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USE OF ELECTRICAL RESISTIVITY IMAGING TO INVESTIGATE DEPTH AND CONCENTRATION OF SUBSURFACE ICE IN A SUSPECTED 'ICE CORED' MORAINE

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ABSTRACT

"Ice Cored" moraines are common features near many alpine glaciers. The presence of subsurface ice in both recessional and lateral moraines is believed to be indicated by slopes steeper than would be expected from the normal angle of repose of unconsolidated glacial debris. The 'ice core' probably takes the form of discontinuous ice lenses that serve as structure holding the otherwise unconsolidated material in an oversteepened state. The work reported herein tested electrical resistance image tools to confirm the presence of ice in the lateral moraine of the Elliot glacier, Mt. Hood Oregon. The presence of what are believed to be discontinuous ice lenses in the lateral moraine is supported by the electrical resistance images. In addition, this tool was found to be potentially very useful in assessing the depth of debris cover for many 'rock glaciers'.

Keywords: Electrical resistance imaging, ice cored moraines, rock glaciers, debris covered glaciers.

INTRODUCTION

Alpine glaciers are sensitive indicators of climatic conditions. From the time of the most recent glacial maximum (~ 11,000 BP), through the glacial retreat and ice free conditions of the 13^{th} and 14^{th} centuries, through the Little Ice Age of the 1600's when glaciers globally show evidence of advance, to the current evidence of warming and melting, alpine glaciers record very clearly changes in climatic conditions.

Globally, it appears that glacial retreat occurring as part of the overall warming trend that started after the retreat of the most recent continental glaciation (~11,000 BP) ceased during the Little Ice Age (mid 1600's). Glacial retreat (melting) began again during recent time, as the globe warmed (Lonne and Laesa, 2005). Abundant evidence for fluctuations in alpine glaciers is readily visible in the mountainous areas of the globe. In the United States, the stratovolcanoes of the High Cascades of the Pacific Northwest have a long record of advances and retreats and the formation/destruction of supraglacial features. Glaciers in the Cascades of Oregon have been shown to be in continuous retreat since at least 1900 with the greatest retreat occurring in the first decades of the 20^{th} century (1900-1924) (McDonald, 1994). These observations fit with many other published reports suggesting that the global climate has re-entered a warming period. However, in many places in the Cascades glacial ice is still present and active glacial processes can be directly observed at relatively low elevations (6000 to 10,000 feet).

During retreat of an alpine glacier, ice continues to flow down slope, but the rate of ablation (loss due to melting and sublimation) exceeds advance and sediments cover the ice front forming what is called a debris-covered glacier. Glaciers of this type form a significant population of alpine glaciers worldwide. Ice left in the core of moraines usually forms steep sided features with the ice core covered by 1-3 meters of glacial debris (Kruger and Kjaer, 2000). There is well-accepted support for an assumption of an 'ice core' when the slopes of a moraine are extremely steep and the relief is higher than would be expected under the simple limits of gravity and the angle of repose of glacial debris [Photo 1 shows the steep slopes of the lateral moraines of the Elliot glacier].

Photo 1 (1990): Steep slopes and high local relief of this moraine provides strong evidence of an ice core.

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Rapid melting of ice-cored moraines forms a significant potential natural hazard. Ice cored moraines often act as dams, holding back melt-water lakes at high altitudes. Failure of these dams has the potential to cause great damage to communities and environments on the lower slopes (Richardson and Reynolds, 2000). In recently deglaciated areas in the Cascade Range, at least 30 lakes are dammed by unconsolidated moraines that are susceptible to breaching (O'Connor *et al*., 2001) [Photo 2 is a vertical air photo of a meltwater lake (Carver Lake on South Sister, Oregon) with what appear to be ice cored moraines acting as the dam containing the lake].

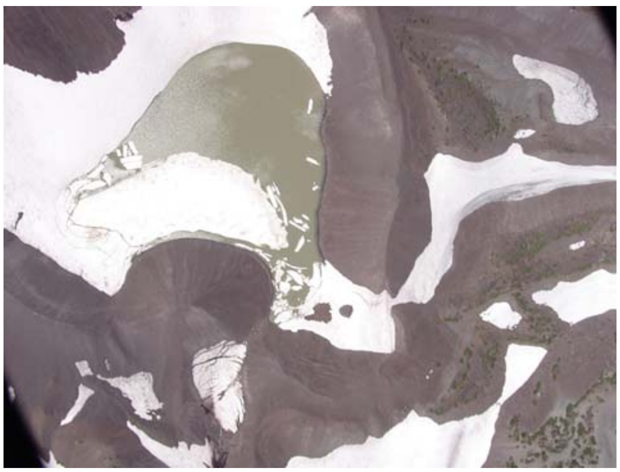

Photo 2. 2006: Vertical Air Photo of Carver Lake, South Sister. This lake is formed by steep moraines that are believed to be ice cored.

Anecdotal evidence suggests that not only is glacial ice retreating, but supraglacial features such as ice-cored moraines are rapidly retreating (melting) (Rosenfeld, 2005 Personal Communication) [Photos 3 and 4 clearly show the retreat of the debris covered Elliot glacier between 1990 and 2006].

Photo 3 (1990): Lateral Moraine (ice cored) and debris covered Elliot glacier, Mt. Hood again, the steep slope of the lateral moraine suggests an ice core and the hummocky irregular surface indicates debris covered glacial ice.

Photo 4. 2006: The retreat of Elliott glacier is obvious when compared with the 1990 photograph (Photo 3). Saturated sediments ('weeping') on both sides of the main valley and at the base of the lateral moraines indicate melting ice.

Electrical resistance imaging tools are fairly common in geophysical investigations. Electrical current is injected into the ground from a line of electrodes. Resistance to the flow of electrical current is measured at other electrodes along the array line. Image processing software integrates the measured resistance and models a cross section of electrical resistance in the sub-surface. While an extremely useful tool, the results are very open to interpretation. In spite of any limitations, used alone or integrated into an array of other geophysical archeological tools, electrical resistivity imaging equipment has been widely used at archeological sites in Great Britain, Europe, the Middle East and the United States. Electrical resistance imaging allows location of a variety of underground features including building sites, resource production sites, and graves.

Because data is gathered quickly and non-invasively, electrical resistance imaging is ideal for preliminary evaluations of archeological impact at modern building and development sites and for location of unmarked graves at established cemeteries. See for example; Powell 2004, Iowa Office of the State Archaeologist 2003, and Johnson 2003.

Confirmation of the surface expression of the ice cored features should be possible by examining an electrical resistivity cross section of the subsurface. Elvin *et al*. (1997), briefly reported success in identifying and mapping ice lenses in rock glaciers of the Yukon using electrical resistance tools.

Water or saturated subsoil are good conductors of electrical current. Saturated glacial debris should show low resistance to electrical current. Dry, unconsolidated glacial materials should show moderate resistance to the

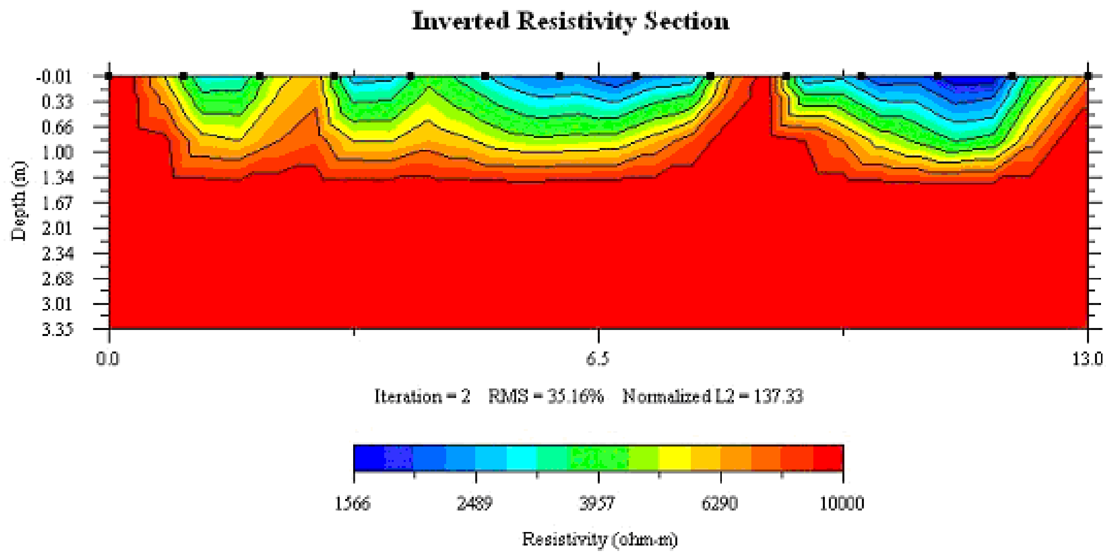

Fig. 1. Electrical Resistance cross-section from site 2 which is the debris field covering known glacial ice. The extremely high resistance can be anticipated, as glacial ice is an extremely poor conductor of electrical energy.

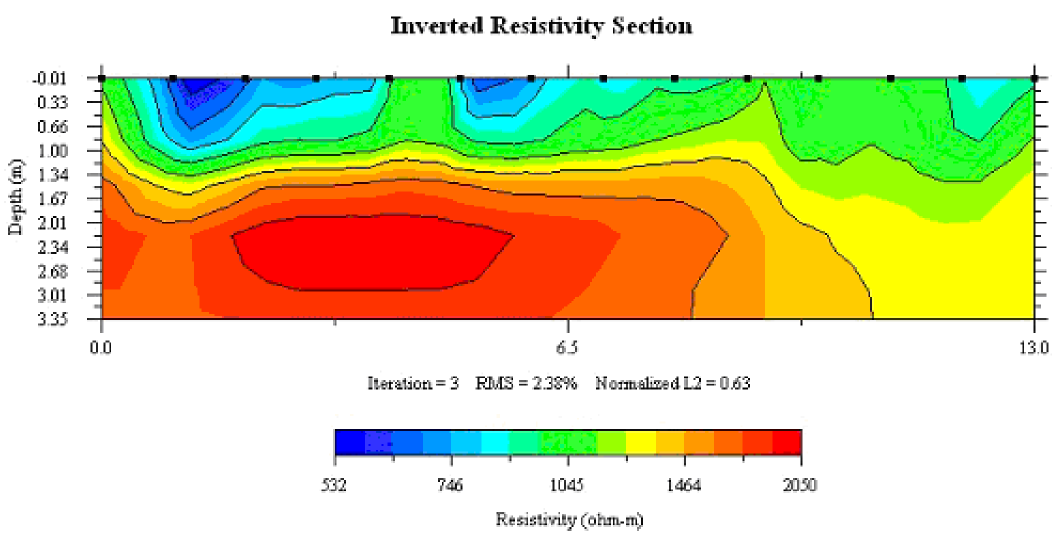

Fig. 2. Electrical resistance cross section from lateral moraine. Upslope is to the right of the figure. Moderate resistance near on the upper slopes indicates dry, unconsolidated glacial materials. Low resistance near the surface on the downslope end of the section (the left side of the figure) indicates water in the glacial material. The high resistance area that occurs at approximately 1.5 meters beneath the surface indicates discontinuous ice lenses.

passage of electrical current and ice, which is very poor conductor of electricity, should be highly resistant to electrical current flow.

MATERIALS AND METHODS

Glaciers of the Cascades of Oregon are well suited for this study. Found at relatively low elevations with comparatively easy access the Elliott glacier on Mt Hood was chosen for this study. A SuperSting R1/IP, a single channel automatic resistivity instrument developed by Advanced Geosciences of Austin TX was packed to the lateral moraines of the Elliott Glacier in July 2006. A survey line was established down the slope of the lateral moraine just below the current debris covered terminus of the glacier. Fourteen electrodes were placed 3 meters apart down the slope. A second line was established across the surface of the debris-covered Elliott glacier. Melting ice indicated by the presence of melt water saturating the sediments was visible in the cut below the location of the electrical resistance line. Again, fourteen electrodes were placed at 3 meter spacing.

Current injections and resistance measurements were performed at both sites using three different patterns (Schlumberger, Wenner and Dipole-Dipole).

Slopes at the moraine site and both up valley and down valley were measured using the clinometer of a Brunton pocket transit. An average value was calculated for the morainal slope.

The accepted penetration and accurate assessment of sub surface conditions by these methods is 10-20% of the total length of the electrode array (Advanced Geosceinces 2006). Fourteen electrodes at 3 meter spacing should provide an accurate picture of conditions 4 to 8 meters beneath the surface. It was expected that this number and spacing of electrodes would be sufficient to locate and identify ice lenses in the moraines.

RESULTS AND DISCUSSION

Figure 1 shows the electrical resistance cross section produced by the array over known glacial ice. Clearly, at depths slightly more than one meter this environment shows an extremely high electrical resistance ~ 10,000 micro ohms, suggesting solid ice. There is little doubt that this environment produces results as expected.

Figure 2 shows the electrical resistance cross section produced from the electrode array down the slope of the moraine. The electrode array was started near the top of the moraine (the left side of the cross section) and run directly down slope for approximately 50 meters. Moderately low resistance materials to the right side of the section suggest dry unconsolidated glacial materials at the drier top of the moraine. Near the lower end of the run, blue colors show low resistance indicating the presence of saturated sediments beneath the surface. Observations made when driving the electrodes support this interpretation, as it was possible to remove 8-10 inches of dry material and exposing visibly moist conditions. Higher resistance beneath this layer of moisture is logically interpreted as ice. The resistance values ~2000 micro ohms are significantly lower than found on the solid glacial ice, lending support to an interpretation of discontinuous ice lenses that begin about 1.5 meters below the surface.

Slope measurements at the location of the electrode run and immediately up and down valley were very consistent (79% to 82%) with an average of 80% slope; this converts to a slope of 40-42 degrees. The expected slope of unconsolidated earth materials, the angle of repose, is expected to be approximately 35 degrees. The electrical resistance results lend support to a theory that includes ice structures within the moraine that provides structure to the otherwise loose moraine materials.

CONCLUSIONS

These results provide powerful support of the utility of electrical resistance imaging equipment as a tool to evaluate the presence and characteristics of subsurface ice in many glacial environments. The glaciers of the Cascades produce very heterogeneous sediments, from silt to boulders with good contact between materials in the moraine. In a glacial environment of hard rock, the moraine materials can be large rocks with very little particle-to-particle contact and no opportunity to obtain good electrical contact. Glacial moraines in the Snowy Range of Wyoming between Laramie and Saratoga are perfect examples of an environment where electrical resistance imaging equipment would be of very limited utility. The dense quartzite of the mountains has shattered into very large boulders, which make up the moraines.

In the Cascade glaciers with well mixed sediments and good electrical contact, electrical resistance imaging is projected to be superior to other subsurface imaging equipment such as ground penetrating RADAR (GPR). GPR functions best in a dry environment, the saturated conditions of the glacial moraine may make GPR problematic in this environment. The Electrical Resistance imaging equipment has no limitations from saturated materials and results actually improve with the presence of some moisture.

While not conclusive, these results tend to support the long held tenet that steep slopes on a moraine indicate support from sub-surface ice. If current warming trends continue, not only will the surface area of alpine glaciers continue to decrease, but the ice supporting many moraines will also melt causing the moraine to collapse, reaching a new equilibrium. In the case of melt-water lakes that are contained by these ice reinforced moraines, there is an increasing likelihood that these dams will fail as the supporting ice melts.

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