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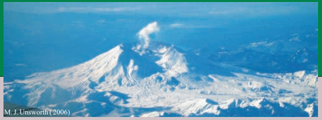
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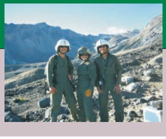

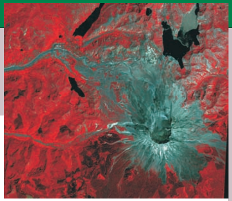

Groundwater Hydrology within the Crater of Mount St. Helens

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Motivation

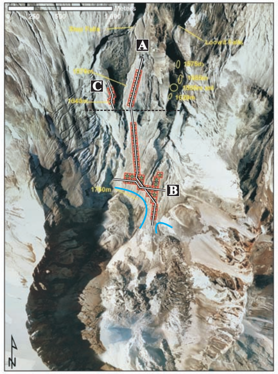
Hydrologic systems within volcanoes are complex. Hydrothermal fluids moving within the volcanic edifice facilitate alteration, creating zones of mechanical weakness that can lead to sector collapse or lahar generation. In addition, the interaction of surface or groundwater with the magmatic system can trigger phreatic eruptions which may precede large-scale magmatic eruptions.

Despite the vital role of groundwater in volcanic hazards, little is known about subsurface volcano hydrology. Efforts to develop groundwater models are hindered by a lack of data on water-table elevation and poor constraints on water budget. Geophysical data generally suffer from decreasing resolution with increasing depth, thus limiting our ability to resolve deep structure. At Mount St. Helens, the removal of 450m of elevation during the 1980 eruption provides a unique window into the deeper plumbing of an active stratovolcano.

Background

Mount St. Helens (MSH) reawakened in September, 2004 following unusually heavy August rainfall. The eruption began with a swarm of shallow seismicity beneath the central crater and was not preceded by anomalous deformation or gas emissions. Lave dome extrusion began in October, 2004 just south of the 1980-86 dome and continued until the declared end of activity in mid-2008.

Our studies took place in Summer 2007, during the waning phase of the eruption. Spatial coverage was limited by advance of the crater glaciers and rockfall hazards near the growing dome.



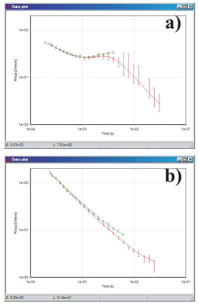
The crater of MSH during dome building in summer 2006. Locations of TEM soundings denoted by red squares (transmitter loops) and green stars (receiver locations). At the time of the 2007 survey, the east and west crater glaciers had advanced to the lines drawn in blue; they have since merged north of the 1980-86 dome. Yellow ellipses indicate the location of hot springs feeding Loowit Creek. Black dashed line indicates the Rampart, a pronounced topographic step.

Method & Data Processing

Time-domain electromagnetics (TEM) is a near-surface geophysical technique capable of imaging resistivity structure on scales intermediate between DC resistivity and magnetotellurics (50-500m). As an inductive technique, it is well suited to volcanic terrains where high contact resistance often hinders current injection and/or potential measurement.

In practice, the TEM method consists of transmitting current through a large wire loop (here a 50m x 50m square) and then turning it off rapidly. The current turn-off induces ring currents in the earth which diffuse downward and outward with time. In subsurface conductors, eddy currents are generated, which in turn produce secondary magnetic fields that are measured at a receiver located in the center of the transmitter loop. It is the time decay of the measured secondary fields that contain information about earth resistivity.

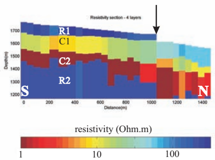
Measured data are averaged and converted to an apparent resistivity versus time curve. These data are then inverted to produce 1D resistivity models using the SiTEM/Semdi inversion package (Aarhus Geophyics).



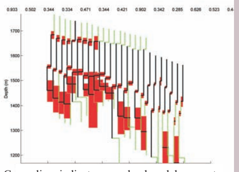
Characteristic TEM apparent resistivity data and model fits from Mount St. Helens. a) characteristic sounding within the breached north face, b) characteristic sounding atop the Sasquatch Steps (westernmost 3 soundings).

Inversion

Profile A

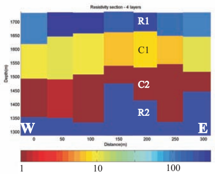


Resistor R1 consists of unsaturated 1980 avalanche and pyroclastic deposits. Both R1 and conductors C1 and C2 can be traced north until the Rampart. C1 is consistent with an aquifer within or below the 1980 deposits. C2 may be an aquifer within an older Castle Creek breccia. R2 may be of Pine Creek age. Structural changes south of the Rampart suggest the absence of the unsaturated 1980 deposits or down-dropped structure, ie differential erosion of pre-1980 units. Arrow denotes location of Rampart. VE=1:1.

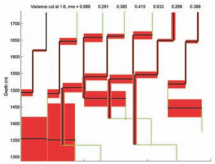


Green lines indicate unresolved model parameters. Red bars show range of acceptable parameters. For each curve, resistivity increases to the right.

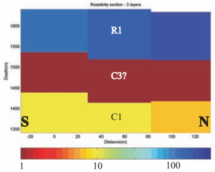
Profile B



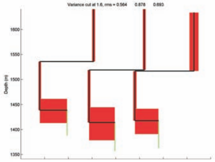
Profile B crosses just north of the toe of the west crater glacier. The resistivity structure is similar to profile A. R1 is thicker closer to the dome than further to the north. The increased resistivity of R1 toward the center of profile B may reflect the influx of cold fresh water into the 1980 avalanche deposits from the encroaching glacier. VE=2:1.



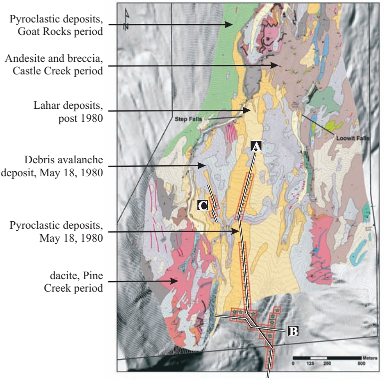
Profile C



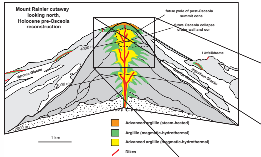
Profile C runs along one of the Sasquatch Steps, a remnant of the pre-1980 edifice that stands 50-60m above the surrounding area. The resistivity structure includes a highly conductive unit, C3, between the 1980 avalanche deposits and the inferred C1 seen elsewhere. This suggests that C1 is pre-1980; if C1 is of Castle Creek age, than the overlying C3 may be associated with the Goat Rocks or Kalama eruptive cycles. VE=2:1.

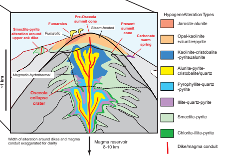


Interpretation



Geologic map of the crater from *Hausbeck* (2000). Major units relevant to this work are labeled. The Goat Rocks eruptive period spans 1800-1858AD, the Castle Creek period spans 2200-1700bp, and the Pine Creek period spans 3000-2500bp.





The elevation of the top of C1 agrees with the elevation of hot springs that flow into Loowit Creek near the Rampart. Furthermore, north of the Rampart, this conductive layer comes to the surface, and in this region hot seeps occur which feed Step Creek.

The deeper conductive layer likely falls within a thick brecciated member of Castle Creek age, and may be perched above the basal andesitic flow of the Castle Creek period, or possibly a pyroclastic flow of the Pine Creek period. _The extremely high conductivity of this layer suggests the presence of clays_ - argillic alteration products typically formed between 70°C and 200°C. These temperatures are reasonable for estimated burial depths of 500-750m prior to the 1980 eruption.

Our work suggests that in young, active stratovolcanoes there exists a complex, _multi-tiered groundwater system_. The geometry of this system is to first order governed by the heterogeneous permeability distribution presented by the composite stack of lava flows, pyroclastic flows, breccias, and debris flow deposits comprising the edifice.

This picture is in accordance with the work by *John et al.* (2008), who examined alteration products shed from Mount Rainier to infer a 'Christmas tree' pattern of alteration within the edifice (above). The alteration 'branches' map out regions of past and present hydrothermal flow. The authors suggest that alteration is most intense in brecciated units due to higher permeability and porosity that facilitate flux of hydrothermal fluids. It is the alteration products within these units which give rise to the enhanced conductivity as seen at MSH. _Due to increased temperature (500-1000m burial depth) and localized fluid flow, these alteration products have formed within the last 3000 years_, as constrained by crater geology.

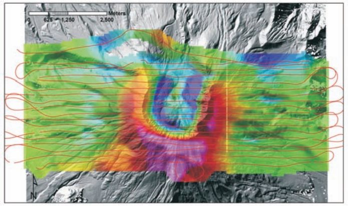
Additional Geophysical Data

Self-potential (SP) data were collected in 2000-01 (green), and 2007 (yellow) within the crater. The 2000-01 data discovered _a shallow hydrothermal system beneath the 1980-86 dome, interpreted to be fed in part by fluids exsolved from cooling magma_, and likely connected to the thermal springs and seeps associated with Loowit and Step Creeks [*Bedrosian et al.,* 2007].

The 2007 data were collected to examine changes to the hydrothermal system in response to the 2004-08 eruption. It was hypothesized that the hydrothermal system would be 'boiled off' early in the eruptive sequence. Initial analysis of the 2007 data indicate that the largest SP changes occurred closest to the 2004-08 dome, however, the similarity of the SP fields before and during the eruption _suggest a remarkable resilience of the hydrothermal system to dome-building processes immediately to the south._

Aeromagnetic data were also collected in 2007 over the bulk of the MSH edifice. Shown at right is total magnetic field intensity continued to a height of 300m and leveled along profile [C. *Finn & E. Anderson,* pers. comm.]

This data is presently being examined to determine Curie depth within the crater. Additionally, it will be examined in combination with the TEM data presented here and earlier airborne electromagnetic (EM) data to look for areas of hydrothermal alteration within the shallow subsurface. Due to its relative youth, MSH shows little surface alteration, however the combined interpretation of magnetic and EM data has been quite successful at mapping alteration zones on Mt. Rainier and Mt. Adams [*Finn et al.,*



Conclusions

- **An active hydrothermal system exists within the crater of Mount St. Helens and has not abated during the 2004-08 eruption.**
- **Within the crater, a perched aquifer is imaged at 60-120m depth within or at the base of the May 18, 1980 debris avalanche deposits. Thermal waters associated with this aquifer feed Loowit Creek.**
- **A more conductive boundary is imaged at 200m depth, indicating a deeper aquifer confined within a breccia deposit of Castle Creek age and perched above a less permeable basal lava flow of Castle Creek age or pyroclastic deposits of Pine Creek age.**
- **The extremely high conductivity of this deeper boundary suggests clay alteration. Though young in age, the elevated temperatures at 500-750m burial and localized fluid movement along flow boundaries support the rapid formation of hydrothermal alteration products.**

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