Cascades Volcano PBO Instrument Clusters

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INTRODUCTION

The 1300-km-long Cascade volcanic arc is a major structural element in the enigmatic Juan de Fuca–North American (JDF-NAM) plate boundary, and it is the largest and most active volcanic system in the conterminous United States. The rate and style of volcanism varies along the arc, with a zone of basaltic andesite shield volcanoes in Oregon and composite statovolcanoes elsewhere.

Recent geologic and geodetic studies reveal a complex plate boundary with a tightly coupled main thrust zone and a large rotating forearc sliver (Oregon coast block – OC, fig. 1). Oblique subduction between the JDF and NAM plates and collision of the translating Sierra Nevada block cause the OC block to rotate (Wells and Simpson, *Earth, Planets, and Space*, in press). The volcanic arc accommodates the rotation of OC block to the west and extension of Basin and Range Province to the east.

We propose to densely instrument two groups of Cascade volcanoes: Mount St. Helens and Mount Rainier, located near the northeastern transpressional end of the rotating OC block, and Mount Shasta and Medicine Lake, a composite/shield pair, located at its southeastern transtensional end (fig. 1). Together they include the most active and potentially dangerous volcanoes in the arc. They exhibit a range of eruptive styles from explosive (Mount St. Helens) to effusive (Medicine Lake), and include steep-sided stratovolcanoes with unstable ice-capped edifices (Mount Rainier and Mount Shasta).

Tracking magmatic processes and edifice instabilities requires high spatial and broad temporal strain resolution near the volcano. Understanding interactions between magmatic and tectonic processes requires broad-scale deformation monitoring. Our proposed work will complement and be coordinated with that planned by the Pacific Northwest Geodetic Array (PANGA) community and other tectonic researchers. In addition, the PBO backbone network and PANGA clusters will provide anchors for campaign-style GPS monitoring of other Cascade volcanoes.

VOLCANO DEFORMATION MONITORING

Volcanoes are episodically active and are best monitored continuously. Earthquakes currently provide the best indicator of impending magmatic activity, but they provide an incomplete picture.

The eruptive cycle is characterized by an extended period of magma accumulation in the crust followed by rapid transport to the surface through new cracks or existing conduits. Borehole strain and GPS have been used to track magma intrusions at several well-instrumented volcanoes. Real-time, continuous deformation monitoring along with analysis tools, such as the Network Inversion Filter (Segall and Mathews, *JGR*, 1997), offer the possibility of characterizing the eruptive cycle as it proceeds, including periods of aseismic magma accumulation. A record of magmatic events that documents changes occurring over periods from seconds to years is crucial to understanding how volcanoes work.

Volcanic edifices are often unstable and may fail, even in the absence of magmatic forcing. Debris avalanche deposits throughout the Cascades document past occurrences of catastrophic flank failures. Mount Rainier, with its massive edifice, steep slopes, and location near the densely populated Puget Lowlands, poses a particular hazard. Geodetic monitoring must be dense and broad enough to allow discriminating between magmatic, tectonic, and landslide events.

PROPOSED PBO INSTRUMENT CLUSTERS

We briefly summarize characteristics of target volcanoes and then outline a generic Cascade volcano monitoring strategy.

Mount St Helens and Mount Rainier Group

Mount St. Helens is the most active Cascade volcano (fig. 1). In the last 515 years it has produced four major explosive eruptions and dozens of lesser eruptions. Eruptive products from the May18, 1980, blast, five smaller explosive eruptions, and sixteen dome-building eruptions totaled about 1km^3. Gas and pulverized debris erupted six times in 1989 from a 275-m-high lava dome in the crater. Petrologic studies suggest material erupted in 1980 originated in a magma reservoir 6.5–11 km deep. A vertically elongate magma chamber with a radius less than 0.25 km and a volume of 10–20 km^3 is consistent with the aseismic zone observed in 1980 and with tomographic studies. The volcano remains seismically active. Focal mechanisms of deep seismicity (6.5–10 km) since 1986 are consistent with repressurization of the magma chamber. Increased seismic activity in 1998 was accompanied by increased CO_2 emissions, suggesting the intrusion of new magma. Shortly after the 1980 eruption, the M5.5 Elk Lake earthquake occurred on the 90-km-long NNW striking St. Helens Seismic Zone. The St. Helens seismic zone remains a source of persistent seismic activity, with mostly right-lateral strike-slip focal mechanisms.

One of the most seismically active Cascade volcanoes, Mount Rainier is potentially the most dangerous (National Research Council, 1994). Just 70 km from the Seattle-Tacoma megatropolis, even a small eruption could melt its ice cap or trigger flank collapse. A persistent (a few earthquakes/month) source of volcano-tectonic (VT) earthquakes lies just below the inferred base of the edifice. The VT earthquakes are believed to result from gravity-induced slip in an edifice weakened by circulation of magmatic and hydrothermal fluids (Moran et al., *Bull. Volcanology*, 61, 2000, pp. 425-436). In addition, the 40-km-long north/south trending western Rainier seismic zone (WRSZ) lies about 12 km west of the summit. Right-lateral strike slip focal mechanisms indicate tectonic forcing. Seismic tomography suggests a cylindrical10-kmdiameter low-velocity anomaly that extends from 8-to18 km below the summit (Moran et al., *JGR*, 1999, pp 775–786). No earthquakes occur within this volume, suggesting elevated temperatures and, possibly, pockets of hot fluids or melt. Deep long period earthquakes occur along the eastern edge of the WRSZ. If these earthquakes result from the transport of magma from depth, then the relatively weak WRSZ may provide a path for recharging the magmatic system. Mount Rainier with its unstable edifice, active magmatic/hydrothermal system, and complex tectonic setting provides an ideal target for increased geodetic monitoring.

Mount Shasta and Medicine Lake Volcano Group:

These volcanoes offer the opportunity, unique in the Cascade Range, to monitor active magmatic and tectonic processes where volcanic risk is relatively high and both regional and volcanic deformation are known to be occurring. Even though they are separated by only 50 km, they are the two largest volcanoes by volume in the Cascade Range. The number of eruptive episodes at each in the last 4000 years (fig. 1) trails only Mount St. Helens.

Medicine Lake is the only volcano in the Cascade Range known to be actively deforming. Leveling surveys in 1954, 1989, and 1999 reveal that the entire edifice is subsiding at rates up to 8 mm/yr. Sporadic earthquake swarms in the area suggest that deformation may be episodic rather than continuous.

Mount Shasta, like Mount Rainier, has a large, unstable ice-capped edifice. Eruptions during the past 10,000 years produced lava flows and domes on and around its flanks and pyroclastic flows extending out to 20 km from the summit. Most of these eruptions produced large mudflows. Relatively high eruption rates combined with nearby population centers make Mount Shasta one of the highest risk volcanoes in the Cascade Range.

Cluster Design

Previous deformation monitoring at Mount St. Helens and other Cascade volcanoes was designed to detect the intrusion of magma within a few km of the surface. Little is known about how magma accumulates in the crust or how tectonic interactions influence eruptions.

A spatially dense, wide-aperture continuous monitoring network is needed to characterize the deep magmatic reservoir that feed these intrusions, to track the ascent of magma to the surface in real-time, and unravel magmatic-tectonic interactions. We propose deploying a network of GPS, tiltmeters, and strainmeters to address these issues.

Displacements, strain, and tilt from pressurization of a spherical- (Mogi) and a pipe-shaped magma reservoir, end-member magma storage geometries, are shown in Figure 2. The depths to the magma reservoirs (fig. 2a) are those estimated for Mount St. Helens. Large and variable deformation is concentrated above the magma chamber out to a radial distance of one source depth. Maximum vertical displacement and dilatational strain are found directly above the Mogi source (fig. 2b, 2c), but they found at a distance of about one half the source depth above a pipe-shaped magma chamber. Tilt changes are large and very different for these two types of sources out to distances of one source depth (fig. 2d). Detectable deformation extends out to distances of several source depths.

We propose monitoring networks consisting of five GPS/tiltmeter stations deployed at different distances and in different sectors of the volcanoes out to distances of 10 km, five strainmeters as close as practically possible and out to distances of 15 km, and five GPS stations in a line extending across the arc from distances of 10 to 30 km.

Borehole tiltmeters offer a low-cost, real-time, easily deployed, and very sensitive method to monitor near-field deformation. Combining GPS with tiltmeters has many practical advantages. Power, telemetry, and on-site data management can be shared. The data are complementary: tiltmeters are most sensitive to vertical deformation over short periods (minutes to days) and GPS to horizontal deformation over longer periods (days to years). Tiltmeters can be installed in relatively shallow holes (>6 m), which could be drilled with a small rig that could be easily transported by light truck or helicopter. The cased tiltmeter hole could serve as a deep-anchored monument for GPS.

SUMMARY

We propose installing PBO instrument clusters on two groups of Cascade volcanoes; Mount St. Helens – Mount Rainier and Mount Shasta –Medicine Lake Volcano. Together they include the most active and potentially dangerous, most effusive and most explosive, and most unstable volcanoes in the arc.

The proposed instrument clusters will be deployed in radial arrays within 15 km of the volcanoes and in linear arrays across the arc at distances from15 to 30 km. A total of 20 GPS/tiltmeter stations, 20 strainmeters, and 20 GPS stations are requested for the four target volcanoes.

Dense spatial and broad temporal deformation monitoring will allow us to characterize and track both deep and shallow magmatic processes, and may reveal previously undetected episodes of crustal magma accumulation. We can also study whether magmatic activity is the primary trigger for large landslides and how adjacent seismic zones accommodate tectonic and magmatic activity.

Our work will be coordinated with studies of Cascadia subduction tectonic deformation to better understand the forces at work in this enigmatic convergent plate boundary. Campaign GPS surveys anchored to nearby PBO backbone or cluster stations are planned for other Cascade volcanoes.

Real-time data download and analysis are an integral part of our volcano monitoring networks, allowing tracking of unrest and intrusions as they occur. This system could serve as a model for deployments at other volcanoes.

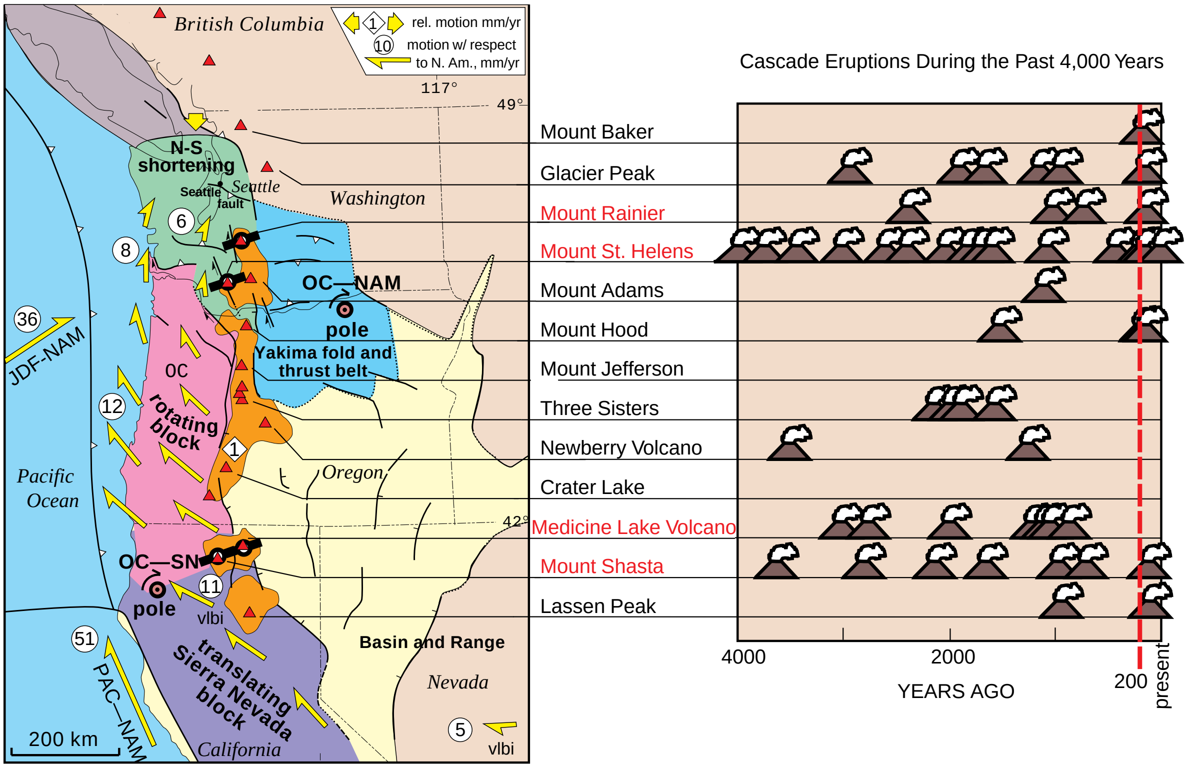

Figure 1. Cascadia tectonic setting (Wells and Simpson, in press) and history of Cascade volcano eruptions. Yellow arrows shows motion relative to North American Plate (NAM). Proposed target volcanoes have red names and cluster deployments are marked with black bowties.

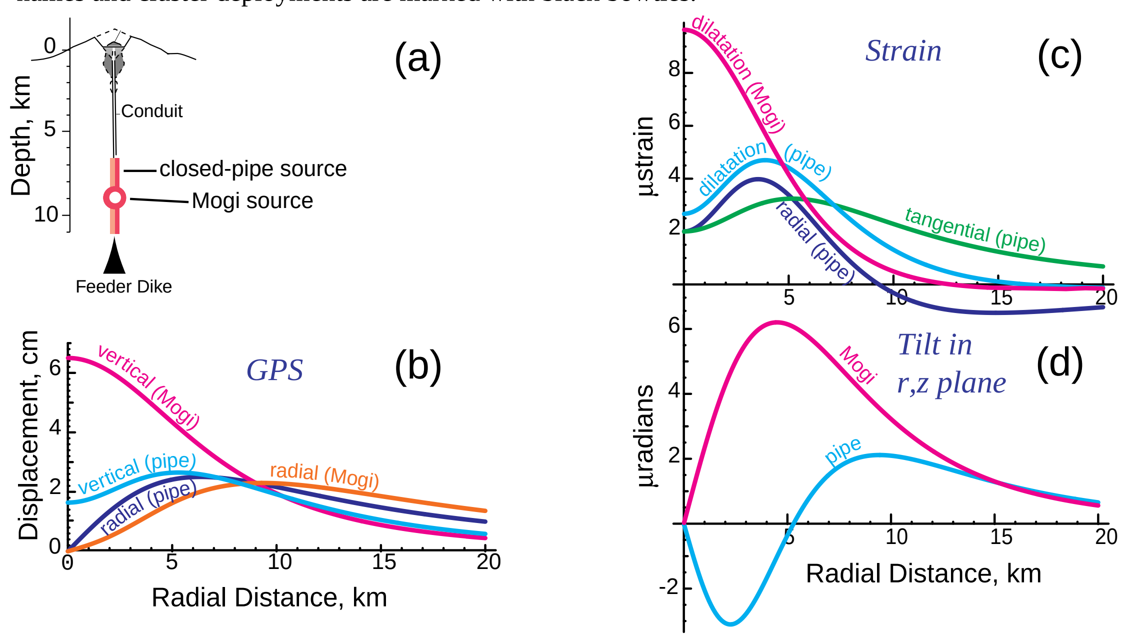

Figure 2. Elastic dislocation model of surface deformation from 100 MPa pressure increase in a deep magma reservoir. Mogi (spherical) source has a radius of 0.6 km and a depth of 9 km. Closed- pipe source (Bonaccorso and Davis, JGR, 1999) top is at 6.5 km, bottom at 11 km, and it has a radius of 0.25 km. For our assummed shear modulus of 3000 MPa and Poisson ratio of 0.25, a 100 MPa pressure increase would result from the injection of 0.02 km^3 of magma.