funding sources. Individual elements of the project are aligned with standard topical NSF programs (e.g., EAR Geophysics). However, the interdisciplinary scope of the project lends itself to cross-cutting NSF programs. For example, Okmok is located in a research corridor of the NSF GeoPRISMS Aleutians Primary Site. Alternatively, the interdisciplinary nature of SINOOK is well aligned with the objectives of NSF FESD. Additionally, the anticipated computational requirements for modeling and analyses of SINOOK data could serve as the basis for an NSF Geoinformatics initiative. Remote sensing data, such as InSAR imagery, continue to play a key role in understanding Okmok volcano (Figure 2). Thus SINOOK may be of interest to ongoing or future missions sponsored by NASA, JAXA, or ESA. The energy analogies may provide opportunities to engage the interest and support of private industry, as well as the Departments of Energy and Defense. Potential ecological (e.g., fishery) aspects of the project may be of interest to NOAA. Finally, the project may integrate with the interests and evolution of the local Native American community of Nikolski (Figure 1). For example, what are the modern socio-economic impacts of the episodic eruptions? What are the archeological impacts? Could SINOOK lead to geothermal energy resources for the region?

References

Arnoult, K. M., J. V. Olson, C. A. L. Szuberla, S. R. McNutt, M. A. Garcés, D. Fee, and M. A. H. Hedlin (2010), Infrasound observations of the 2008 explosive eruptions of Okmok and Kasatochi volcanoes, Alaska, *Journal of Geophysical Research 115*, doi:10.1029/2010JD013987, 12pp.

Aster, R.C., B. Borchers, and C.H. Thurber (2005), Parameter estimation and inverse problems, Elsevier, San Diego, ISBN:0-12-065604-3, 301 pp.

Biggs, J., Z. Lu, T. Fournier, and J.T. Freymeuller (2010), Magma flux at Okmok Volcano, Alaska, from a joint inversion of continuous GPS, campaign GPS, and interferometric synthetic aperture radar, *Journal of Geophysical Research 115*, doi:10.1029/2010JB007577, 11pp.

Burgisser, A. (2005), Physical volcanology of the 2,050 BP caldera-forming eruption of Okmok volcano, Alaska, *Bulletin of Volcanology 67*, doi:10.1007/s00445-004-0391-5, 497-525.

Caplan-Auerbach, J., S. Moran, G. Tytgat, T. Plucinski, J. Paskievitch, and S.R. McNutt (2003), Mystery Seismicity: The search for volcanic tremor source(s) in the eastern Aleutians, Alaska, *Seismological Research Letters 74*(1), 8-21.

Dehn, J., K. Dean, and K. Engle (2000), Thermal monitoring of North Pacific volcanoes from space, *Geology*, *28*(8), doi:10.1130/0091-7613(2000)28<755:TMONPV>2.0.CO;2, 755-758.

Finney, B., S. Turner, C. Hawkesworth, J. Larsen, C. Nye, R. Grorge, I. Bindeman, and J. Eichelberger (2008), Magmatic differentiation at an island-arc caldera: Okmok volcano, Aleutian islands, Alaska, *Journal of Petrology 49*(5), doi:10.1093/petrology/egn008, 857-884.

Fournier, T., J. Freymueller, and P. Cervelli (2009), Tracking magma volume recovery at Okmok Volcano using GPS and an unscented Kalman filter, *Journal of Geophysical Research 114*, doi:10.1029/2008JB005837, 18pp.

Haney, M.M. (2010), Location and mechanism of very long period tremor during the 2008 eruption of Okmok Volcano from interstation arrival times, *Journal of Geophysical Research 115*, doi:10.1029/2010JB007440, 13pp.

Johnson, J.H., S. Prejean, M.K. Savage, and J. Townend (2010), Anisotropy, repeating earthquakes, and seismicity associated with the 2008 eruption of Okmok volcano, Alaska, *Journal of Geophysical Research 115*, doi:10.1029/2009JB006991.

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 90*, 173-180.

Larsen, J.F., C.A. Neal, J.R. Schaefer, J.E. Beget, and C.J. Nye (2007), Late Pleistocene and Holocene caldera-forming eruptions of Okmok caldera, Aleutian islands, Alaska, in *Volcanism and Subduction: The Kamchatka Region*, edited by E. G. J. Eichelberger, P. Izbekov, M. Kasahara, and J. Lees, 343-363.

Lu, Z. (2007), InSAR imaging of volcanic deformation over cloud-prone areas-Aleutian islands, *Photogrammetric Engineering & Remote Sensing 73*(3), 245-257.

Lu, Z., T. Masterlark, and D. Dzurisin (2005), Interferometric synthetic aperture study of Okmok volcano, Alaska: Magma supply dynamics and post-emplacement lava flow deformation, *Journal of Geophysical Research 110*, doi:10.1029/2004JB003148, 18pp.

Lu, Z., D. Mann, J.T. Freymueller, and D.J. Meyer (2000), Synthetic aperture radar interferometry of Okmok volcano, Alaska: Radar observations, *Journal of Geophysical Research 105*(B5), 10791-10806.

Lu, Z., E. Fielding, M.R. Patrick, and C.M. Trautwein (2003), Estimating lava volume by precision combination of multiple baseline spaceborne and airborne interferometric synthetic aperture radar: The 1997 eruption of Okmok volcano, Alaska, *IEEE 41*(6), doi:10.1109/TGRS.2003.811553, 1428-1436.

Mann, D., J. Freymueller, and Z. Lu (2002), Deformation associated with the 1997 eruption of Okmok volcano, Alaska, *Journal of Geophysical Research 107*(B4), doi:10.1029/2001JB000163, 12pp.

Masterlark, T. (2007), Magma intrusion and deformation predictions: Sensitivities to the Mogi assumptions, *Journal of Geophysical Research 112*, doi:10.1029/2006JB004860, 17pp.

Masterlark, T., M. Haney, H. Dickinson, T. Fournier, and C. Searcy (2010), Rheologic and structural controls on the deformation of Okmok volcano, Alaska: FEMS, InSAR and ambient noise tomography, *Journal of Geophysical Research 115*, doi:10.1029/2009JB006324, 22pp.

Masterlark, T., K.L. Feigl, M.M. Haney, J. Stone, C.H. Thurber, and E. Ronchin (2012), Nonlinear estimation of geometric parameters in FEMs of volcano deformation: Integrating tomography models and geodetic data for Okmok volcano, Alaska, *Journal of Geophysical Research 117*, doi:10.1029/2011JB008811, 17pp.

Miyagi, Y., J.T. Freymueller, F. Kimata, T. Sato, and D. Mann (2004), Surface deformation caused by shallow magmatic activity at Okmok volcano, Alaska, detected by GPS campaigns 2000-2002, *Earth Planets Space*, *56*(10), e29-e32.

Mogi, K., (1958), Relations between the eruptions of various volcanoes and the deformations of the ground surface around them, *Bull. Earthquake Res. Inst. Univ. Tokyo 36*, 99-134.

Ohlendorf, S.J. (2010), Seismicity and structure at Okmok Volcano, Alaska, Thesis thesis, University of Wisconsin, 50 pp.

Patrick, M.R., J. Dehn, and K. Dean (2004), Numerical modeling of lava flow cooling applied to the 1997 Okmok eruption: Approach and analysis, *Journal of Geophysical Research*, *109*, doi:10.1029/2003JB002537, 17pp.