Multi-Disciplinary Working Group Report

1. General Problem and State-of-the-art

Ground-surface displacement (GSD) rates detectable with modern geodetic techniques (e.g., tilt-meters, InSAR, and GPS) are of special interest, because they are often interpreted as indicators of magma intrusion into the shallow crust, a major cause of volcanic unrest [*Dzurisin*, 2006]. Ongoing developments in ground and space-borne geodetic technologies, software and computing power have allowed for unprecedented ability to detect spatial and temporal trends of ground surface displacement.

Traditionally, interpretations of GSD invoke volume change of a discrete source (often assumed to be a magma chamber) with a specified geometry in a homogeneous, isotropic, and elastic [*Fialko et al.*, 2001; *Mogi*, 1958; *Walsh and Decker*, 1971; *Yang et al.*, 1988], or viscoelastic [*Bonafede et al.*, 1986; *Newman et al.*, 2001] half-space. The calculated depth, shape, and volume change of the source in these models are derived from inversion of the measured GSD.

Nevertheless, in many cases, observed surface displacements display a multifaceted pattern, implying that the magma plumbing system has a complex geometry [*Battaglia and Vasco*, 2006; *Wicks et al.*, 2006]. Additionally, available models cannot distinguish between an aqueous, low-density, low-viscosity fluid and a dense and viscous magma. Further, an increasing number of observations indicate a causal link between transient groundwater and/or gas pressures and GSD in volcanoes [*Battaglia et al.*, 2006; *Chiodini et al.*, 2003; *Gottsmann et al.*, 2007; *Watson et al.*, 2000]. This suggests that deformation is likely induced by multi-phase, compressible fluids in a permeable media. Recent numerical modelling studies have indeed demonstrated that rates of GSD measured by geodetic techniques could theoretically be induced by poroelastic transients in the shallow hydrothermal system [*Hurwitz et al.*, 2007; *Todesco et al.*, 2004].

Despite the growing number of observations, the interplay between multiphase (magma - aqueous fluids - gas) flow dynamics and crustal mechanics in active volcanoes is poorly understood. Such inherent limitations hamper the ability to obtain reliable insight on processes associated with volcano deformation and thus, to provide an insightful hazard assessment.

2. Current short-comings

There is little direct knowledge of the structure and phase distribution in active volcanoes because only very few deep drill holes are located near the vents of recently erupting volcanoes (Kilauea and Unzen). Subsurface imaging has been carried out at many volcanoes and large calderas with a variety of geophysical techniques including seismic, electric and electromagnetic (MT, EM, SP, DC), magnetic, and gravity. However, in most cases, results from these surveys have been processed and interpreted separately from one another, which resulted in ambiguous, non-unique, and sometimes conflicting interpretations. In most cases the geophysical surveys were carried out for imaging the volcano plumbing system at a specific time. Geophysical surveys designed to detect time variations in structure are quite rare, with the exception of studies of seismicity.

Some deep holes drilled in large calderas, mainly for geothermal exploration, have shown that pre-drilling imaging surveys have provided an unrealistic interpretation of the subsurface. Examples include the Long Valley Exploratory Well (LVEW) in Long Valley and the Keller Well in Hawaii. The ~3 km LVEW drilled on the summit of Long Valley's resurgent dome in the 1990's was designed to investigate both, the potential for near-magmatic temperature energy extraction and the occurrence of magma under the dome [*Rundle et al.*, 1986]. In contrast to pre-drilling assumptions that were based on a variety of geophysical surveys, bottom-hole temperature at a depth of ~ 3 km was only 103°C, typical of a regular continental geotherm.

Many of the problems with the geophysical surveys resulted from either the lack of multi-disciplinary joint inversion modeling, imprecise inversion techniques (2-D rather than 3-D inversions), or insufficient consideration of geochemical and geological observations.

It has been known for decades that magma ascent in the crust leads to crystallization, degassing and bubble formation, which in turn, leads to the formation of a compressible three-phase mixture. The compressibility of the fluids can have a major effect on surface deformation but was not considered until recently [*Mastin et al.*, 2008; *Rivalta and Segall*, 2008]. One of the major obstacles in assessing magma compressibility is the lack of knowledge regarding the distribution of gas and magma in the subsurface.

Numerical simulations have demonstrated that pressure perturbations in the porous/fractured media of shallow hydrothermal systems might also be a significant agent for volcano deformation, especially in calderas with a vigorous hydrothermal system and abundant seismicity [*Hurwitz et al.*, 2007; *Todesco et al.*, 2004]. Such results are consistent with numerous observations of large fluxes of magma-derived gases at the ground surface. Such high rates require a permeable medium to transport the gases. Pressure perturbations in shallow hydrothermal systems are also consistent with many observations of very long period seismicity, which suggest a strong coupling between aqueous fluids, gases, and host rock [*Chouet*, 1996].

3. Suggested experiment

To overcome the major gaps of knowledge listed above, we propose to carry out a multi-disciplinary experiment at Kilauea Volcano in Hawaii, one of the most active volcanoes on Earth, to be followed by a similar experiment at Yellowstone, the largest restless caldera on Earth. The major goals of the proposed experiments, termed **Kilauea-MRI (Kilauea M**ultidisciplinary **R**esearch **I**nvestigation) and **Yellowstone MRI**, are to provide a robust characterization of the volcano's subsurface, quantify its multiphase dynamics, and relate these observations into a coherent model of volcano deformation.

The objective of the experiment is to eliminate some of the ambiguity and non-uniqueness obtained from the processing and interpretation of data from a single technique, by carrying out simultaneous collection of many data sets to arrive at a consistent interpretation. Such a large-scale, multifaceted experiment with modern techniques has never been carried out at an active volcano.

The proposed experiment will include a broad range of imaging techniques including seismic, electric, and gravity measurements that will allow characterization of the volcano's plumbing system and the transient phenomena associated with volcanic activity. The experiment will be augmented with gas flux and composition at high temporal resolution, period measurements of lava effusion rates, continuous GPS data, and radar interferometry (InSAR) observations.

- If results of the Kilauea experiment are encouraging, a similar experiment would be conducted at Yellowstone starting in project year 2. With sufficient funding, logistical support, and National Park Service approvals, the entire experiment could be completed in 4 years (deployments subject to National Park Service approval):

- Year 0 (2008) – Final experiment design and proposal writing.
- Year 1 (2009) – Proof-of-concept deployment at Kilauea and preliminary analysis of results.
- Year 2 (2010) – Full deployment at Kilauea and continuing analysis.
- Year 3 (2011) – Write final report for Kilauea experiment; full deployment at Yellowstone and preliminary analysis of results.
- Year 4 (2012) – Complete analysis of Yellowstone results, write final report, and write synthesis report.

Several "target" volcanoes were considered for the multi-disciplinary experiment, and it was unanimously concluded that Kilauea and Yellowstone are the best options for many reasons:

Kilauea:

- It has been erupting continuously for the past 25 years and thus a short-term experiment would most likely capture some transient phenomena.
- It is currently deforming at various time-scales, often including oscillatory behavior. For example, there are common inflation/deflation cycles in the summit region and in the ERZ lasting for 1-2 days superimposed on a gradual deflation trend of the summit region. The inflation/deflation cycles are most likely associated with a large gas vent in Halema'uma'u pit crater, but this association is not well understood.
- It is actively degassing and rates of gas discharge are routinely measured by the staff of HVO.
- It has one of the most extensive volcano monitoring networks, which would provide real-time, precise, and high-resolution information on ground-surface displacements throughout the proposed experiment [http://hvo.wr.usgs.gov/]
- Numerous geophysical surveys were conducted in the past [*Kauahikaua*, 1993; *Kauahikaua and Miklius*, 2003] and can be combined with new data to create a comprehensive data base and assess long-term changes in the plumbing system.
- The Hawaiian Volcano Observatory can coordinate the experiment with Hawaii Volcanoes National Park authorities, and access to most measurement sites can be done by vehicle or relatively short hikes.
- The deep Keller Well [*Keller et al.*, 1979] located very close to the most active pit crater in the summit region can provide necessary constraints for the inversion of raw geophysical data. Water pressure transients in the well were previously correlated with intrusive activity [*Hurwitz and Johnston*, 2003].

Yellowstone:

- The largest and most vigorously restless silicic caldera on Earth, Yellowstone has experienced intense seismicity, variable ground deformation (both uplift and subsidence at three major centers), and strong hydrothermal activity throughout historical time [*Smith and Siegel*, 2000; *Chang et al.*, 2007; *Vasco et al.*, 2007].
- Yellowstone is intensively monitored by the Yellowstone Volcano Observatory [http://volcanoes.usgs.gov/yvo/], a partnership among the USGS, University of Utah [http://www.seis.utah.edu/], and Yellowstone National Park; the Yellowstone region is the site of a Plate Boundary Observatory (PBO) [http://pboweb.unavco.org/] volcano instrument cluster, including continuous

GPS stations and borehole strainmeters, tiltmeters, and seismometers [*Puskas et al.*, 2007].

- Extensive seismic and deformation imaging studies of the caldera system have been conducted [*Husen et al.*, 2004; *Waite et al.*, 2005; *Waite et al.*, 2006; *Vasco et al.*, 2007], which provide a three-dimensional model to be tested by the experiment.
- The Yellowstone Volcano Observatory, comprising USGS, University of Utah, and Yellowstone National Park, can facilitate the permitting process in the Park.
- The Yellowstone hydrothermal system is among the most vigorous on Earth, and therefore Yellowstone provides an unparalleled opportunity to study the roles of magmatic and hydrothermal fluids in causing and affecting ground deformation [*Waite and Smith*, 2002; *Husen et al.*, 2004].
- At the time of this writing (spring 2008), Yellowstone has been deforming more rapidly (4-7 cm/yr uplift since mid 2004) than at any time since the first leveling survey in 1923; therefore the experiment is timely.

The initial experiment at Kilauea will be carried out for 7-10 days with the goal of (1) static imaging of the plumbing system and (2) observing transient phenomena associated with magma and gas transport. The experiment will be followed by a week of joint data processing and interpretation. The ultimate goal is to formulate a model of volcano deformation consistent with all the acquired datasets, with continuous data acquired with the current Kilauea monitoring network, and with the extensive data that was acquired in numerous studies at Kilauea. Results of the initial experiment will guide further experiment design for both Kilauea and Yellowstone, and serve as a basis for proposal writing starting in late 2008.

<u>4. Key scientific questions to be addressed:</u>

- What is the relationship between subsurface structure and surface deformation (Kilauea and Yellowstone)?
- How does the subsurface phase distribution (liquid, gas, solid) relate to volcano deformation (Kilauea and Yellowstone)?
- What are the magma transport mechanisms between the deforming summit region and the East Rift Zone where eruptions usually take place (Kilauea)?
- What are the mechanisms by which magmatic and hydrous fluids cause or modify ground surface deformation, and what is the nature of the observed interplay between deformation sources beneath the Sour Creek resurgent dome, Mallard Lake resurgent dome, and north caldera rim (Yellowstone)?
- What do the observed deflation/inflation (DI) events indicate in terms of source processes and how they relate to phase separation (magma degassing) in the shallow subsurface (Kilauea)?
- How do changes in the summit plumbing system evolve over short time-scales (Kilauea)?
- How does gas flux and composition correlate with potential field measurements (Kilauea and Yellowstone)?
- What is the nature of the causative source (Kilauea and Yellowstone)?
- How do changes in the shallow hydrothermal system relate to magma dynamics (Kilauea and Yellowstone)?

<u>5. Methods to be used in the initial experiment at Kilauea:</u>

Abundant geophysical surveys conducted at Kilauea and Yellowstone during the past three decades have provided invaluable information on the subsurface structure. However, because many studies were conducted in campaign mode, they have not provided much needed information on magma and gas dynamics and their relation to deformation [*Kauahikaua*, 1993; *Kauahikaua and Miklius*, 2003]. Further, many of the surveys had non-unique results and there are many conflicting interpretations. Thus, a coherent and robust understanding of the subsurface structure and volcano dynamics is lacking. Methods that might be used in **Kilauea-MRI** and **Yellowstone MRI** include:

Seismic – Many studies that have used data from the HVO seismic network and from temporary deployments [*Almendros et al.*, 2002; *Haslinger et al.*, 2001] and a variety of inversion techniques to obtain tomographic images of Kilauea's structure and hydrothermal system. HVO operates a dense seismic network, including several broadband seismometers. The abundant seismicity in Kilauea allows for excellent ray coverage of complex subsurface features. The abundant long-period and very-long-period earthquakes provides robust evidence for coupling and interaction between aqueous fluids, gases, magma, and rocks [*Dawson et al.*, 2004; *Ohminato et al.*, 1998]. Nevertheless, there are some major discrepancies between the interpretations of these studies. For example, it is not known if the magma in the shallow subsurface is accumulated in a complex pattern of sills and dykes [*Dawson et al.*, 2004] or if there is sizable and well-defined reservoir underlying the southern part of Kilauea Caldera [*Haslinger et al.*, 2001].

Gravity - Continuous, high-precision microgravity measurements may be used to discriminate between magma intrusion and hydrothermal injection at shallow depths. This method works because the density of magma differs by a factor of 3 or more from the density of superheated vapor or gas [*Carbone et al.*, 2003; *de Zeeuw-van Dalfsen et al.*, 2005; *Gottsmann and Rymer*, 2002; *Rymer*, 1994; *Williams-Jones et al.*, 2003]. Combining geodetic and microgravity data with quantitative dynamic models should provide insight into the nature of the fluid inducing deformation. The current state-of-the-art regarding gravimetric investigations includes static and dynamic observations. The latter include campaign style (time-lapse) observations [*Kauahikaua and Miklius*, 2003] and few sites also have continuous observations. Absolute gravimeters have not been used widely at volcanoes, owing to their high cost and limited availability. However, the unique capabilities of absolute gravimeters hold considerable promise for illuminating the structure and dynamics of volcanoes [*Furuya et al.*, 2003].

Magnetic – changes in magnetic fields have been associated with a number of volcanic eruptions, including Kilauea [*Keller et al.*, 1972]. Several physical mechanisms can causes these effects including (1) magma is non-magnetic and become magnetized below the Curie temperature and (2) a possible piezo-magnetic effect. In basaltic volcanoes, both remnant and induced magnetization must be considered. Temporal changes in the magnetic field at Kilauea may be associated with ongoing deformation. Effects of external field variations and ground motion must be accounted for in any data analysis.

Electrical and electromagnetic methods– Electric and magnetic fields can be generated by crustal deformation and earthquakes through a range of effects that include (1) piezomagnetism, stress/conductivity, (2) electrokinetic effects, (3) charge generation and dispersion, and (4) magnetohydrodynamic effects [*Johnston*, 1997; *Skokan*, 1993]. Several geo-electric techniques were used in the past to image different depth ranges and processes in volcanoes including Kilauea [*Kauahikaua et al.*, 1986; *Zablocki*, 1978]. Time-domain EM or DC resistivity methods can provide information about the distribution of fluids and clay-rich alteration zones in the upper few hundred meters of a volcano. At greater depths it might be possible to image magma bodies with natural source EM methods such as magnetotellurics [*Aizawa et al.*, 2004; *Wannamaker*, 1991]. The near surface resistivity structure in volcanic regions is highly variable and relatively dense spatial sampling is needed in these surveys to avoid spatial aliasing. In addition, the 3-D nature of most volcanoes requires a fully 3-D approach. These factors have limited previous studies. However, in recent years new MT systems have been developed that are lightweight and which do not require the continuous presence of an operator. This allows much larger datasets to be collected that can address the problems listed above. Advances in data analysis techniques now permit both 2D and 3D inversion of MT data to give a model of subsurface resistivity. A fundamental limitation of MT that cannot be overcome by these advances is the fact that zones of low resistivity can be due to hydrothermal fluids, alteration or magma. Additional information is required to overcome this ambiguity and this fits in well with the philosophy of the proposed study at Kilauea. Self Potential (SP) data can provide information on shallow fluid flow by analysis via wavelet transforms. SP data is easy to collect but interpretations is complex and potentially ambiguous [*Jackson and Kauahikaua*, 1987; *Johnston et al.*, 2001; *Revil*, 2002]. Surface processes such as changes rainfall can mask the effects of deeper changes. Having a resistivity model (from DC resistivity or MT) can greatly assist in interpretation of SP data).

Gas –Direct and indirect measurements of volcanic gas composition and flux have proven critical in gaining insight into magmatic systems and have been a key component of volcano monitoring. HVO has made and continues to perform routine gas emissions (principally SO_2 and CO_2) measurements at the summit and at the ERZ since the 1970s. Recent technological developments and instrumental cost reductions have enabled semi-continuous monitoring of SO_2 flux from persistently active volcanoes such as Stromboli (Italy), Soufrierre Hills (Montserrat) and Mt. Etna (Italy). Integration with other geophysical studies [*Watson et al.*, 2000; *Williams-Jones et al.*, 2003; *Zapata et al.*, 1997] has also proven particularly powerful in understanding magmatic processes. Continuous measurements (for limited time periods) of gas composition can be made accurately, remotely, and with a high degree of temporal resolution at active gas vents using open path Fourier transform infrared spectroscopy (OP FTIR). This is a spectroscopic technique that utilizes the precise absorptivity of a particular gas to determine its concentration. Indeed, successful application of the method was carried out at Pu`u`Ō`ō, the location of current eruption in the ERZ [*Edmonds and Gerlach*, 2007].

GPS – HVO, in collaboration with Stanford University and the University of Hawaii, operates a dense network of continuous GPS stations at Kilauea that provides near-real time information about ground surface displacements in the summit area and along the East Rift Zone. YVO and PBO operate a similar, though less dense, network at Yellowstone.

InSAR – InSAR is the best method to map the spatial distribution of GSD, but the temporal pattern is poorly constrained as a result of satellite orbit repeat times that are typically 35–42 days. An attempt will be made to coordinate possible repeat orbits of operational SAR satellites (Envisat, Radarsat-1, ALOS) during the experiment to allow for a robust correlation with land-based measurements.

6. Expected results and achievements

It is expected that simultaneous inversion of multiple geochemical and geophysical datasets will provide the basis for a unique, robust, and coherent image of Kilauea's subsurface that may clarify the complex physical and chemical relationships and the multiphase dynamics between summit activity and activity at Pu'u 'O'o. At Yellowstone, the experiment will improve understanding of subsurface structure and the mechanisms responsible for GSD, especially the roles played by fluids of magmatic and meteoric origins. Use of gravity, magnetic and electric techniques in conjunction with gas geochemistry in the routine monitoring systems has the potential to substantially enhance forecasting of changes in eruptive activity at Kilauea as well as at numerous other volcanoes would provide the methodology for imaging volcanoes, which in turn, would improve of understanding of precursory signals of volcanic unrest. Overall, it is expected that the proposed work will initiate a longer term effort to better understand volcano dynamics.

7. Plans of action

- Shaul Hurwitz (USGS), Glyn Williams-Jones (Simon Fraser U. – Canada), Martyn Unsworth (U. Alberta – Canada), and Dan Dzurisin (USGS) will serve as the steering committee of **Kilauea-MRI**. They will design and coordinate the proposed experiment together with Jim Kauahikaua and Mike Poland at HVO and John Eichelberger, coordinator of the Volcano Hazards Program.
- Dan Dzurisin will initiate discussions with Jake Lowenstern, Hank Heasler, and Bob Smith of YVO to create a similar steering committee for the Yellowstone experiment.
- John Eichelberger will communicate with program managers at NSF and the European scientists will try to obtain funding through their respective science foundations.
- Mike Poland will deploy a gravimeter at the basement of HVO to quantify short-term variability in the gravity field strength. That would indicate if the level of noise is low enough to justify locating a sensitive absolute gravimeter there.
- If funding is provided, the proof-of-concept **Kilauea-MRI** will be conducted in spring 2009.

- 8. Funding opportunities
- The USGS Volcano Hazards Program has endorsed that the idea of **Kilauea-MRI**, will sponsor the experiment, and will provide some funds. The Yellowstone component was added upon reflection following the 2008 Volcano Deformation and Gravity Workshop; VHP support will be sought starting with the FY 2009 Basis Plus funding cycle.
- Scientists from American academic institutes interested in participating in **Kilauea-MRI** and **Yellowstone-MRI** will be encouraged to apply for NSF grants. To accommodate the ambitious timetable for the **Kilauea-MRI** "proof-of-concept"

experiment (spring 2009), scientists will be encouraged to submit Small Grants for Exploratory Research (SGER) Proposals (http://www.nsf.gov/pubs/gpg/nsf04_23/2.jsp#IID1), which are processed faster than standard NSF proposals.

- Non-American scientists will investigate the possibility of parallel expedited funding from their respective science foundations.

9. Five years down the road

- The ability to have a more reliable and robust understanding of geodetic signals as precursors to volcanic unrest.
- Provide constraint on the nature of the deforming fluid (magma, hydrothermal fluids, and/or gas) during periods of unrest using improved technology for subsurface imaging and fluid dynamics.
- More accurate and comprehensive modelling tools that would account for multiphase and compressible fluids in elastic as well as poroelastic media through complete integration of deformation and gravity data
- Incorporation of continuous micro-gravity and geo-electric networks into the volcano monitoring program.
- Analysis of geodetic signals in conjunction with gas emission rates and composition.
- Application of the knowledge gained from **Kilauea-MRI** and **Yellowstone MRI** to other similar volcanic systems.

10. References

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