Late Quaternary glacial geology and paleoclimate interpretations of the Anthony Lakes drainages, Elkhorn Mountains, Oregon

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INTRODUCTION

The Elkhorn Mountains of eastern Oregon offer an exciting opportunity study the past glacial events that have shaped the geomorphology of the range. The glacial geology of these mountains is virtually unstudied despite evidence of extensive glaciation. This study is a report on the late Quaternary glacial and periglacial history of the valleys that drain Anthony Lakes area of the Elkhorns (Figure 1). The Anthony Lakes glacial complex is described by detailed mapping of the glacial and periglacial features such as moraines, ice limits, protalus ramparts, and rock glaciers. In addition, glaciological properties such as equilibrium line altitudes (ELA's), basal shear stress, flow velocities, and discharge have been calculated for the paleoglaciers. The calculated glacial properties contribute to paleoclimatic interpretations.

Study Area. The Anthony Lakes cirque fed three valley glaciers during the Pleistocene (Figure 1). At roughly 11 km^2, this is a large cirque for the Elkhorn Mountains. The Anthony Lakes drainages preserve evidence of at least two different glaciations, an older and a younger event respectively correlated as Bull Lake and Pinedale glaciations. There is extensive evidence of Holocene periglacial activity in the cirque including an extinct rock glacier and protalus ramparts but no evidence of true glacial activity during the Holocene.

The Grande Ronde River, Anthony Creek and Antone Creek drain the Anthony Lakes Cirque (Figure 1). These valleys exhibit a variety of glacial features. The Grande Ronde valley has very poor preservation of glacial features. The ice limits in this valley are mapped as approximate (Figure 1), and were determined primarily by a study of the occurrence of surface boulders that were judged to be ice-transported boulders. The Anthony Creek valley displays a far more distinct "textbook" glacial geomorphology. This valley exhibits massive lateral moraines and recessional moraines associated with the Pinedale advance and lateral moraine fragments associated with the Bull Lake advance (Figure 1). In addition to these features ice rafted boulders and lacustrine sediments in the Indian Creek valley, adjacent to the terminal position of the Anthony Creek paleoglaciers, indicate the existence of an ice-dammed lake (Figure 1). The Antone Creek valley also exhibits Pinedale and Bull Lake lateral moraines and recessional moraines. This valley is distinct in that its Bull Lake moraines are well preserved including a terminal moraine (Figure 1). The Bull Lake moraines are well preserved because they were not over run by the Pinedale glaciation.

Bedrock Geology. The Anthony Lakes field area is underlain by the Baker terrane associated with the accreted Blue Mountain island arc complex (Vallier, 1995). The main basement rock in the Anthony Lakes field area is the granodiorite of Anthony Lakes (Taubeneck 1995) K-Ar and Rb-Sr ages and Sr isotopic compositions suggest that the granodiorite was emplaced about 160 Ma in a volcanic arc environment (Taubeneck 1995). The granodiorite is a medium grained pale-gray rock containing from 9 to 30 modal percent biotite and hornblende with a color index of 11 (Taubeneck 1995). The granodiorite is highly jointed. The most prominent controlling sets strike northeast and dip 35-45 degrees NW and 60 degrees SE.

METHODS

Field investigation. Ice limits were determined on the basis of field mapping and air photo interpretation. Mapping of the Anthony Lakes Cirque and its drainages required establishing criteria for mapping glacial limits. Ice limits could not be determined on the basis of erratic location as the underlying bed rock for the most of the glaciated area is granodiorite. The exception to this is in the terminal area of the Anthony Creek glaciated valley where the northwest striking contact between the granodiorite of Anthony Lakes and older metagabbro is in the vicinity of Gorham Butte (Figure 1) (Taubeneck 1996). The greatest extent of the Anthony Creek paleoglacier is marked by granodiorite erratics. Ice limit mapping in the Antone and Anthony creek valleys was accomplished by lateral moraine identification (Figure 1). Ice limit identification in the Grande Ronde valley was accomplished by identification of ice transported boulders (ITB's). The prominent joint sets aided in distinguishing ITB from weathered out core stones on the basis of joint orientation. No striations or crescentic gouges were preserved on the granodiorite bedrock due to its high weatherability reflecting a high biotite percentage. Ice limits above the lateral

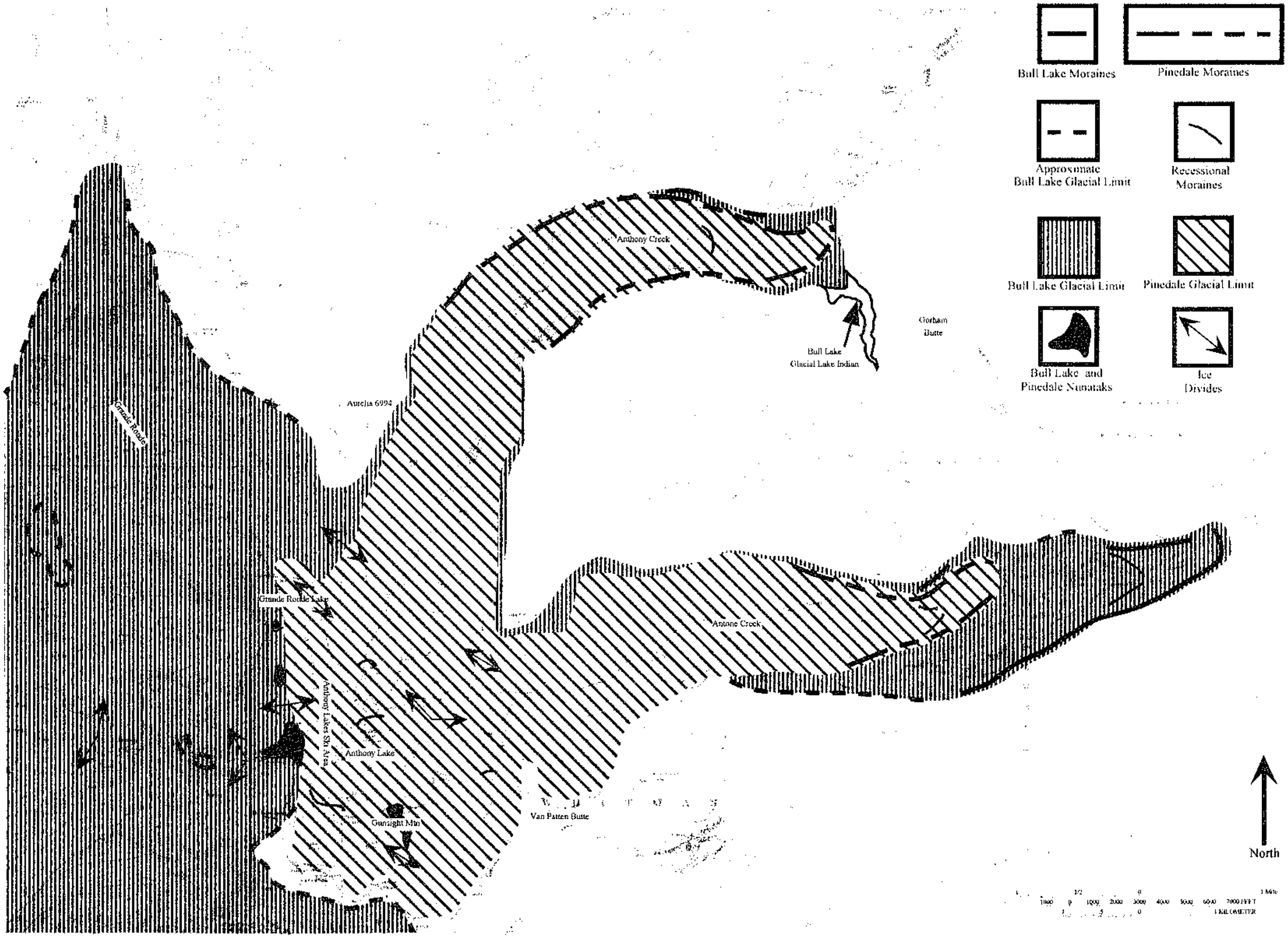

Figure 1: Map of the Anthony Lakes field area showing Pinedale and Bull Lake glacial extents, Pinedale and Bull Lake moraines, recessional moraines, and indicating ice divides. The contour interval is 40 feet in the southern portion of the map, 20 feet in the northern portion.

moraines were determined by identification of ITB's, roche moutonnée's, and rock drumlins. Ice limits in the cirques were determined by identifying area exhibiting a high degree of dissection and periglacial weathering. These areas were presumably above the ice surfaces during both glaciations. Feasibility of the field-mapped ice limits in Antone and Anthony creek valleys was tested by construction theoretical ice profiles assuming a perfect plastic model for ice deformation with a yield stress of approximately 100 kPa.

Moraines of the Pinedale and Bull Lake advances were distinguished on the basis of topographic position, weathering and soil development. Anthony Lakes granodiorite grüsifies easily due to its high biotite content. Bull Lake moraines are characterized by granodiorite boulders in various stages of grüssification, while Pinedale moraines exhibit over 75% firm granodiorite boulders.

Correlative ages were assigned to the moraines based on a comparison of their weathering characteristics to those of moraines described by Crandell (1967) in the nearby Wallowa Mountains. Richmond (1986) correlated the moraines described by Crandell with the Bull Lake and Pinedale glaciations first described in the Wind River Range, Wyoming, by Blackwelder (1915).

Glaciological investigation. Pure plastic modeling of the paleo ice surface for both Bull Lake and Pinedale glaciations for Antone and Anthony Creek was accomplished with the use of the basal shear stress equation $\tau = \rho \mathbf{g} \mathbf{h} \sin \alpha\, \mathbf{f}$ (where τ is basal shear stress, ρ is the density of ice, **g** is the acceleration due to gravity, **h** is the thickness of ice measured perpendicular to the glacial base, α is the slope of the surface of the glacier, and **f** is the valley shape factor). Using the basal shear stress equation to solve for α given **h** and assuming a reasonable basal shear stress of about 100 kPa enables the projection of the ice surface in to areas where the paleo ice surface is not well constrained by moraines. Average paleoglacier basal shear stress was also estimated using this equation by adjusting the input basal shear stress until the modeled ice thickness goes to zero at the elevation of the field mapped terminal position of the paleoglacier.

ELA's were calculated and compared using three methods developed by Andrews (1975), Sutherland (1984), and Furbish and Andrews (1984). A comparison between Antone and Anthony Creek Bull Lake and Pinedale ELA's shows all three methods in agreement. The Furbish and Andrews (1984) method of paleo ELA calculation assuming an ablation to accumulation area balance ratio of 2 was judged to be the most accurate method for calculating paleo ELA's. The Andrews accumulation area ratio method does not account for the altitudinal distribution of a glacier's surface area, and the Sutherland method assumes a linear mass balance gradient.

The average discharge through the ELA of the Antone and Anthony Bull Lake and Pinedale paleoglaicers was calculated using Glen's flow law adapted for glacier flow by Nye (1957). This discharge was used to determine the mean net balance of the ablation zone. When combined with

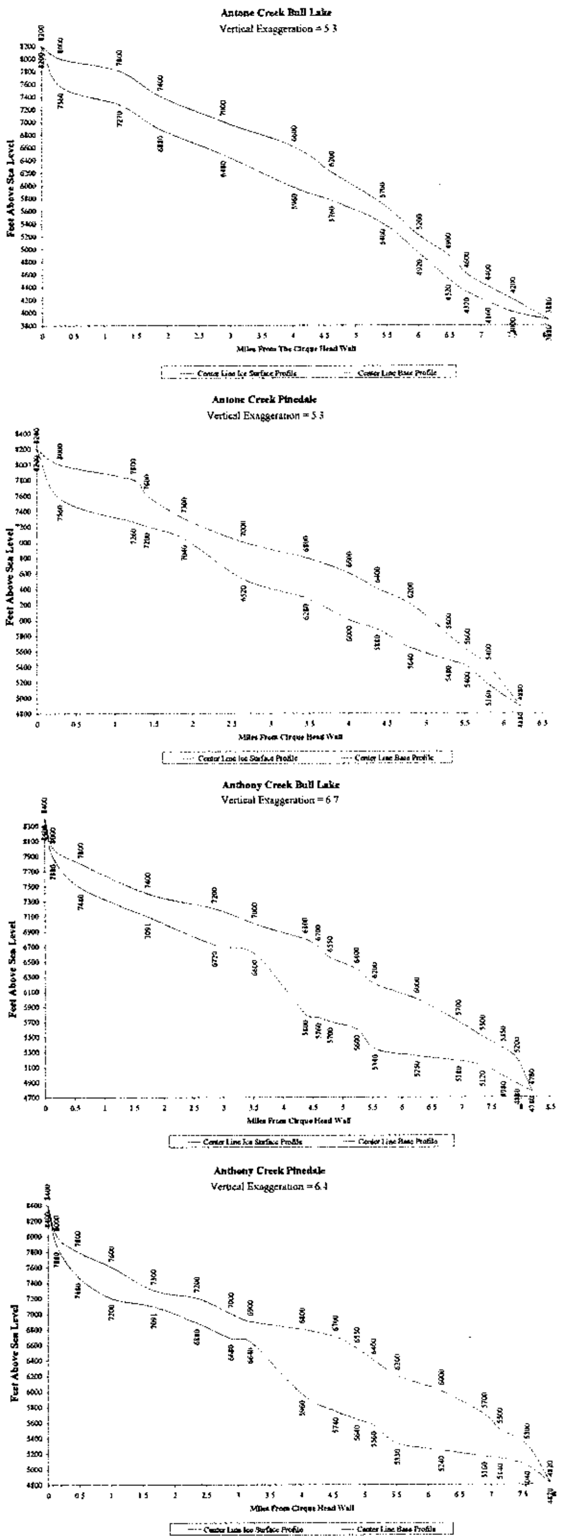

Figure 2: Glacial center line profiles For Bull Lake and Pinedale Antone and Anthony Creek paleoglaciers. Ice surface profiles are derived from ice surface elevations corresponding to mapped ice limits. Base profiles are derived from modern valley center line elevations.

the calculated area-weighted mean elevation of the ablation zone, the ablation zone net balance gradient was determined. This is a climatically-sensitive parameter of modern glaciers that can be applied to paleoglaciers.

Results. The perfect plastic model yielded best fit ice surfaces for the Bull Lake and Pinedale Anthony Creek paleoglaciers and the Pinedale Antone Creek paleoglacier assuming average basal shear stresses of 116, 108, and 105.4 kPa respectively. These modeled ice surfaces were in close agreement with the field mapped ice surfaces shown in figure 2. The Bull Lake Antone Creek paleoglacier moraine constrained down valley ice surface profile required a low input basal shear stress of 75 kPa to terminate at the mapped terminus. This low basal shear stress did not lend itself to good up valley ice surface projections.

The Bull Lake ELA's for Antone and Anthony Creek paleoglaciers were 1964 m and 2080 m respectively. The Pinedale ELA's for both paleoglaciers were both approximately 2075 m. All three methods used to calculate ELA's were in agreement that the Bull Lake Antone Creek paleoglacier had a lower ELA than Bull Lake Anthony Creek Paleo Glacier.

Assuming zero basal slip, average discharge for the Pinedale and Bull Lake Anthony Creek paleoglaciers was 1.9×10^6 and 7.6×10^6 m^3/year respectively. Assuming there is basal slip equal to half to the velocity due to internal deformation (50% basal slip) average discharge for the same paleo glaciers was 2.9×10^6 and 1.1×10^7 m^3/year respectively. Ablation zone gradients for the Pinedale and Bull Lake Anthony Creek paleoglaciers were 1.4 and 2.9 mm/m respectively assuming no basal slip and 2.1 and 4.3 mm/m respectively assuming 50% basal slip.

DISCUSSION

The low basal shear stress that is required to fit a perfect plastic modeled ice surface to the Bull Lake correlated moraines in the Antone Creek Valley may reflect enhanced basal slip or sub glacial sediment deformation. The discrepancy of over 100 m between Bull Lake ELA calculations for the Antone and Anthony Creek paleoglaciers may be related to the hypothesized basal conditions in the terminal area of the Antone Creek paleoglacier. If the Bull Lake Antone Creek ELA calculations do in fact relate an enhanced velocity instead of paleoclimatic conditions during the Bull Lake glaciation, this paleoglacier is not a good candidate for paleoclimatic analysis.

Ablation zone gradients for the Bull Lake and Pinedale Anthony Creek paleoglaciers are comparable with ablation zone gradients for modern glaciers in the Brooks Range, Alaska. These gradients are lower than Brooks Range gradients when no basal slip is assumed and very comparable when 50% basal slip is assumed. Low ablation zone gradients such as these indicate that the Anthony Cirque glaciers have formed under paleoclimatic conditions that are comparable with conditions in modern glaciated ranges that are continental, high latitude, very cold, and very dry.

REFERENCES CITED

Andrews, J. T., 1975, An approach to glaciers and their environments: Duxbury Press, 191 p.

Blackwelder, E. 1915, Post-Cretaceous history of the mountains of central western Wyoming:: Journal of Geology, v. 23, p. 97-117, 193-217, 307-340

Crandell, D. R., 1967, Glaciation at Wallowa Lake, Oregon: U. S. Geological Survey, Professional Papers, Number 575C, p. C145-C153

Furbish D. J., and Andrews J. T., 1984, The use of hypsometry to indicate long-term stability and response of valley glaciers to changes in mass transfer: Journal of Glaciology, v. 30, No.105, p. 199-211

Nye, J. F., 1957, The distribution of stress and velocity in glaciers and ice sheets: Proceedings of the Royal Society of London , Series A 239, p. 113-133

Richmond, G. M., 1986, Stratigraphy correlation of glacial deposits of the Rocky Mountains, the Colorado Plateau and the ranges of the Great Basin, *in* Sibrave, V., Bowen, D. Q., and Richmond G. M., eds., Quaternary glaciation of the northern hemisphere: Oxford, United Kingdom, Pergamon Press, p. 183-196

Sutherland, D. G., 1984, Modern glacier characteristics as a basis for inferring former climates with particular reference to the Loch Lomond Stadial: Quaternary Science Reviews, v. 3, p. 291-309

Taubeneck, W. H. 1995, A closer look at the Bald Mountain batholith, Elkhorn Mountains, and some Comparisons with the Wallowa batholith, Wallowa Mountains, northeastern Oregon, *in* Vallier, T. L., and Brooks, H. C., eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington: U. S. Geological Survey, Professional Paper, Number 1438, p. 45-123

Vallier, T. L. 1995, Petrology of pre-Tertiary igneous rocks in the Blue Mountain region of Oregon, Idaho, and Washington: Implications for the Geologic evolution of a complex island arc, *in* Vallier, T. L., and Brooks, H. C., eds., Geology of the Blue Mountains Region of Oregon, Idaho, and Washington: U. S. Geological Survey, Professional Paper, Number 1438, p. 125-209