PROCEEDINGS OF THE TWENTY-SIXTH ANNUAL KECK RESEARCH SYMPOSIUM IN GEOLOGY

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Dr. Robert J. Varga, Editor
Director, Keck Geology Consortium
Pomona College

Dr. Jade Star Lackey
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Pomona College

Carol Morgan
Keck Geology Consortium Administrative Assistant

Christina Kelly
Symposium Proceedings Layout & Design
Office of Communication & Marketing
Scripps College

Keck Geology Consortium
Geology Department, Pomona College
185 E. 6th St., Claremont, CA 91711
(909) 607-0651, keckgeology@pomona.edu, keckgeology.org

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Robert J. Varga
Editor and Keck Director
Pomona College

Keck Geology Consortium
Pomona College
185 E 6th St., Claremont, CA 91711

Christina Kelly
Proceedings Layout & Design
Scripps College

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Keck Geology Consortium: Projects 2012-2013
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Keck Geology Consortium
Pomona College
185 E. 6th St., Claremont, CA 91711
Keckgeology.org

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USING GEOPHYSICAL TECHNIQUES IN THE CRITICAL ZONE TO DETERMINE THE PRESENCE OF PERMAFROST

GABRIEL M. LEWIS, Williams College
Research Advisor: David P. Dethier

INTRODUCTION

Mountain permafrost is an excellent indicator of climate change and has been rapidly disappearing due to rising air temperatures through the past several decades in both Europe and North America (Leopold et al., 2013). Permafrost has been extensively studied in the Arctic through the 20th century, and is defined as rock or soil that may contain water, which has a temperature continuously at or below 0 °C for at least two consecutive years. Large-scale melting of permafrost has brought the decline of frozen ground into the public spotlight; the melting of permafrost alone could raise global temperatures by 0.2 - 0.8 °C by 2100 (Leopold, 2010; Romm, 2012).

Niwot Ridge is located at an elevation of approximately 3,600 meters in the Front Range of Colorado, at the threshold of temperatures that support the development of permafrost. Conclusive evidence of frozen ground was recorded in the 1970's along Niwot Ridge (Benedict, 1970), but my research indicates that permanent ice lenses no longer exist at this location. The climate and thermodynamics of periglacial regions along Niwot Ridge are reviewed below to establish the processes and conditions that favor permafrost.

Climate change provides first-order control on the extent of permafrost in many locations, although exact climatic conditions may be difficult to calculate and predict. The paleoclimate community uses small alpine glaciers as sensitive indicators of climate variations, allowing glacial geologists to reconstruct an accurate local late-Pleistocene climate history (Dühnforth and Anderson, 2011). Niwot Ridge's combination of low temperatures, high effective precipitation, and large snow-free expanses of tundra created an environment during at least late-Quaternary time that favored permafrost and periglacial processes with their associated deposits (Benedict, 1970).

Non-invasive geophysical techniques such as Electrical Resistivity Tomography (ERT) and Ground Penetrating Radar (GPR) have become increasingly popular for detailed observation of the critical zone. ERT allows detailed mapping and visualization of deposits in sensitive alpine environments with minimal excavation (Leopold et. al, 2008). This technique portrays the individual subsurface layers' various DC electrical resistivities, which are characteristic of specific subsurface structures and compositions such as soil, saprolite, and ice (Leopold, 2008).

RESEARCH AREA

Both Niwot Ridge and Gordon Gulch are located in the upper part of the Boulder Creek catchment within Boulder County, Colorado, in the Boulder Creek Critical Zone Observatory (CZO) (Anderson et al., 2008). This area has been tectonically quiescent since the end of the Laramide orogeny (~40 Ma), allowing erosion and weathering to produce the critical zone architectures exposed at Niwot Ridge and in Gordon Gulch (Anderson et al., 2006).

The last Pleistocene glaciers retreated from the Front Range approximately 14,000 years. As glaciers sculpted U-shaped valleys in the landscape, periglacial features such as gelifluction lobes and rock glaciers modified areas adjacent to glacier ice such as Niwot Ridge and those lower in elevation such as the currently forested areas within Gordon Gulch. Relict

periglacial features extend 500 to 750 meters below the present periglacial level on Niwot Ridge, well into the forest belt (Marker, 1990).

NIWOT RIDGE

Niwot Ridge extends east from the Continental Divide from 3450 to 3800 m, with several knolls standing above the ridge along the central axis (Berg, 1986). Most of the ridge is composed of low, rounded hills and shallow saddles covered by a thick mantle of periglacial deposits, which reflect the influence of prolonged mass wasting upon structurally complex igneous and metamorphic basement (Benedict, 1970). Since only four months out of the year have average temperatures above freezing, most of the vegetation above tree line consists of grasses, sedges, and low perennial herbs (Greenland, 1989).

Much of Niwot Ridge is covered by widespread periglacial deposits, including gelifluction lobes, turf-banked lobes, terraces, hummocks, and patterned ground, all of which were active from the Holocene and late Pleistocene (Fig. 1) (Gable and Madole, 1976). The top 10-20 cm of deposits typically consists of roots and an organic-rich A-horizon, covering a thick layer of cobbles and pebbles that rest within a poorly sorted fine-grained matrix of sand and fines derived from bedrock and dustfall (Fahey, 1975). Geophysical methods and drilling data show that depth to bedrock ranges from 4 to over 10 meters on Niwot Ridge, and that deposit thickness is not simply related to the local

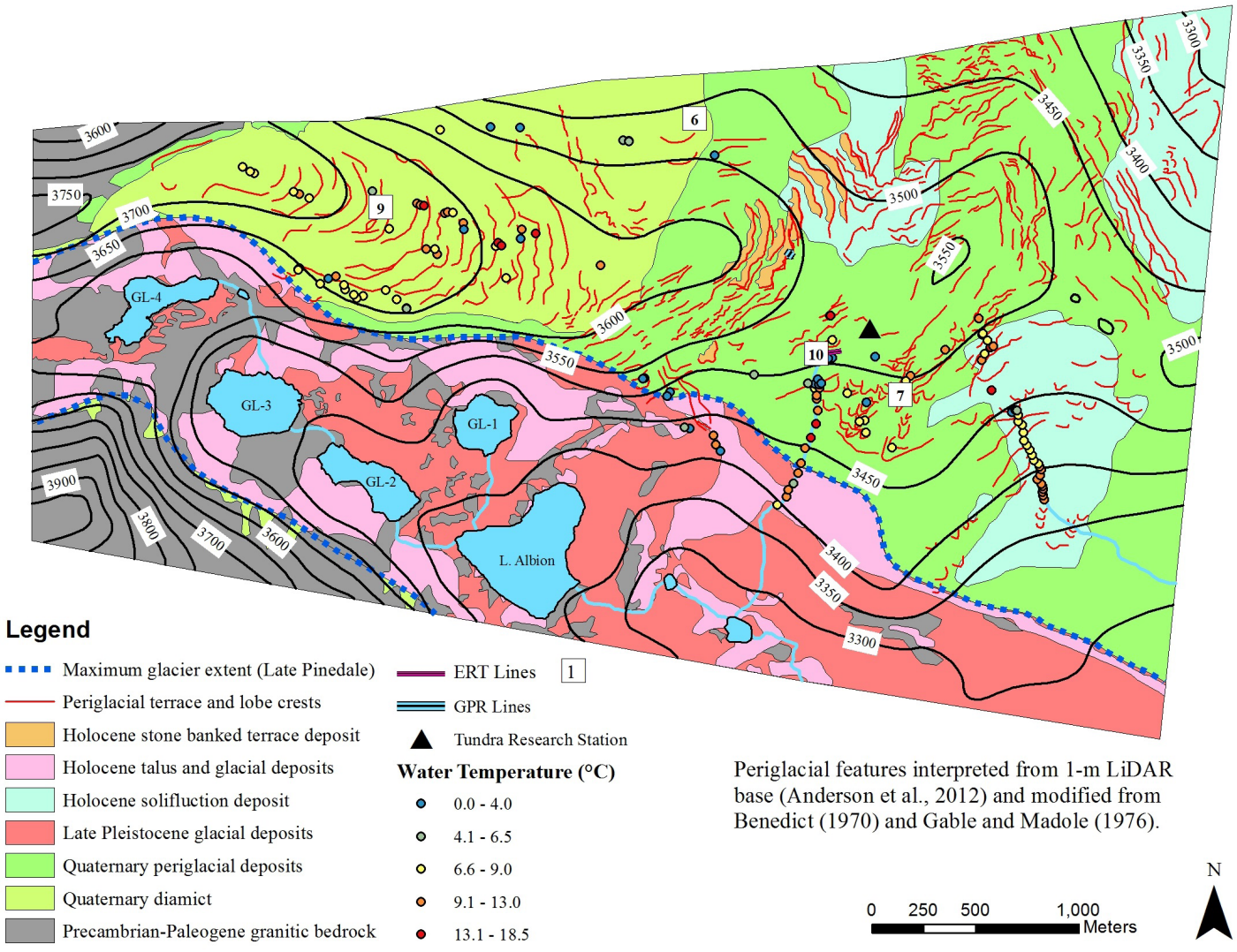

Figure 1. Surficial geology map showing ERT and GPR lines, and surface water temperature measurements along Niwot Ridge. The location of the Tundra Research Station and ERT Line 10 are also displayed.

slope (Leopold, 2008).

The mean annual temperature (MAT) on Niwot Ridge near the Tundra Research station (3528 m) is -2.13 °C, with a local lapse rate of approximately 7.1 °C/km (Greenland, 1989). More than half the days record measurable precipitation, with a mean annual precipitation (MAP) ranging from 800-1000 mm, most of which falls as snow during the winter and spring (Barry, 1973; Williams et al., 2006; Leopold et al., 2010). Summer air temperatures measured at the D1 meteorological station on Niwot Ridge have shown nearly a 2 °C rise since 1950 with decreased variability in winter temperatures (Leopold et al., 2010).

Gordon Gulch

Gordon Gulch is located 12 km to the east of Niwot Ridge and ranges in elevation from 2446 to 2737 m amidst a rolling surface of low-relief (Birkeland et al., 2003). The surface exemplifies deep weathering, with an average regolith thickness of 3.3 m and denudation rates of 20 μm/year (Anderson et al., 2006). The erosion rate exceeds the rock weathering rate in the gulch, exposing isolated bedrock outcrops as soil is removed. Most of Gordon Gulch is dominated by lodgepole pine (especially on the north-facing slopes) as well as Ponderosa pine and Douglas fir (which dominate the south-facing slopes). Toeslope areas support aspen groves and moist meadows at the bottom of the gulch.

The Gordon Gulch climate contrasts with that recorded on Niwot Ridge. Located in the upper montane climatic zone, MAP at Gordon Gulch is ~519 mm, most of which falls as rain (Barry, 1973; Hinckley et al., 2012). The north-facing slope maintains a MAT of 5.1 °C, while the south-facing is slightly warmer due to solar radiation. Paleoclimatic data indicate that periglacial conditions may have existed throughout Gordon Gulch during the late Pleistocene (Barry et al., 1973).

PERIGLACIAL DEPOSITS AND FEATURES

Locations with a MAT near 0 °C and an abundant supply of liquid water provide conditions that drive ice-related processes that are highly susceptible to warmer winters driven by climate change (Anderson et al., 2010). Periglacial processes are driven mainly by frost heave and creep, the ratchet-like downslope movement of particles heaving perpendicular to the slope and subsequently settling vertically upon thawing (Washburn, 1967). The most prominent of these processes is gelifluction: downhill transport of saturated material above a seasonally or perennially frozen substrate (Andersson, 1906; Washburn, 1967). Sufficient water availability and a fine matrix allow gelifluction to cause frost heave as lobes or terraces precede downhill (Washburn, 1973). Both banked terraces and banked lobes exist on Niwot Ridge; banked terraces are accumulations of moving soil that lack visible sorting overlying a relatively stone-free moving subsoil, while banked lobes are accumulations of moving rocky debris or soil that lack visible sorting (Embleton and King, 1975).

According to Ward et al. (2009), glaciers extended far into many valleys in the Front Range when the equilibrium line altitude was at approximately 3300 m, lowing the MAT at Gordon Gulch below 0 °C. We can be certain that there is no active permafrost in Gordon Gulch, but marginal periglacial conditions likely existed in Gordon Gulch during the late Pleistocene. Subzero temperatures would have caused frost-cracking and regolith transport that rapidly damaged the parent bedrock and moved large amounts of material downslope.

METHODS

Working with Dr. Mathias Leopold from the University of Western Australia, I collected Electric Resistivity Tomography data throughout Niwot Ridge (7 lines), Green Lakes Valley (4 lines), 4th of July Valley (3 lines), and Gordon Gulch (2 lines) using equipment from Lippmann Geophysikalishe Messgeräte. The location of each ERT line was chosen to be representative of its surrounding area in order to ascertain subsurface measurements from a diverse region. At each location, we hammered conductive metal stakes into the ground at equal intervals along a 25 or 50 meter line (Fig. 2). We recorded both GPS points and inclination measurements at each terminus and every five meters along the line. The field computer used GeoTest© to carry out the resistivity tomography measurements and RES2DINV© for the mathematical inversion necessary to account for topography, water content,

and surface interaction as well as to calculate statistical accuracy. We calculated at least five iterations of the inversion process to reach the convergence limit of 3.0% using parameters from Oldenburg and Li (1999), yielding root mean squared errors of 1.4 to 15.8% with an average of 6.6%.

Figure 2. a. Electrical Resistivity Line 5 showing the electrodes, stakes, and ribbon cable connecting them with data collection in the background. b. Data collection process using the field laptop and Lippmann Geophysikalishe Messgeräte equipment.

We compared inversion resistivity values with ground-truth measurements to correlate the resistivities of specific deposits. Combining these values with Leopold et al. (2013) allowed us to assign specific resistivity ranges to fine- and coarse- grained slope deposits, weathered and fractured bedrock, saprolite, ice lenses, and permafrost.

We collected water temperature data at many locations where surface water was present along Niwot Ridge using a VWR Lollipop-type thermometer (H-B Instrument Company) with an accuracy of ±0.5 °C. In excavated pits, we also measured a temperature profile every 10 cm along the south-facing wall of the profile.

RESULTS

ERT Results

This study recorded a total of 16 ERT lines, 2 GPR lines, and 153 temperature measurements along Niwot Ridge and Gordon Gulch. Many of these ERT lines show various periglacial deposits and subsurface compositions that are difficult to detect from surface data collection alone. Two representative lines are displayed and discussed in detail below.

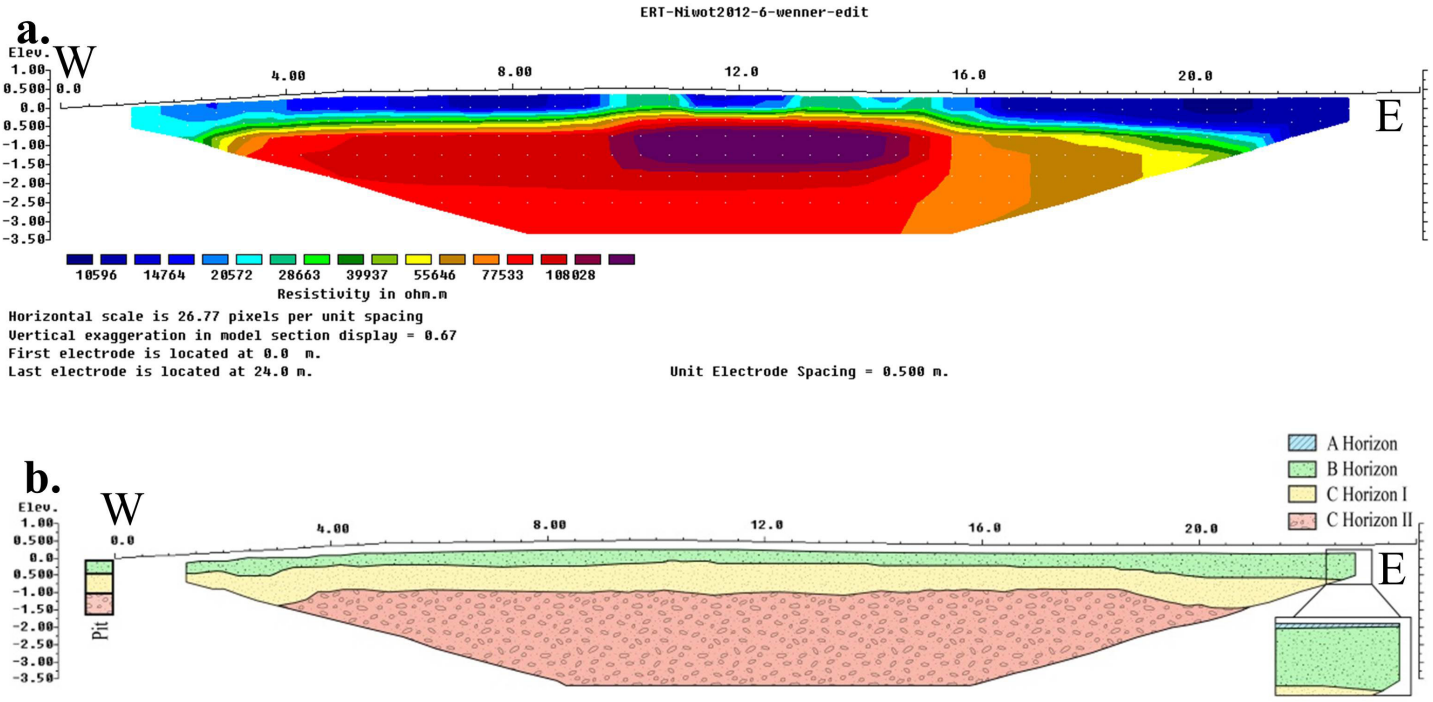

Figure 3: a. Profile of ERT Line 10 on Niwot Ridge showing surface vegetation, unsorted Quaternary diamict, and a layer of open work gravel below =1 m. b. Interpretation of ERT Line 10 showing organic A Horizon, B Horizon, C Horizons I and II; inset shows expanded view of east end of line.

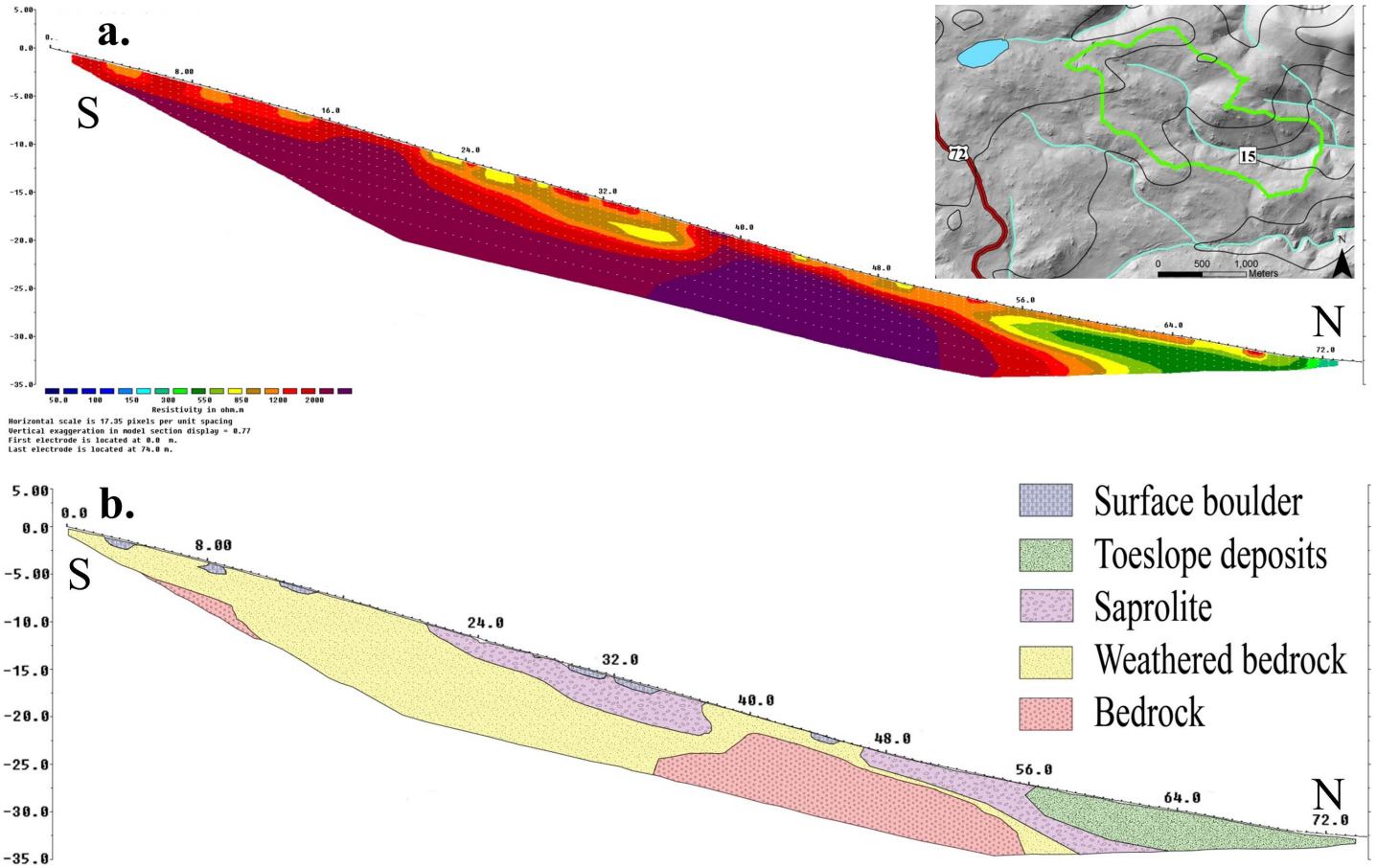

Figure 4: a. Profile of ERT Line 15 in Gordon Gulch (green outline in inset) showing areas of high resistivity (>2500 Ωm) and low resistivity (<50 Ωm). Black lines represent soil pits along the line. b. Interpretation of ERT Line 15 showing surface boulders, toeslope deposits, saprolite, weathered bedrock, and bedrock.

ERT Line 10 is located at an elevation of 3500 m on Niwot Ridge, 200 meters southwest of the Tundra Research Station, and is representative of an area containing periglacial and terrace crests (Fig. 1). A small spring emanates from the hillside at 1.5°C a few meters south of the line, eventually feeding Saddle Stream. A low resistivity organic layer covers the top 50 cm of this line (Fig. 3), underlain by an extremely high resistivity layer that extends horizontally in both directions. We excavated two 100 and 150 cm deep soil pits at the west end of this profile to determine the origin of the high resistivity layer and to measure soil temperatures along the profile wall.

ERT Line 15 is located on a steep north-facing slope in Gordon Gulch at an elevation of 2500 m (Fig. 4). We excavated five pits along this line (black lines in Figure 4), which reveal the composition of the subsurface and that depth to bedrock varies much more than previously imaged. Results of the ERT line indicate

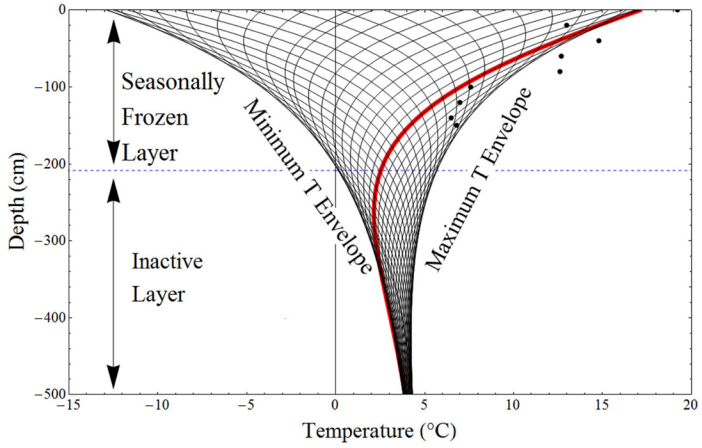

Figure 5: Annual temperature-depth profile near ERT Line 11 interpolated from temperature measurements (Eqn. 1). The seasonally frozen layer is able to develop seasonal ice lenses when temperatures are below freezing, but the inactive layer does not experience sub-zero temperatures. The black dots are temperature measurements from the soil pit on July 24 and the red line is their calculated temperature profile.

that high resistivity bedrock underlies most of the line and crops out at the surface near the 40 meter mark. The ERT line shows a pocket of lower resistivity saprolite surrounded by solid weathered bedrock near the center of the line, and a toeslope deposit of very low resistivity material at the bottom of the slope adjacent to the creek.

Heat Flow

Anderson and Anderson (2010) derive a heat flow equation (Eqn. 1), which states that the temperature at depth, z, on Julian calendar day, t, is a function of the MAT at the surface, $\bar{T}_s$, amplitude of surface temperature variation, T_{amp}, the local geothermal heat flow, $\frac{Q}{k}$, and the depth at which the temperature is 1/e the surface temperature, z_*.

$$\bar{T}(z) = \bar{T}_s - \frac{Q}{k}z + T_{amp}Exp\left[-\frac{z}{z_*}\right]Sin\left[\frac{2\pi t}{365} - \frac{z}{z_*}\right] \quad \text{(Eqn. 1)}$$

Using Mathematica©, I fit exponential curves to field temperature measurements in excavated pits along Niwot Ridge, yielding statistically reliable parameters. By modeling Equation 1 throughout an entire year, I generated a temperature-depth profile showing the location of the seasonally frozen and inactive layers (Fig. 5).

DISCUSSION

A combination of geophysical, field, and meteorological measurements indicate that the present subsurface on Niwot Ridge does not contain permafrost. While in the 1970's permafrost was pervasive on Niwot Ridge above 3500 m, present landforms of Figure 1 are moving slowly, if at all (Benedict, 1970; Ives and Fahey, 1971). Water temperature measurements indicate that the shallow ground water on Niwot Ridge is mainly above 1.5 °C, providing difficult conditions for ice lenses to persist through the summer.

The results of ERT lines on several aspects of Niwot Ridge do not reveal permafrost beneath periglacial terrace and lobe crests. Published studies and the initial interpretation of data shown in Figure 3 suggested the possible presence of permafrost in the high (>70 kΩm) layer underlying the surface. Field observations of excavated pits showed that the high resistivity material is open-work gravel, which conducts electricity very poorly due to the interstitial air between large clasts.

Soil temperature measurements from soil pits and heat modeling of the subsurface thermodynamics demonstrate that the temperature at depth is too high to support permanent ice lenses or permafrost. Based on the temperature model from Anderson and Anderson (2010), it is evident that the subsurface below two meters does not remain frozen throughout the year, eliminating the possibility of permafrost at this depth. Regolith less than two meters below the surface may freeze for several months during the spring, but melts again once the surface temperature warms substantially. This freeze-thaw action provides the necessary conditions for slow movement of gelifluction lobes mapped in Figure 1.

While holding all other parameters constant, we can vary the MAT to replicate conditions of the early 20th century based on data from meteorological stations along Niwot Ridge. This model produces a thin, permanently-frozen subsurface layer that provides conditions in which permafrost could form. Modeling of Gordon Gulch using temperatures estimated from the LGM suggests that the area could have also supported ice lenses and permafrost.

Gelifluction lobes transport portions of hill slopes and locally erode the subsurface as they slowly process downhill. Associated frost-cracking and freeze-thaw action may increase the regolith transport rate past equilibrium, resulting in toeslope deposits at the bottom of many slopes (Fig. 4). The weathered bedrock pattern and toeslope deposits within Gordon Gulch provide evidence that periglacial conditions were maintained throughout the late Pleistocene at an elevation of 2500 m.

CONCLUSION

By using non-invasive geophysical techniques along Niwot Ridge and Gordon Gulch, this study examines the subsurface of recently active and relict periglacial features in the Front Range of Colorado. Niwot Ridge appears to be at the threshold of becoming a completely permafrost-free location within the next decade based on resistivity interpretations, water and

soil temperature measurements, and field observations. Using climate records as the main driving mechanism for gelifluction forming locations, one can infer that freeze-thaw conditions were present in Gordon Gulch during the LGM and contributed to shaping the present geomorphology of the region.

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