An Analysis of Suspected Neoglacial Ice-Cored Moraines Impounding Carver Lake, South Sister Region, High Cascades, Oregon

by

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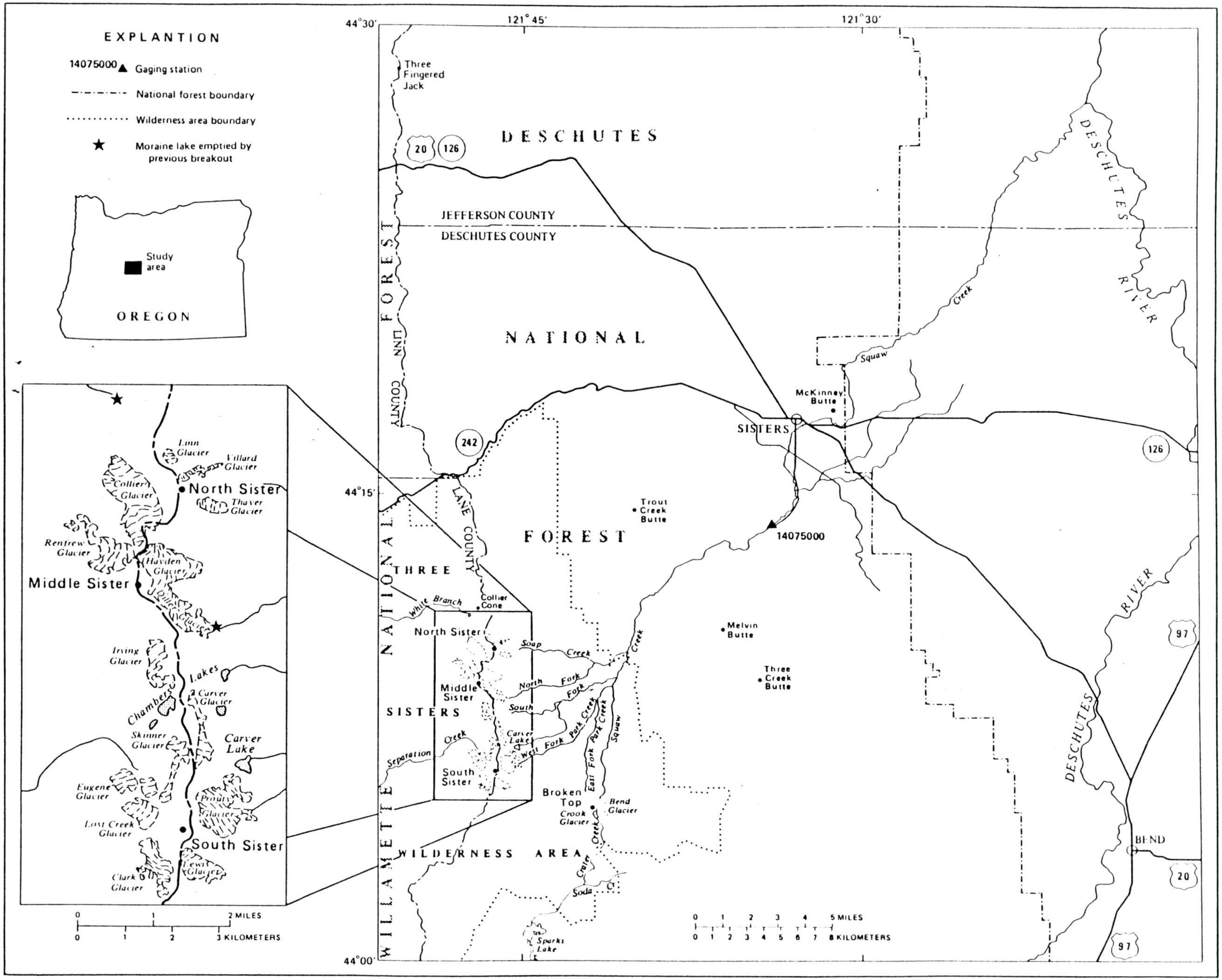
are completely mine and I take full responsibility for them.

Introduction

The purpose of this study is to determine if the moraines damming proglacial Carver Lake are ice-cored. The methodology to be employed consists of interpretation of aerial photographs and field observations. The results of these studies will be compared to past research of known ice-cored moraines in other regions of the world. This study was prompted by research done by the United States Geological Survey indicating that there may be a potential for flood hazard to the town of Sisters, Oregon should this morainal dam fail (Laenen, et al. 1987). Specifically, this paper discusses the results of three months of field study which the following procedures were completed: 1) The Neoglacial geomorphology surrounding Carver lake was mapped; 2) ground data was collected to verify aerial photographic interpretation; 3) test pits were excavated to detect the existence of an ice-core in the terminal moraines impounding Carver Lake. It was determined from this research that these moraines did have ice-cores.

Setting

Carver Lake is located 35 kilometers southwest of the town of Sisters, Oregon (Map #1). It is situated in the Alpine Zone at 2370 meters on the east slope of South Sister Mountain (3150 meters). The lake occupies a small



MAP 1: Location Map (source, USGS, 1987)

Photo mosaic showing the steep east face of South Sister and Prouty Glacier. An active terminal moraine and dead ice mass are in the foreground.

basin left by the retreat of Prouty Glacier since the turn of this century (Marshall, 1979). It is impounded by Neoglacial morainal deposits on the north, east and south, and on the west by the toe of Prouty Glacier. The alpine topography above Carver Lake is dominated by steep gradient Prouty Glacier and the glacially over-steepened east face of South Sister. Bathymetric data supplied by Laenen, et al. (1987) indicates the volume of Carver Lake to be approximately 912,864 m^3 of water.

Geology and Glacial History of South Sister

The geologic setting of Carver Lake has been dominated by the volcanic evolution of South Sister Mountain. According to Clark (1983), Scott (1977) and Williams (1944), South Sister was constructed during three distinct eruptive phases, beginning in the late Pliocene or early Pleistocene. Initial volcanism consisted of basalt, basaltic andesite and andesite flows that formed an overlapping shield volcano to an elevation of around 2400 meters. Atop this shield volcano, beginning at circa 700,000 yr. BP, explosive andesite eruptions built the stratovolcano that is South Sister Mountain. This period ended approximately 10,000-12,000 yr BP (Clark 1983). The final episode of volcanism took place during the Holocene, approximately 7000 to 10,000 yr BP. During this period, basaltic andesite flows, basalt flows and tephra built parasitic cinder cones in the South Sister/Broken Top area (Clark, 1983).

The glacial history of South Sister began with extensive glaciation during the Wisconsin period of the Pleistocene (Dethier, 1980). However, this investigator was unable to find any research that focused on the glacial history of the South Sister region. Numerous studies have dealt with the glacial history of areas in the general High Cascades region. These include Mount Jefferson (Thayer, 1939), Metolius River area, (Scott, 1977), Broken Top (Dethier, 1980), and the entire Pacific Northwest region (Crandell, 1965; Porter, S.C., 1975; Porter and Denton, 1967; Grove, 1979).

According to Thayer (1939) and Scott (1977), there were three distinct glacial advances during the late Pleistocene, (25,000-10,000 yr BP) in the Mount Jefferson/ Metolius River area. During the final phase, termed "Sumas Stade" by Crandell (1965), and "Cabot Creek glaciation" by Scott (1977), a cordilleran ice sheet encompassed the High Cascades from 30 km north of Mt. Jefferson to Mt. McLoughlin in southern Oregon. This period also saw the expansion of alpine glaciers in high cirques (Crandell, 1965). It would be logical to conclude that the South Sister area experienced similar glacial activity, though no mention of it could be located in the literature.

In the High Cascades, the division between the Pleistocene and the Holocene has been identified by a layer of Mazama ash, resulting from the eruption of Mt. Mazama approximately 6800 yr. BP (Scott, 1977). This eruption occurred during the "Thermal Maximum," in which there was a relative warming trend across the Northern hemisphere, approximately 8,000-10,000 yr. BP (Miller, 1985). During this period, ice probably retreated to the upper most cirques in the Alpine region of the High Cascades.

Neoglacial Period

The Neoglacial period of the Holocene began approximately 4600 yr. BP and reached its maximum 2800-2600 yr. BP (Miller, 1985; Porter & Denton, 1967). During this period Alpine glaciers in the High Cascades reached their maximum down valley advance since the end of the Pleistocene. Dethier (1980) used Mazama ash and lichenometric measurements to determine that the three moraine systems on Broken Top Mountain, 5 kilometers east of South Sister were formed 2500 yrs BP to 6800 yrs BP. These moraines are 1 to 2 kilometers down valley from the current position of the Bend, East Bend and Crook Glaciers. A similar three sequence moraine complex was noted by this researcher down valley from Prouty Glacier on South Sister. This moraine complex is assumed to be of the same age as the Broken Top moraines, though dating was not undertaken.

Inside these Neoglacial moraines is another complex of more recent moraines. The morphology of these moraines differs from that of older ones in that they are massive, sharp crested, constructed of poorly sorted bouldery till and are steeply angled (> 35°). On both Broken Top and South Sister, those moraines are within 100 and 300 meters of the current glacial position. Scott (1977) cites similar moraines on Three Finger Jack and Mount Jefferson.

There are historic accounts that state these moraines were in contact with their glaciers during this century. Dethier (1980) said that aerial photographs of Crook Glacier in 1955, showed it was in contact with a large active moraine. Marshall (1979) states that a 1928 aerial photographic reconnaissance showed that Prouty Glacier was in active contact with the large moraine which currently impounds Carver Lake. As a result of general retreat and downwastage, these glaciers have left large, unstable moraines, some of which impound small proglacial lakes (William, 1944).

It is these very recent moraines that are suspected of containing ice-cores. This hypothesis is reasonable, as all of these moraines are large, unstable features that require some sort of internal structure to maintain integrity. Scott (1977) suggests that one of these large moraines on Three Finger Jack has evidence of an ice-core which is in the process of melting. He cites the numerous

View of the steep inner slope of the northern moraine impounding Carver Lake.

View of the steep inner slope of the southeastern moraine impounding Carver Lake. In the foreground is ablation till over dead glacial ice.

Crest of southeastern moraine, showing the sandy, bouldery till of which the moraines surrounding Carver Lake are constructed.

View to the north showing the steep distal slope of the southeastern moraine impounding Carver Lake. In the background are Middle (left) and North Sisters.

wet landslide scars on the distal face as an indicator of this process.

Previous Work

Research concerning ice-cored moraines has come from many regions. Ostrem (1959, 1961, 1963, 1964 and 1971) focused on the detection and mapping of ice-cored moraines in Scandinavia. Work in Europe includes Haeberli (1978), Haeberli and Epitani (1986) and Whalley (1983). In North America, research includes Johnson (1971) and Rutter (1969) in the Yukon, Slatt (1971) in Alaska, Hooke (1970) in Greenland and Baffin Island (1973) and Flint (1971) throughout North America. Lliboutry et al. (1977) have done extensive research in the Cordillera Blanc, Peru.

Ostrem (1964) described the parameters by which ice-cored moraines can be mapped using aerial photography. He felt that ice-cored moraines would be located in areas of continental climate with low accumulation and ablation, and would be large in size relative to their source glacier. Originally, he believed that ice-cores in these moraines were from buried glacial ice, but upon investigation he discovered many that formed from snowbank ice. He proved this through crystallographic studies.

This may be the case in Scandinavia, but elsewhere research attributes ice-cored moraines to buried dead glacier ice and surging glaciers (Hooke, 1970 & 1973;

Johnson 1971). In these studies, debris covered dead ice masses have been over run by readvance of surging glaciers. Hooke (1970, 1973) developed a model by which these surging glaciers create ice-cored moraines. He termed this type of moraine a "shear moraine." Haeberli and Epitani (1986) mapped this type of moraine complex in the Italian Alps. Flint (1971) felt that small cirque glaciers in alpine areas of North America tend to respond much like surging glaciers in the Yukon and Greenland. This results from their steep gradients and relatively small size, which allow for rapid fluctuation of snout position due to changes in the glacier's mass balance. He also noted that due to the high erosive power of these alpine glaciers, a good deal of morainic material is available to bury dead ice masses.

All of these authors note that ice-cored moraines will be large in relation to their source glacier. Johnson (1971) notes that ice-cored moraines in the Yukon were 100-150 meters in height. Flint (1971) cites that alpine ice-cored moraines could reach 300 meters in height. It was Hooke (1970) who proposed that it was possible to determine the relative age of ice-cored moraines using crest morphology. He felt that recently formed ice-cored moraines will be sharp crested features, and as the ice-core melts the crest will take on a broad hummocky appearance. As the moraine undergoes this morphological change, the height will decrease in response to loss of internal mass.

Since the impetus for this study arose from research concerning the potential glaciofluvial hazard associated with morainal dammed Carver Lake, the following section will review literature concerning this hazard. Morainal dam failures and resultant outburst floods are often grouped with glacial outburst floods or jokulhlaups. Jokulhlaups are rapid drainages of glacially impounded water. The source of this water may be supraglacial, englacial or subglacial reservoirs. It is also possible that a glacier may advance across a river, forming a dam. In all cases the jokulhlaup drainage mechanism is created when the hydrostatic pressure becomes greater than that of the glacial dam (Embleton & King, 1975).

Morainal dams and lakes are most often associated with areas of active alpine glaciation. The topography tends to be high relief and high energy, resulting in glaciers with steep bed gradients. Today, glaciers in this environment are generally in a state of negative mass balance, resulting in downwastage and retreat. These areas include the Himalaya of Nepal, the Cordillera Blanc, Peru and the European Alps, the North American Rocky Mountains, and the High Cascades of Oregon and Washington.

In the Nepal Himalaya, Vuichard and Zimmerman (1985) chronicle the catastrophic drainage of a moraine-dammed lake in the Khumbu region. This flood resulted when an ice avalanche of approximately 150,000 m^3 entered the lake. The resultant wave breached the moraine dam, sending 5 million m^3 of water and debris down valley. The flood destroyed a hydropower plant, 14 bridges, 30 houses and eroded many hectares of farmland.

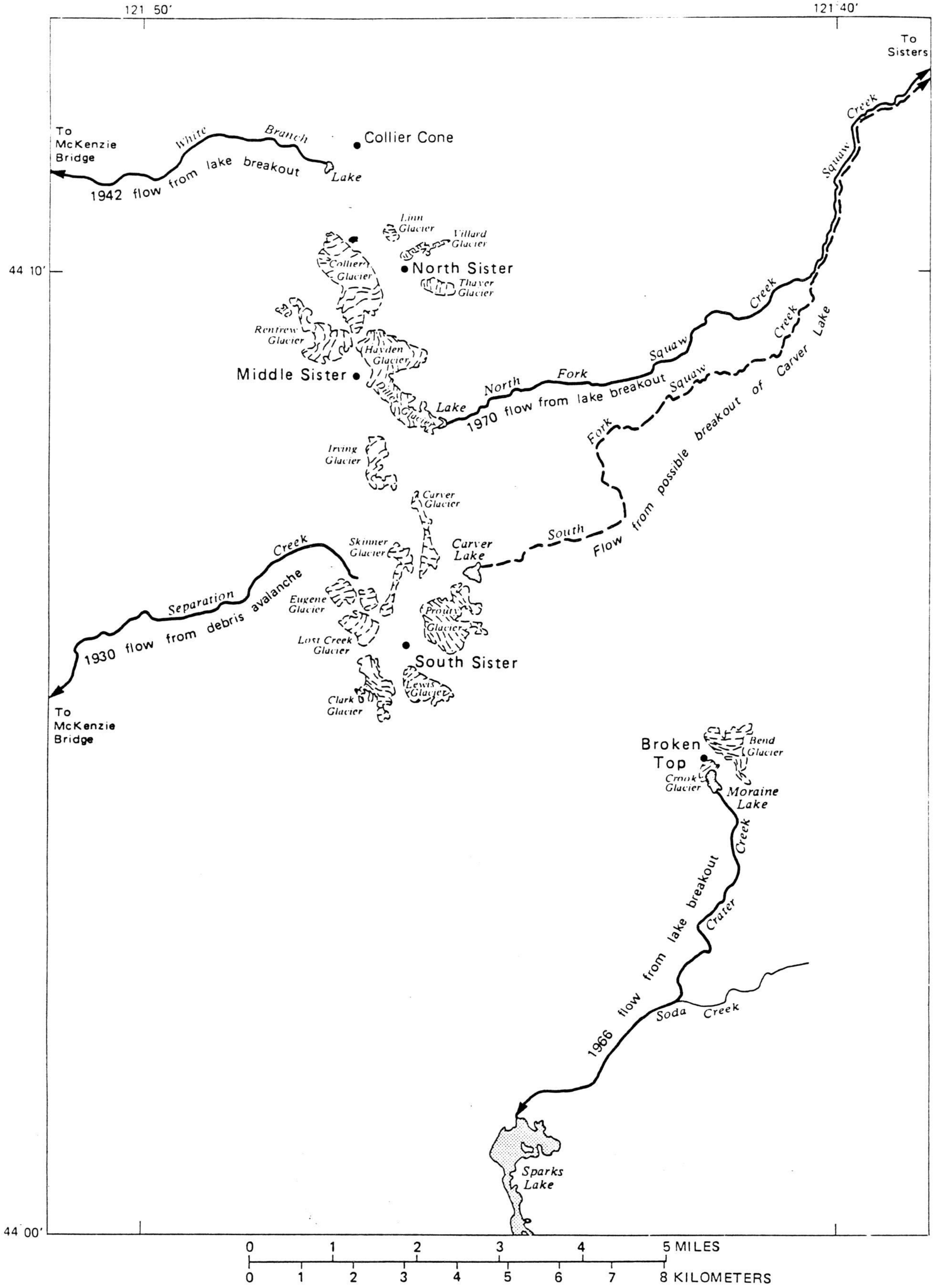
In a similar event, Fushimi, et al. (1985) modeled a morainic dam failure and flood in the Dudh Kosi region, Nepal. This event resulted when an ice-core melted out of a morainal dam. The collapse of the morainal dam sent 400,000 m^3 of water down valley, causing damage 70 kilometers from the source.

In the Cordillera Blanc, Peru, Lliboutry, et al. (1977) detailed the problems associated with identifying and controlling dangerous moraine lakes. In their review of past morainal dam failures, they cite ice avalanching and landslides triggered by earthquakes as the mechanism responsible for dam failure. Eisbacher (1982) reviews the consequences to the human population as a result of Andean moraine dam failures.

In British Columbia, Clague, et al. (1985) detailed a debris flow caused by the breaching of a morainal dam in the Coast Mountains. The dam was weakened by piping, but the actual breach was triggered by avalanche generated wave action. The resultant 1.7 million m^3 debris flow caused extensive channel damage and temporary damming of the Homathko River 8 kilometers downstream. In a similar event in the Coast Mountains, Blown and Church (1985) document a morainal dam failure triggered by an ice avalanche off the Cumberland Glacier. This avalanche resulted in rapid erosion of the moraine dam, emptying the lake in less than five hours with a resultant flood of 6.5 million m^3 of water and debris.

In both of these cases, the morainal dams were of Neoglacial origin, most likely from the 19th century 'Little Ice Age.' In neither case were the moraines ice-cored, though frozen ground water may have provided some internal structure. It was believed that significant changes in the glaciers' mass balance was a primary reason for the ice avalanches (Clague et al. 1985; Blown & Church, 1985).

In the vicinity of the Carver Lake study site, Laenen, et al. (1987) document 4 morainal dam failures and outburst floods (Map #2). In all of these cases, the moraines were of recent Neoglacial origin, probably this century. Nolf (1966) describes a 1966 moraine dam failure and flood on the east slope of Broken Top Mountain, 5 kilometers east of South Sister. This morainal dam was breached by wave action resulting from an ice avalanche off Crook Glacier. Though the moraine was only partially breached, the resulting flood deposited 10-20,000 tons of debris into Sparks Lake, 8 kilometers downstream. These



MAP 2: Historic Floods Resulting from Morainal Dam Failures in the Vicinity of Carver Lake. (source, USGS, 1987)

Photo mosaic looking northeast toward Sisters, OR. from the crest of the southeastern moraine. In the foreground hummochy morainal deposits formerly with ice-cores. This is the general direction any outburst flood would follow.

historic morainal floods suggest that Carver Lake has the potential to drain catastrophically.

What is a Moraine?

Moraines by definition are depositional features associated with glacial environments. They consist of unstratified, unconsolidated, poorly sorted sediments ranging from silt to boulders. They may be classified by several criteria, including position, process of formation, and whether they are active. The position scheme cites the location of the moraine relative to its glacier, i.e. terminal, lateral and medial. The process of formation is divided into ablation or ground moraine. Ablation moraines consist of relatively coarse material that has accumulated on the glacier surface and is deposited by downwasting or ablation of the glacier. Ground moraines are subglacial deposits consisting of a finer matrix of material, often termed lodgment till. Active moraines are those which are still in contact with a glacier, regardless of position (Embleton & King, 1975).

Ice-cored moraines have been placed in a special category (Embleton & King, 1975). Flint (1971) states that ice-cored moraines by definition must be terminal moraines. However, Ostrem (1964) mapped both terminal and lateral ice-cored moraines in Scandinavia. There are two processes which can create ice-cored moraines. In one, the debris covered snout of a downwasting glacier becomes detached by differential ablation rates. Then when the glacier readvances, this dead ice is overridden by additional morainic material. This is the process termed shear moraine by Hooke (1970). The second process occurs when a snowbank on the distal side of a moraine is covered by readvancement of a glacier. In this case, the buried ice does not make up a true ice-core; instead, it is a lens of ice (Ostrem, 1964; Flint, 1971; Embleton and King, 1975). In both cases, the buried ice is covered by a relatively thin layer of morainic material, less than 10 meters (Embleton & King, 1975).

Criteria to Identify Ice-Cored Moraines

Several criteria have been established to aid in the identification of ice-cored moraines using aerial photographs. The most common of these is that ice-cored moraines tend to be quite massive in relation to the size of the source glacier (Ostrem, 1964; Embleton & King, 1975). Factors associated with moraine size, include proximity to the glacier's snout, slope angle and general morphology. Hooke (1970, 1973) and Scott (1977), found that the closer the snout is to a large moraine, the greater the probability it will be ice-cored. Factors of slope angle and overall morphology seem to be less reliable. Both Hooke (1970) and Scott (1977) believe that recently formed ice-cored moraines will be sharp crested with steep slopes (> 35°). However, Embleton and King (1975), Flint (1971) and Ostrem (1964) suggest that ice-cored moraines will have lower angled slopes (< 25°) and a board, hummocky appearance. In this study, it will be assumed that the moraines follow the pattern described by Scott (1977), based on his observations of ice-cored moraines of this type in the Three Finger Jack Area, north of the Carver Lake site.

Other indirect indicators of ice-cored moraines include perennial snowbanks on distal slopes (Haeberli, 1978; Ostrem, 1964) and areas of high surface soil moisture and related slope failures (Scott, 1977). Perennial snowbanks are useful, since buried ice will tend to keep the base of the snowbank cool enough to reduce ablation. However, these snowbanks may be absent if the area has been subject to several years of below normal precipitation (Ostrem, 1964). High surface soil moisture and related slope failures may indicate the melting of the ice-core (Scott, 1977).

Based on the above criteria, the following parameters will be used to map suspected ice-cored moraines surrounding Carver Lake: 1) Moraine size, 2) distance to glacial snout, 3) Morainal slope > 35°, 4) Sharp-crested morphology, 5) Tonal contrast indicating high soil-moisture near the surface, and 6) Late season distal snowbanks. It should be noted, however, that some variability will be allowed in these parameters.

<u>Aerial Photographs for this Study</u>

Aerial photographs for this study were taken during a mission flown by the Oregon Army National Guard in late September, 1986. Photographs from this mission included both vertical and oblique views taken at various scales. these photographs reveal a complex terrain dominated by glacial erosion and deposition. All of the deposition in these photographs appears to be of recent origin. According to Marshall (1979), a 1928 aerial reconnaissance by the Mazamas Mountaineering Club showed the Carver Lake morainic complex still in active contact with Prouty Glacier.

This moraine complex fits the criteria set forth above for possibly being ice-cored. The recent origin of the moraines has allowed them to maintain their steep sloped, sharp crested appearance. The moraines are large when compared to the current size of Prouty Glacier. In the last 35 years, Prouty Glacier has retreated approximately 250 meters from the moraine complex. It appears that the ice abutting the western margin of Carver Lake is in fact a section of stagnant dead ice. This dead ice is separated from the snout of Prouty Glacier by a large active terminal moraine, 50 meters up glacier from Carver lake.

Vertical aerial photograph showing Carver Lake and surrounding morainal dams. See Geomorphological Map for interpretation. North is toward the top of photo. (Photo courtesy of the Oregon National Guard)

Oblique aerial photograph, showing the southeastern moraine damming Carver Lake. Early season snow makes detailed interpretation difficult. (Photo courtesy of the Oregon National Guard)

Since the Carver Lake moraine complex fits the criteria to be ice-cored, it is assumed to be ice-cored. The extent and mass of the ice-core could not be determined from the aerial photographs. Presumably, the ice-core does not extend much above the current water level of Carver Lake. The reason for this assumption is that a breach in the moraine from an earlier outburst flood eroded the upper portion of the moraine. Erosion of the breach was probably interrupted by the presence of the ice core and continual mass wasting from the morainal slope above the breach. Once the overtopping stopped, continued masswasting armored the outlet with boulders. It is this mass wasting debris which has contributed to the maintenance of the ice-core at the outlet.

The existence of an ice-core remained hypothetical until field work could be undertaken in the fall of 1987. Fieldwork objectives were to map the Neoglacial moraine complex and associated deposits and to excavate selected sites. Through these excavations it was hoped that the presence and extent of an ice-core could be determined. If an ice-core was located, then the thickness of the morainic debris could be measured. This is important, since the amount of debris is important in determining the rate of ablation for the ice-core, which may prove significant in predicting the longevity of the morainal dam.

Fieldwork

Initial reconnaissance was undertaken in early October, 1987. On this excursion a route to Carver Lake was laid out. This route followed maintained trails to within 5 kilometers of Carver Lake. At this point, rugged cross-country travel across steep volcanic and glacial deposits was required. This ruggedness meant that any equipment for the study would have to be backpacked in, therefore limiting the scope of fieldwork to relatively basic reconnaissance.

At the study site several procedures were undertaken. Slope angle and length were measured every 50 meters, a long the length of the southeastern moraine. Moraninal and glacio-lacustrine deposits were mapped to an older terminal moraine, 2 kilometers downslope of Carver Lake. Soil samples were measured for relative strength and porosity. Four sites were excavated on the southeastern moraine and two sites were excavated on the active moraine upslope of Carver Lake.

The crest of the southeastern moraine is approximate-ly 500 meters long and averages over 150 meters in height, though at a point just south of the outlet the distal slope is 225 meters high. This moraine is constructed of sandy, bouldery till, having high porosity and low shear strength. Nine slope measurements were taken along the crest. These measurements showed that the moraine has an average angle of 34° with a maximum of 42°. These steep slopes are beyond the angle of repose for this material, with continuous rock slides at the study site. This results in unstable slope conditions susceptible to larger failures and erosion. It should be noted that overland erosion is minimized by the high porosity of the morainic debris.

Given the above observations, it would seem that the morainal dam should be an unstable feature. Close inspection on the distal slope showed no evidence of piping or seepage. This seems to indicate a relatively consolidated feature. Though it is possible that the large mass of moraine is sufficient to maintain stability, it is more reasonable to assume that an ice-core provides structural integrity.

At this point excavation was needed to validate the hypothesis as to the presence or absence of an ice-core. Four excavation sites were located in those areas where buried ice may be near the surface, two on the lake side and two on the distal slope. Due to unstable conditions and constant rock slides, site 1 had to be relocated farther downslope. At this location, 5 meters from the outlet stream and 40 meters below lake level, buried ice was found covered by 30 cm of debris. An area approximately 1 m^2 was undercovered to verify that the ice was of glacial origin and not snowbank ice covered by mass wasting. Hand lens observations of crystal shape showed they were similar to those from the dead ice mass above Carver lake.

A second test pit dug on the distal slope at the other end of the moraine proved inconclusive. After a meter of material had been removed no ice was located. The third test pit was located on the lake side of the moraine across dam pit #2. The elevation of pit #3 was the same as pit #2. At pit #3, buried ice was found 15 cm beneath the surface. This site is the closest to the present snout of Prouty Glacier, and thus is located in the most recently deactivated position of the southeast moraine. Between pit #3 and the snout of Prouty Glacier is approximately 50 meters of ablation till covering dead ice. Test pit #4 also proved inconclusive due to constant slope failure during excavation. It is probable that buried ice is located at both the inconclusive test pits, but is beyond the range of manual excavation, given the unstable nature of the morainic debris.

Given the location of the two positive test pits and their relation to the water line of Carver Lake, it is reasonable to conclude that an ice-core exists in the southeastern moraine. This ice-core has created an impervious barrier to water, hence there is no piping or seepage. Visual inspection of the northern moraine showed

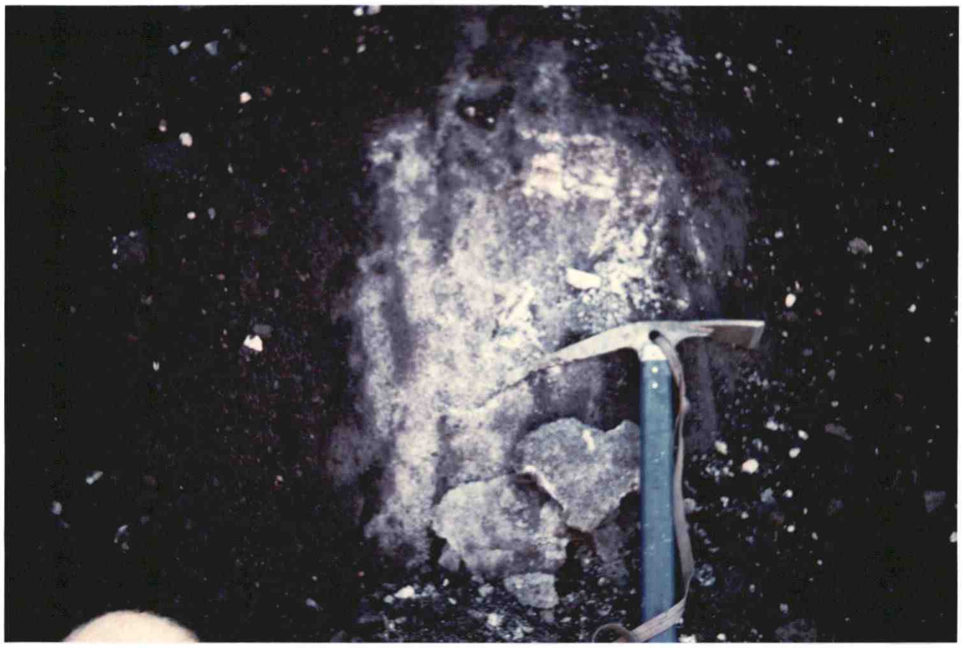


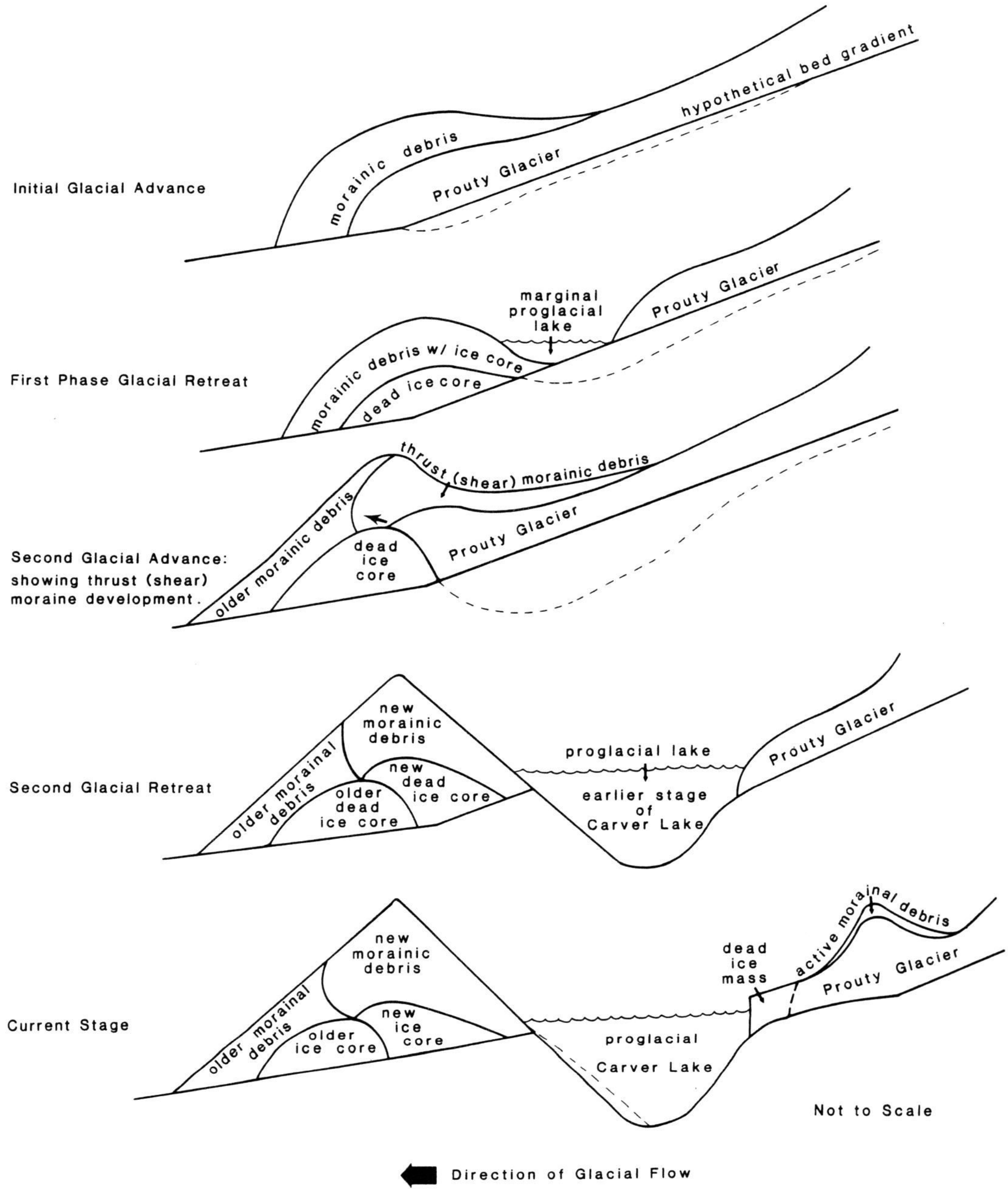
Photo of buried glacial ice-core found at test pit #1.
Depth to the ice 30cm.

Photo of buried glacial ice-core found at test pit #4.
Depth to the ice 15cm.

obvious similarities. This moraine fits all of the criteria to be ice-cored; including that of a perennial snowbank on the distal slope. This observation is important, since the late summer and fall or 1987 were dry and above average in temperature. This would seem to indicate that the ground beneath the snowbank was sufficiently cool to reduce ablation. No test pits were excavated to confirm this assumption due to lack of time.

In an attempt to determine the process by which the Carver Lake moraines were formed, test pits were dug on the active moraine upslope of Carver Lake. Test pit 'A' was located on the distal slope, with test pit 'B' just below the crest on the glacier side. Buried ice was found in both test pits. In pit 'A' ice was 30 cm below the surface and in pit "B" was located 1 m beneath the surface. According to Hooke's model (1973), this would be the first stage in the formation of a shear moraine. In the second stage, Prouty Glacier would readvance, pushing morainal debris over the older moraine.

With the commencement of glacial retreat this morainic debris would rapidly adjust its slope form due to its unconsolidated nature, resulting in a sharp crested, steep slope form atop the older morainic. (See diagram #1) It is postulated that this is the process by which the Carver Lake moraine formed.



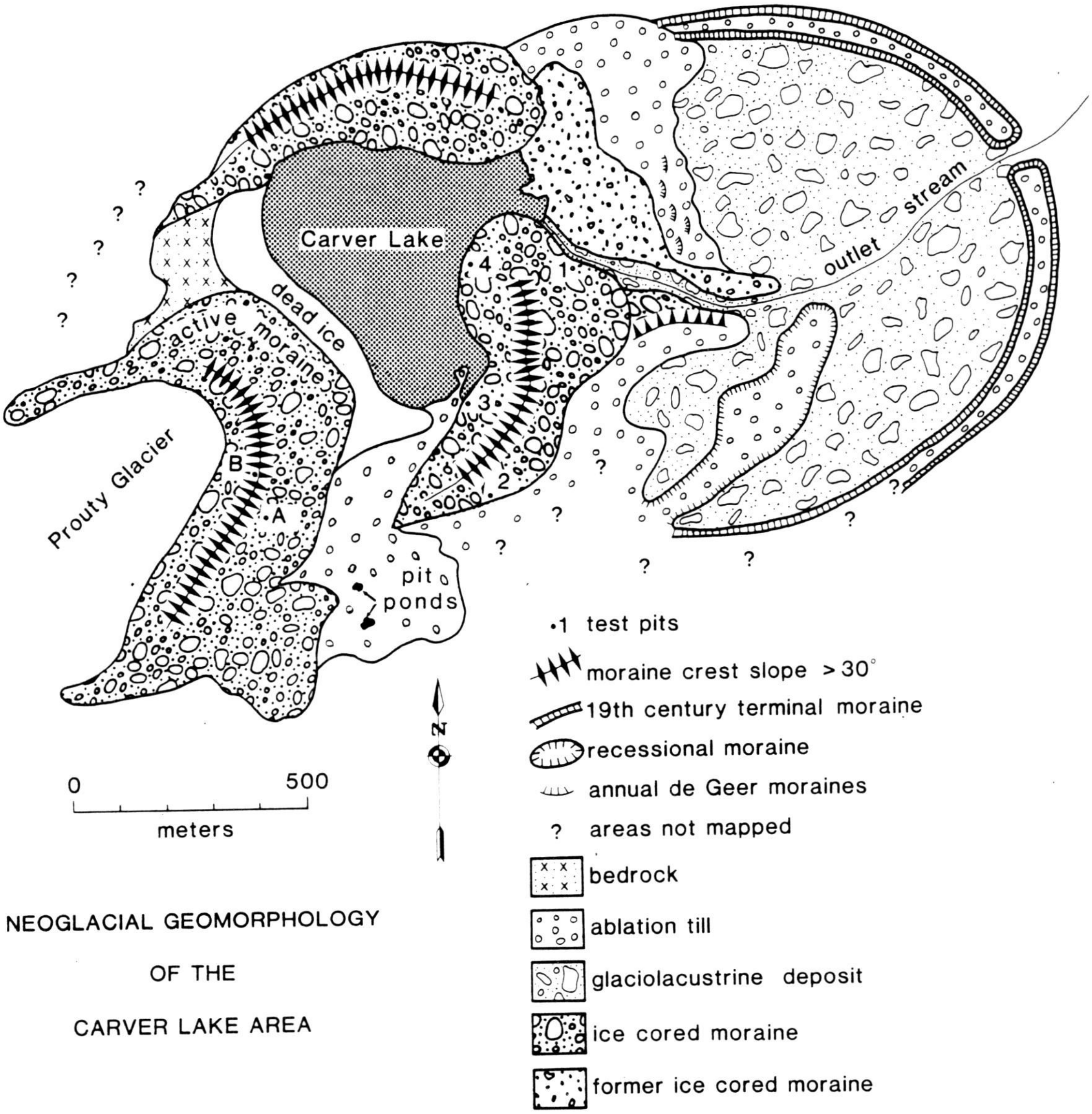
CONCEPTUAL MODEL OF THE DEVELOPMENT OF ICE-CORED MORAINES IMPOUNDING CARVER LAKE
(After Hooke, 1973)

Geomorphological Map

The results of aerial photographic interpretation and field work have been compiled onto a map showing the glacial geomorphology in the Carver Lake region (Map #3). This map extends 2 kilometers down valley from Carver Lake and to Prouty Glacier above. Within this area are glacial deposits of three periods. The outermost moraine complex is probably of the 19th century 'Little Ice Age'. Between this complex and Carver Lake are lateral moraines and glaciolacustrine deposits. Above Carver Lake is the active terminal moraine of Prouty Glacier and Prouty Glacier.

Dating of these deposits was not undertaken in this study. However, vegetation evidence on the outer moraine correlates with a similar depositional sequence found on Broken Top Mountain and dated to the 19th century by Diether (1980). Vegetation on this moraine consists of a sparse stand of lodgepole pine (*Pinus contorta*) and unidentified ground cover. The morphology of this moraine complex is significantly different from more recent deposits up valley, being a low broad crested shallow sloped form. It shows signs of significant erosion and weathering, with a primitive two horizon soil.

One feature on this map that deserves mention is the fluvial/glaciolacustrine deposits located behind this outer moraine complex. These sediments range from sand



NEOGLACIAL GEOMORPHOLOGY
OF THE
CARVER LAKE AREA

through cobbles that have been rounded by fluvial action and deposited in a stratified manner. The coarse cobbles have been deposited closest to Carver Lake, with the finer material being deposited up to the outer moraine. The unique feature of this formation is that the lake drained through a breach in the outer moraine. This breach gives further weight to the argument that morainal dam failures are not unusual processes in the alpine environment of the High Cascades.

Discussion

It has been shown that Carver Lake's moraine complex contains an ice-core. Excavation provides the only direct method of determining the existence of buried ice. There are several problems associated with this technique. First and foremost, manual excavation is the only method available in designated wilderness areas. This designation prohibits the operation of any mechanized equipment. This results in time consuming, laborious and costly field operations. These limitations make it difficult to accurately determine the extent and volume of buried ice masses.

It is possible to overcome these restrictions by employing geophysical techniques. These techniques, including geo-electrical resistivity and seismic refraction provide accurate, though indirect data concerning the nature of subsurface stratigraphy. These techniques, combined with excavation and aerial photographic interpretation, have been proven successful in several locations worldwide. The most extensive application of these techniques was undertaken by Ostrem (1964) in mapping ice-cored moraines in Scandinavia. Lliboutry, et al. (1977) employed them in mapping potentially dangerous morainal dams in the Cordillera Blanc, Peru and Haeberli and Epstani (1986) conducted similar research in the Italian Alps. A detailed discussion of geophysical techniques may be found in Griffith and King, (1965), Telford, et al. (1976), Parasnis (1979) and Gardiner and Dackombe (1983). Haeberli and Epstani (1986) have developed another indirect detection technique for mapping buried ice. They found that the soil temperature beneath the winter snowpack will indicate if there is ice present in the morainic material. In this research, they showed that soil temperatures below -3°C indicate buried ice within 4 to 6 meters of the surface. This methodology was validated using geophysical techniques. All of these techniques were available to this researcher, but were not employed in this study due to insurmountable logistical problems.

Conclusion

This study has shown that it is possible to detect and map ice-cored moraines using aerial photographic interpretation. Although the methodology has been employed elsewhere, this is the first such study in the High Cascades. Based on the results of this research, it should be possible to undertake a similar study at the regional level. Such an expanded study could provide benefits in both pure and applied geomorphology.

In the field of pure geomorphology, mapping the regional distribution of ice-cored moraines may contribute significant data concerning the extent/fluctuation and equilibrium line altitude of High Cascade glaciers during the Neoglacial period. Since ice-cored moraines are relatively unique features in temperate Alpine regions, research remains to be done concerning the processes by which they are formed (Embleton and King, 1975). Other research includes the dating of these features. Ostrem (1961) used organic matter trapped in the ice to date moraines in Scandinavia, some of which were 2600 $\pm$ 100 years old. Similarly, research on the ablation rates for ice-cores could prove significant. In sub-polar regions, ice-core ablation rates are approximately 1 cm/day when covered by 20 cm of debris (Ostrem, 1963, 1964). Both of these topics would prove interesting studies in the temperate Alpine regions.

In an applied perspective, a regional study mapping the distribution of ice-cored moraines and associated lakes is needed to better understand the extent of potential flood hazards. Carver Lake has been labelled such a lake by the United State Geological Survey, in that it poses a significant hydrologic hazard to the town of Sisters, Oregon (Laenen, et al., 1987). The U.S.G.S. has begun a regional study on the extent of dangerous morainal lakes in the High Cascade area, though it is progressing slowly (Laenen, 1987). Regardless of the extent of this problem now, it will grow as the alpine glaciers of the High Cascades continue to retreat. This problem is a worldwide phenomena associated with high mountain areas. As development continues in these areas the risks associated with morainal lakes will also mount.

Though this research has shown positive results concerning the application of aerial photography and field reconnaissance, there remains a good deal of work to be done on the subject. The biggest question still to be answered is whether or not Carver Lake does pose the significant potential flood hazard that the U.S.G.S. has postulated (Laenen, et al., 1987). To determine this a detailed terrain analysis would be needed, combined with the various projected flood level scenarios. In the end, this study is but the beginning of some very interesting research problems.

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APPENDIX

Further Research

The results of this study have shown that more rigorous techniques need to be employed to accurately determine the extent of the ice-core buried in the Carver Lake terminal moraines. It is proposed that the following techniques would provide these data: 1) Geo-electrical resistivity (GER) and 2) soil temperature readings taken beneath winter snow cover (BTS). Both of these techniques have been applied successfully in the mapping of ice-cored moraines in Europe. (See Ostrem, 1964: Haeberli and Epifani, 1986). Adaptation of these techniques would result in the necessary data to accurately map the extent of the ice-core within the Carver Lake terminal moraines.

The GER study would employ equipment with a maximum depth range of 30 meters. This limited range combined with the large size of the moraines (> 150 meters in height) requires that some modifications to the traditional GER methodology be made. It is proposed that a modified Schlumberger electrode configuration, suggested by Gardiner and Duckombe (1983) be employed. This method would allow lateral exploration profiles to be developed from lake level to the crest of the moraine. It would take a minimum of 10 GER transects to profile the eastern moraine. (See Map #3 in text). A similar number of profile trans would be needed on the northern moraine.

In addition to a GER study, the measurement of soil temperature beneath winter snowpack (BTS) would provide a semi-quantitative analysis as to the extent of the buried ice mass. This technique uses heat flow characteristics to differentiate between frozen and unfrozen ground beneath the snow cover. It is based on the insulating properties of snow which results in a temperature reading of approximately 0°C, if the subsoil is not frozen. Haeberli and Epifani (1986) have shown that BTS readings of -3°C or lower indicate 'cold (ice) layers' beneath the surface. Their results have been corroborated with GER data. This technique is accurate in areas where the buried ice is within 4 to 6 meters of the surface. Since the results of this current study have shown buried ice to be near the surface (< 1 meter), a BTS study should provide good results.

The results of this additional research would provide an accurate assessment as to the extent of the buried ice-core in the terminal moraines impounding Carver Lake. This research could then be incorporated into work being done by the U.S.G.S. on determining the probability for failure of these morainal dams. In addition to these data, a detailed program of terrain analysis and mapping would result in the necessary information to develop an accurate outburst flood hazard model. This type of detailed study is important given the remote and politically sensitive location of Carver lake and the need for timely mitigation of the potential flood hazard to the town of Sisters, Oregon.