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Gordon, some fodder for your pondering box. Jim

Geologic and Hydrologic Hazards in Glacierized Basins in North America Resulting from 19th and 20th Century Global Warming

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Abstract. Alpine glacier retreat resulting from global warming since the close of the Little Ice Age in the 19th and 20th centuries has increased the risk and incidence of some geologic and hydrologic hazards in mountainous alpine regions of North America. Abundant loose debris in recently deglaciated areas at the toe of alpine glaciers provides a ready source of sediment during rainstorms or outburst floods. This sediment can cause debris flows and sedimentation problems in downstream areas. Moraines built during the Little Ice Age can trap and store large volumes of water. These natural dams have no controlled outlets and can fail without warning. Many glacier-dammed lakes have grown in size, while ice dams have shrunk, resulting in greater risks of ice-dam failure. The retreat and thinning of glacier ice has left oversteepened, unstable valley walls and has led to increased incidence of rock and debris avalanches.

Key words. Climate change, floods, rockfall, debris flows, sedimentation, glaciers, North America.

1. Introduction

Global climate fluctuations have strongly affected mountain environments, especially those containing alpine glaciers. Past periods of global warming in particular can provide instructive analogies of the possible future consequences of human-induced climate perturbations. The purpose of this paper is to focus on the 19th and 20th century global warming associated with the end of the 'Little Ice Age' and, specifically, to review some of the geologic and hydrologic processes and hazards resulting from glacier retreat during the last century in mountain environments of North America. These processes include rapid proglacial sedimentation, floods and debris flows from rapid releases of moraine- and glacier-dammed lakes, and rock and debris avalanches from oversteepened valley walls. These geologic and hydrologic processes are well known and there have been numerous case studies (e.g. Eisbacher and Clague, 1984). We consider them, however, in the larger context of the relation between glacierized alpine environments and climate change. Taken together, we consider these processes to constitute a large portion of the geomorphic response to rapid alpine glacier retreat. We focus on North American examples; however, the geologic and hydrologic processes and hazards that accompany glacier retreat in North America occur in glaciated areas worldwide.

Climate change between the 16th and 20th centuries has had profound effect on glaciated environments throughout the world (Lamb, 1977, 1979; Wallén, 1986; Grove, 1987, 1988). The Little Ice Age of the 16th–19th centuries was followed by a period of substantial warming during the 19th and early 20th centuries. Although recent warming has occurred in tandem with increased burning of fossil fuels and the introduction of large volumes of carbon dioxide and other 'greenhouse gases' (such as methane, chlorofluorocarbons, nitrous oxide) into the atmosphere, it is difficult to separate unequivocally the climatic impact of these gases from the natural variability of climate change (Ellsaesser *et al.*, 1986; Mitchell, 1989; Ellsaesser, 1990; Houghton *et al.*, 1990). Nevertheless, historic warming has been of a magnitude and rate broadly similar to that predicted to result from the potential future effects of 'greenhouse' warming over the next 50 years (Mitchell, 1989; Schneider, 1989), and evaluation of the effects of this historic period of global warming is relevant for assessing hazards resulting from possible future warming in alpine environments.

2. Historic Climate Change and Glacier Response

The term 'Little Ice Age' (Matthes, 1939) is widely used by climatologists, geologists and glaciologists to describe a period of worldwide lower temperatures and advanced glacier terminus positions from the 16th century through the late 19th century (Grove, 1988, pp. 3–5; Porter, 1986). The Little Ice Age is generally regarded as the culmination of the 'Neoglacial Period' (Porter and Denton, 1967), a period of generally lower temperatures that has encompassed the last few millennia (Davis, 1988). On the basis of terminus altitudes of Little Ice Age glaciers, Porter (1986) suggested that mean annual temperatures have risen 0.5–1.2 °C between the coldest period of the Little Ice Age and present in the northern mid-latitudes. This estimate is consistent with historic temperature changes documented by instrumental records dating back to the late 19th century (Jones *et al.*, 1986; Hansen and Lebedeff, 1988) (Figure 1).

The Little Ice Age ended abruptly and broadly synchronously with a period of rapid warming between about 1885 and 1940 when global mean temperatures increased 0.3–0.6 °C (Hansen and Lebedeff, 1988; Houghton *et al.*, 1990) (Figure 1). In some local areas the warming trend began several decades earlier. Warming has been greater in the northern latitudes between 23.6° N to 90° N where there has been about an 1.2 °C increase in mean near-surface air temperature (Hansen and Lebedeff, 1988). A large part of this warming, especially in the northern latitudes, was between 1910 and 1940. The period between 1940 and 1970 was characterized by little change globally and slight cooling in the Northern Hemisphere. From 1970 to present, temperatures have been rising at a rate similar to that of between 1910 and 1940 (Figure 1). The five warmest years recorded through

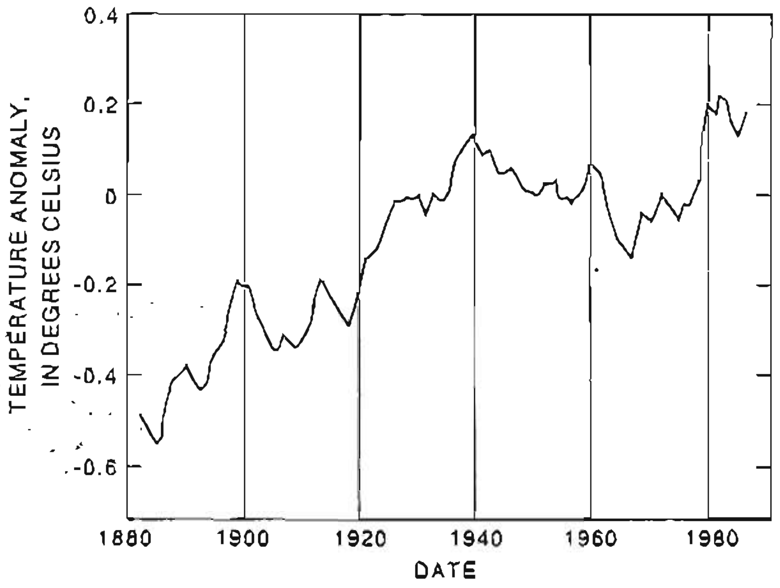

Fig. 1. Global surface air temperature fluctuations plotted as running five-year mean anomalies with respect to 1950–1979 mean temperature. Modified from Hansen and Lebedeff (1988).

1990 all occurred in the 1980's (Hansen and Lebedeff, 1988; Houghton *et al.*, 1990).

Mountain glaciers are especially sensitive to climate change because longer, warmer melt seasons and reduced accumulation-season precipitation result in a reduction of glacier mass. Sustained periods of mass-balance deficit result in glacier thinning and upvalley retreat of glacier termini. Conversely, lower temperatures or increased accumulation-season precipitation result in glacier thickening and advance. Many temperate alpine glaciers achieved their most advanced positions of the Holocene Epoch (10 000 years BP to the present) during the late Neoglacial (Little Ice Age) maximum (Grove, 1988). Near-maximum positions generally persisted until the late 19th century, when there was widespread and rapid shrinkage in response to the 1885–1940 period of warming. At some locations, such as Washington State, decreased winter precipitation between 1910 and 1940 was also an important factor (Hubley, 1956; Burbank, 1982). Glacier equilibrium line altitudes have risen 100–200 m since the Little Ice Age maximum (Porter, 1986) and the amount of ice-covered area in many alpine environments has decreased substantially (Figure 2). Many former glaciers have ceased flowing because of reduced ice mass (Tufnell, 1984, p. 17). Glacial retreat has affected water resources (Collins, 1984; Gleick, 1989), sea-level rise (Meier, 1984), and has resulted in a suite of alpine geomorphic processes and associated hazards.

Alpine glacier retreat may continue as a result of human-induced 'greenhouse' warming, although the relation is not straightforward. Important uncertainties

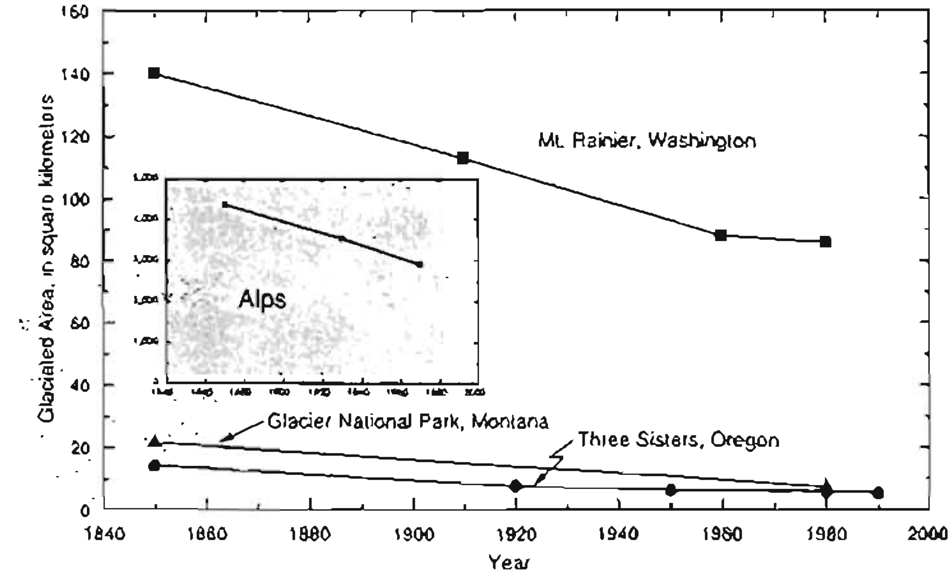

Fig. 2. Extent of ice-covered area for selected regions of temperate alpine glaciers. Glaciers have shrunk substantially since the Little Ice Age maximum. The dates for the earliest data for Mt. Rainier, Washington, the Three Sisters, Oregon, and Glacier National Park, Montana, are approximate and represent mid-nineteenth century estimates. European Alps data from Chen and Ohmura (1990); Mt. Rainier data from Post (1963), and Driedger and Kennard (1986); Glacier National Park data from Carrara (1989). The Three Sisters, Oregon, data are from Driedger and Kennard (1986) and unpublished observations and reconstructions by the authors.

include the role of factors such as precipitation and cloud cover. Most climate models predict that global precipitation will increase by 3–11% if CO_2 concentrations are doubled (Wigley and Jones, 1985). There are, however, strong latitudinal variations (e.g. Schlesinger and Mitchell, 1987) and the response in specific alpine areas will depend on local or regional climate patterns and the resulting balance between possible higher temperatures and greater precipitation.

Most temperate mountain glaciers respond sensitively to decadal-scale climate variations (Tangborn, 1980; Jóhannesson *et al.*, 1989). It should be noted, however, that some glaciers also behave in manners seemingly independent of climatic variability. Examples include surging glaciers (Meier and Post, 1969), advances associated with volcanic meltwater produced by geothermal heat (Sturm *et al.*, 1991), and advancing and retreating tide-water glaciers whose terminus positions are controlled by interactions of fiord depth, ice thickness, and calving rate (Sturm *et al.*, 1991; Warren and Glasser, 1992).

3. Hazards Resulting from Glacier Retreat

Geologic and hydrologic hazards associated with alpine glaciers have long been recognized in mountain communities near active glaciers (Lliboutry, 1971; Grove, 1972, 1987, 1988; Eisbacher and Clague, 1984; Tufnell, 1984; Ives, 1986; Peña and Klohn, 1989; Hewitt, 1989). Most studies that have evaluated glacier hazards with respect to climate variability have emphasized the well-documented hazards and human hardships associated with the *advancing* glaciers of the Little Ice Age (Grove, 1972, 1987, 1988; Tufnell, 1984). There are, however, a variety of geomorphic processes and related hazards that are exacerbated by glacier *retreat* (Evans and Clague, 1993). Many of these hazards are as severe and potentially catastrophic as any associated with Little Ice Age advances. The following processes are ones that we have identified as being due in part to geomorphic conditions associated with glacier retreat: (1) Rapid mobilization of unvegetated, unstable, ice-cored debris by streams and rivers in recently deglaciated areas. (2) Floods from breached moraine-dammed lakes. (3) Floods from breached glacier-dammed lakes. (4) Rockfalls and avalanches from recently deglaciated areas. We have little quantitative information on the frequency of these phenomena or their relative importance. Nevertheless, there is abundant evidence that all have frequently occured in areas of alpine glaciation (e.g. Eisbacher and Clague, 1984; Ives, 1986; Peña and Klohn, 1989; Hewitt, 1989), and we speculate that these geologic and hydrologic processes will continue to pose hazards in mountain environments around the world.

3.1. *Paraglacial Sedimentation*

A major consequence of glacier retreat is the exposure of large quantities of unconsolidated, unvegetated, and commonly ice-cored glacial sediment (Figure 3). These deposits are a heterogenous mixture of particle sizes that are commonly emplaced on steep slopes. This sediment is readily mobilized by a variety of processes and transported downstream. Floods resulting from precipitation, snowmelt, or glacial outbursts can rapidly incorporate large quantities of material exposed by glacier retreat and evolve into debris flows (Richardson, 1968; Walder and Driedger, 1993). Church and Ryder (1972) defined "paraglacial sedimentation" to describe the enhanced sediment flux in recently deglaciated terrain. The attendant problems are not restricted to the alpine environment, but can have persistent downstream consequences, including channel aggradation and associated higher flood stages, reservoir sedimentation, and destruction of fish habitat.

At Mt. Rainier, Washington (Figure 4), Little Ice Age deposits cover 27 km^2 and comprise about 1.35×10^8 m^3 of debris (Mills, 1976). Mills (1976) estimated that at Mt. Rainier, the modern sediment flux rate is about four times the Quaternary erosion rate of the volcano. During periods of advanced glacier positions, sediment is eroded and transported from high parts of the basins and deposited in proglacial areas. These deposits are now being eroded and transported downstream by debris flows, outburst floods, and rainfall-runoff floods. In the recently deglaciated area in front of South Tahoma Glacier, more than 9×10^6 m^3 of sediment has been moved downstream (Figure 5) between 1970 and 1992. At least

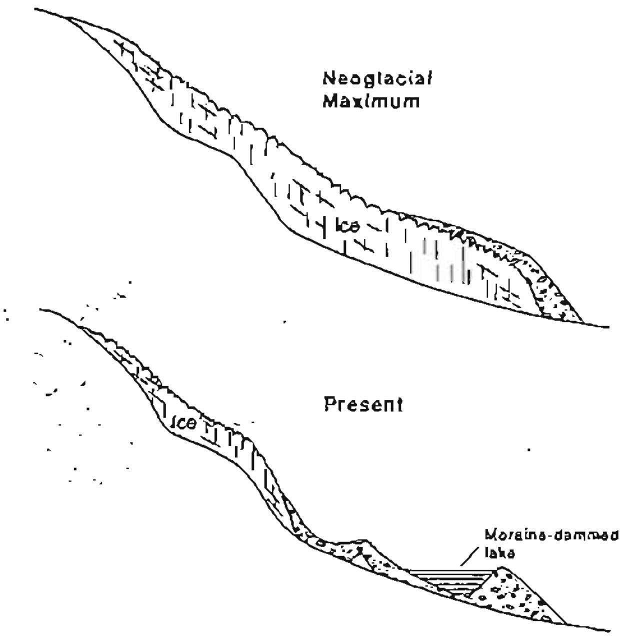

Fig. 3. Schematic representation of alpine glacier conditions in North America at the time of maximum Little Ice Age advance and at present. (a) At the maximum extent of Little Ice Age glaciation, ice extended further downvalley from source areas and deposited large amounts of upvalley derived sediment at glacier termini. (b) In response to warmer twentieth century temperatures, most alpine glaciers have lost mass, resulting in upvalley retreat of terminus positions. Unconsolidated sediment is left on the valley floor, commonly enclosing bodies of stagnant ice. Prominent end moraines may trap proglacial bodies of water

16 debris flows, many probably triggered by outburst floods, have occurred during this time period (Walder and Driedger, 1993).

In the Coast Mountains of British Columbia, present sediment yields from glaciated basins (with drainage areas less than 1000 km^2) are an order of magnitude greater than sediment yields from non-glaciated basins of similar size. Part of the disparity undoubtedly is due to the erosional capabilites of glaciers, but a large component of the present sediment flux is from mobilization of sediment from recently deglaciated areas (Church and Slaymaker, 1989; Church *et al.*, 1989).

Little detailed information is known about the processes that mobilize this sediment and the magnitudes and frequencies with which they occur. Mass movement, debris flow, streamflow, rainsplash, rill erosion, and soil creep all transport Little Ice Age deposits downstream; however, the relative importance of these processes is yet to be determined. Debris flows are probably the dominant mechanism for episodically transporting large quantities of Little Ice Age sediment for long distances. Research is currently underway investigating the triggering mechanisms for these events. It seems that outburst floods, precipitation-induced floods,

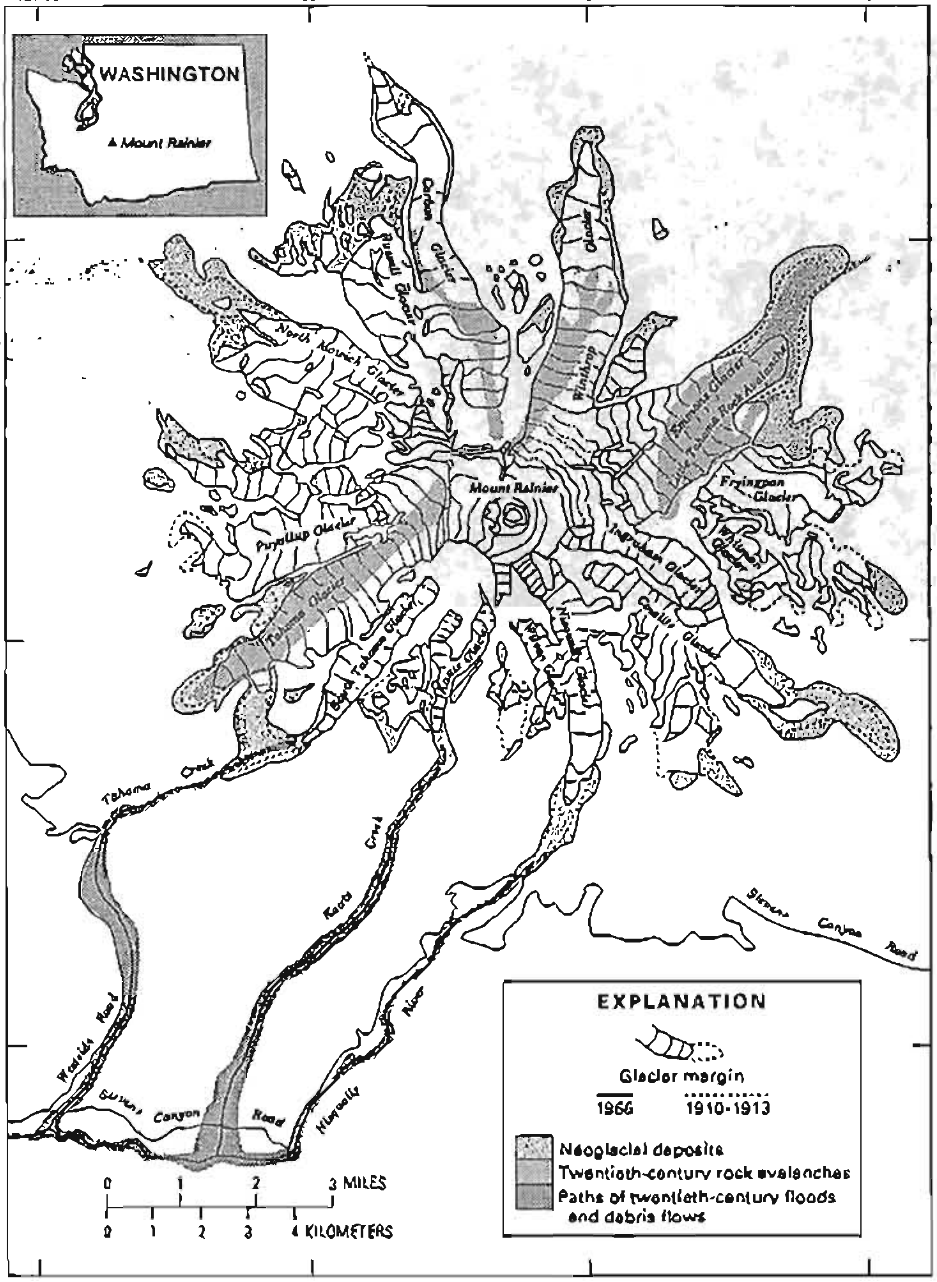

Fig. 4. Past and present limits of glaciation and Neoglacial deposits at Mt Rainier, Washington State. The maximum Neoglacial extent of ice broadly corresponds to the limits of Neoglacial deposits. Also shown are paths of historic rock avalanches and floods and debris flows that originated as outburst floods or from melting and collapse of ice-cored debris [from K. M. Scott (USGS, written commun., 1991), Richardson (1968) and Driedger and Fountain, (1989)]. Glacier limits from U.S. Geological Survey topographic maps, extent of Little Ice Age deposits from Crandell (1969).

Fig. 5. A view of the valley of Tahoma Creek several kilometers downstream of South Tahoma Glacier, Mt Rainier (Figure 4). Erosion of Little Ice Age sediment has led to substantial valley aggradation downstream and closure of a park road (visible on the left portion of the photograph). The stands of dead trees visible in the valley bottom have been killed as a result of aggradation and repeated inundation by debris flows. Photograph by J. Walder.

geothermal heat flow, mass movement, and melting of stagnant ice may all play roles in inducing debris flows in certain alpine environments.

Paraglacial sedimentation can constitute an immediate geologic hazard in some settings. For example, the debris flows along Tahoma Creek have destroyed part of the Westside Road at Mt. Rainier National Park and constitute a hazard to recreational users (Figures 4 and 5). Debris flows, caused by glacial outburst floods incorporating recent glacial deposits on the north side of Cathedral Mountain in the southern Rocky Mountains of British Columbia, have repeated damaged the Trans-Canada Highway and the Canadian Pacific Railroad since 1925 (Jackson, 1989). Other consequences of paraglacial sedimentation, however, are more insidious. Sedimentation of reservoirs and channel aggradation can have long-term consequences with respect to downstream flood hazards. Mountain streams are increasingly being exploited for hydropower, especially in developing countries. The high sediment loads associated with paraglacial sedimentation will extract an economic cost in developing these resources. Awareness of these less obvious effects of deglaciation may help mitigate some of the future costs associated with continued retreat of alpine glaciers.

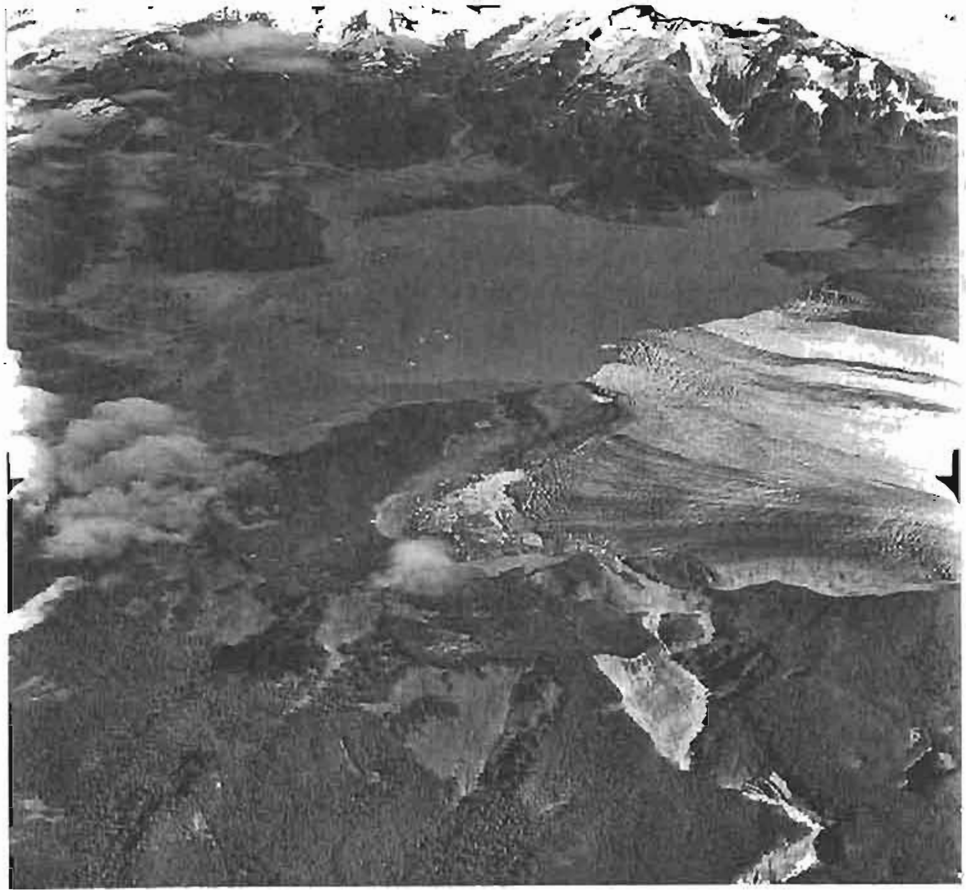

Fig. 6. Berg Lake near Katalla, Alaska. The Bering Glacier (which flows right to left in this view) filled most of this large embayment in 1905. Subsequent retreat of the glacier has resulted in formation and enlargement of a large proglacial lake (Post and Mayo, 1971). Thinning and retreat of the ice dam has led to outburst floods in the channel in the foreground. A previous, higher, lake level is indicated by the trimline above the present lake level. U.S. Geological Survey photograph by R. Krimmel.

3.2. *Ice-Dammed Lakes and Outburst Floods*

Thinning and shrinking of alpine glaciers in response to global warming has produced hazardous situations associated with the formation or enlargement of ice-dammed or ice-marginal lakes (Figure 6). At a number of locations, this particular hazard did not exist until glacier retreat resulted in expansion of proglacial lakes and greater volumes of impounded water pressing against thinning ice dams (Peña and Klohn, 1989; Clague and Mathews, 1992). For example, Ape Lake, British Columbia has been dammed by Fyles Glacier for many centuries, but since the turn of the century, the ice terminus has been thinning and retreating.

Probably as a consequence of the diminished ice mass damming the lake, the first outburst flood from Ape Lake in historic time was in 1984 (Desloges *et al.*, 1989).

Floods and debris flows caused by rapid release of ice-dammed lakes result from formation of drainage channels under, through, or over the impounding ice. Some mechanisms proposed for initiating drainage channels and causing failures include: (1) plastic yielding of the ice by hydrostatic pressure; (2) lifting of the ice dam by hydrostatic flotation; (3) crack propagation resulting from glacier flow in an environment of high hydrostatic pressure; (4) drainage through channels at the ice-rock interface; (5) enlargement of ice tunnels by thermal erosion by exiting lake water; and, (6) overtopping of the ice barrier (Post and Mayo, 1971). In many topographic and glacial settings, these failure mechanisms can be facilitated when the impounded lake enlarges, or the ice dam thins in response to sustained periods of warming. Some examples of places where the hazard from outburst flooding increased as a result of glacier retreat during the late 19th and 20th centuries are listed in Table I.

The downstream risk from some ice-dammed lakes can be evaluated in a general manner by the use of empirical relations between lake volume and peak discharge (Clague and Mathews, 1973; Beget, 1986; Costa, 1988), physically based models of subglacial water release and ice-dam erosion (Clarke, 1982), and by flood-routing techniques (Fernandez *et al.*, 1991). Floods from some ice-dammed lakes recur annually during the melt season, or at regular intervals every few years, thereby allowing some predictive ability.

Outburst floods from englacial and subglacial accumulations of water are more difficult to predict, temporally and spatially (Post and Mayo, 1971; Haeberli, 1983). It is not presently clear how climatic variations may play a role in the incidence of outburst floods; nevertheless, they have been a common phenomenon during recent periods of warming. Throughout the 20th century, many outburst floods from englacial and subglacial sources have occurred in the Swiss Alps where they are generally associated with steep glaciers (Haeberli, 1983). Outburst floods from englacial or subglacial water accumulations have been a significant hazard at Mt. Rainier, where there have been at least 27 such floods since 1926 (Driedger and Fountain, 1989). These floods commonly occur late in the melt season with no hydrological precursors and have resulted in damage to bridges, roads, and trails. Similar floods have also been reported at most other Cascade Range volcanoes (Richardson, 1968). Almost all outburst floods on Cascade Range volcanoes have evolved into debris flows by incorporating large quantities of Little Ice Age deposits downstream of the glacier termini (Driedger and Fountain, 1989; Walder and Driedger, 1993).

3.3. *Failures of Moraine Dams*

One of the most dangerous and unpredictable consequences of historic glacier retreat has been the forming and breaching of moraine dams. Many alpine glaciers

Table I. Examples of outburst floods from ice-dammed lakes resulting from glacier retreat.

Lake and location	Events	Reference
Berg Lake, Alaska	Since 1905, retreat of an arm of Bering Glacier has increased the area of Berg Lake from 12 to 28 km^2 in 1970. Continued melting and thinning of ice dam poses serious threat of outburst floods.	Post and Mayo (1971)
Lake George, Alaska	Until 1967, Knik Glacier advanced every winter and sealed off Knik Valley, forming Lake George. Maximum area was about 65 km^2, and about 50 m deep. Knik Glacier dam released outburst floods every year since at least 1918. Thinning of ice dam resulted in earlier outburst floods since 1935, and larger floods since 1949. Since 1967, Knik Glacier has been unable to close off the valley or impound water	Stone (1963); Hulsing (1981)
Tide Lake, Canada	Tide Lake, impounded by Frank Mackie Glacier, was the largest glacier-dammed lake in Canada prior to emptying for the last time about 1930. Corresponding to the maximum Little Ice Age advance of Frank Mackie Glacier at about 1650 AD, Tide lake achieved a maximum depth of 200 m and impounded 10^9 m^3 of water. During the seventeenth and eighteenth centuries, Tide Lake was apparently stable, probably the result a tight seal formed by the advanced glacier. The first large outburst floods were in the mid 1800's, apparently the result of thinning and weakening of the ice dam formed by the shrinking Frank Mackie Glacier. Outburst floods continued to about 1930, when Frank Mackie Glacier retreated from a valley-blocking position and a remnant lake body breached its Neoglacial moraine dam.	Clague and Mathews (1992)

Table I. *Continued.*

Lake and location	Events	Reference
Strohn Lake, Canada	Melting and retreat of Bear River Glacier from mid-1800s to 1950s uncovered a basin that filled with a lake deeper than 38 m and an area of 0.44 km^2. In 1958 the first outburst flood occurred and damaged a major road. Repeated floods have occured since then.	Matthews (1965)
Tulsequah Lake, Canada	Accelerated retreat of glaciers occurred in this area about 1870. Tributary-valley glacier to Tulsequah Glacier melted more rapidly, leaving main-valley glacier as ice barrier. Numerous outburst floods have occurred. Maximum depth of lake 195 m in 1910. Size of lake reduced by continued melting of main ice barrier.	Marcus (1960)

formed large terminal moraines while at or near their maximum Little Ice Age positions. These moraines are constructional forms composed of unconsolidated glacial debris deposited as ice-contact ridges along perimeters of glacier termini (Figure 3a). Late Little Ice Age terminal moraines are sharp crested and have slopes that commonly exceed 33°; and we have measured moraine slopes as steep as 42°. When glaciers retreat and topographic conditions are appropriate, proglacial lakes form behind the moraines (Figure 3b). Many of these lakes have partly or entirely breached their unstable morainal dams producing large floods and debris flows (Figure 7; Table II).

Moraine-dammed lakes have been a significant hazard worldwide. In the Cordillera Blanca of Peru, several thousand people were killed by three such floods between 1940 and 1950 (Lliboutry *et al.*, 1977). A special commission was established in Peru to address this hazard, and as a result, water levels were lowered in 35 lakes perceived to be dangerous. In the Himalaya of China and Nepal, several moraine-dammed lakes have failed in the last few decades, resulting in substantial loss of life and property (Ives, 1986). There is an ongoing program of hazard evaluation in the region as a result of these floods and the potential effect of future moraine and ice-dam lake failures on the development of hydroelectric facilities.

Because of the relative paucity of development in alpine areas of western North America, hazards associated with breaching of moraine dams have been largely ignored. Recently, interest has increased as development and recreational pressures have intensified in North American alpine areas. There have been several

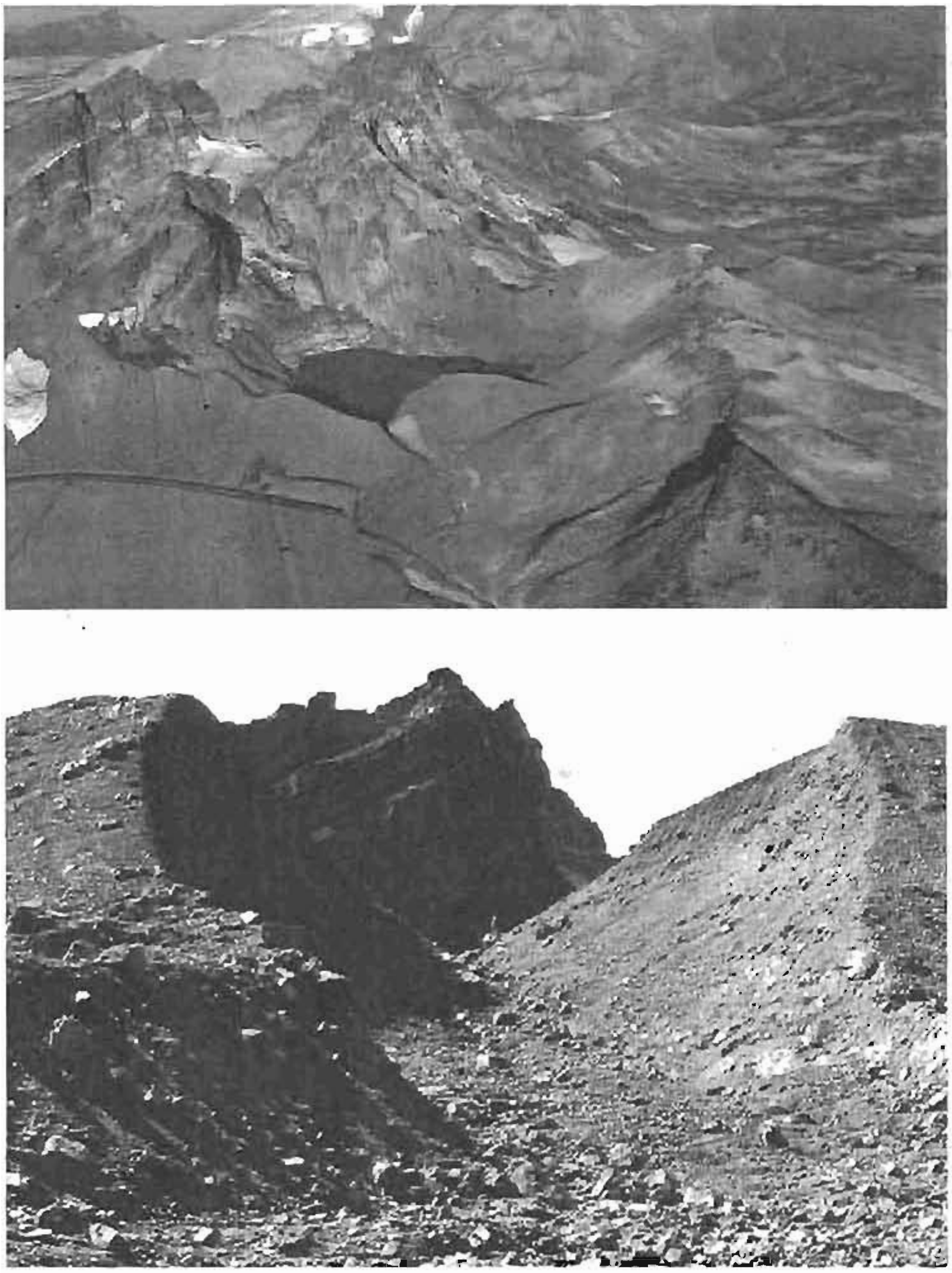

Fig. 7. The partially breached moraine dam of 'Moraine Lake' at Broken Top of the Three Sisters volcanic complex in Oregon. Approximately 115 000 m^3 of water was released 7 October 1966 when the moraine dam failed and the lake level dropped by about 5 m (Nolf, 1966). (a) An oblique view to the northwest. Only a small remnant of the glacier that deposited the moraine remains. (b) A view of the breach from the base of the moraine. Dam erosion may have been halted by armoring of the outlet during the release. Note the person standing on a large block near the present lake outlet. The flow rapidly evolved into a debris flow by incorporating a large quantity of the loose and unstable morainal debris.

Table II. Western North American examples of moraine-dammed lakes that have failed.

Lake and location	Description	Reference
Klattasine Lake, British Columbia	The lake breached its moraine dam sometime between June 1971 and September 1973. 1.7×10^6 m^3 of water was released, resulting in a debris flow that travelled down Klattasine Valley and temporarily dammed the Homathko River. The cause for failure is unknown.	Clague *et al.* (1985); Blown and Church (1985)
Nostetuko Lake, British Columbia	The lake breached its moraine dam on 19 July 1983 and released more than 6.5×10^6 m^3 of water in less than 5 hr. Failure may have been triggered by a large wave formed by calving ice.	Blown and Church (1985)
Unnamed lake, St. Elias Mountains, British Columbia	Lake overflowed moraine dam crest for unknown reason on 28 June 1990. About 4000 m^3 of water was released and bulked into a debris flow. Lake was only partially drained.	Clague and Evans (1992)
'Moraine Lake', Three Sisters Wilderness Area, Oregon	The moraine dam failed on 7 October 1966, releasing 1.15×10^5 m^3 of water. The breach may have been caused by a wave from an ice or rock fall.	Nolf (1966), J. E. Costa (unpub. data)
'Collier Lake', Three Sisters Wilderness Area, Oregon	The moraine dam failed in July 1942 after a winter of heavy snowpack and a summer of unseasonably warm temperatures.	Hopson (1960)
'Boomerang Lake', Three Sisters Wilderness Area, Oregon	Failure occurred 7 September 1970, resulting in a peak flow rate of about 300 m^3 sec^{-1}.	Laenen *et al.* (1992); A. Laenen, J. E. Costa, and J. E. O'Connor (unpublished data)

failures of moraine dams in British Columbia, Canada (Blown and Church, 1985; Clague *et al.*, 1985; Clague and Evans, 1992) that have been studied in conjunction with hydroelectric resource development. In the Three Sisters volcanic complex in Oregon, there have been at least four documented moraine dam failures since 1933 (Figure 7) and there are several extant lakes that are susceptible to failure (Laenen *et al.*, 1992). The U.S. Forest Service has issued a 'hazard alert' for moraine-dammed Carver Lake, which is upstream of an area of heavy recreational use.

Some degree of hazard assessment can be accomplished simply determining where these moraine-dammed lakes exist. For example, in the Cascade Range of Washington and Oregon, several moraine dams are judged to be susceptible to failure. Although there is some level of hazard downstream from each of these lakes, quantitatively determining the likelihood, timing, and magnitude of a dam failure is difficult. Some moraine dams have apparently failed by overtopping as a result of waves generated by rockfall or ice avalanches into the lakes (for example, Blown and Church, 1985). Some dams may fail by piping, melting of ice cores, or by other processes not yet determined.

The breach hydrograph and downstream flow behavior of flood waves from moraine-dam failures are also difficult to predict. In many instances, failures of moraine dams do not result in complete emptying of the lake (Figure 7) (Clague and Evans, 1992); rather, erosion of the outlet proceeds to a certain extent and halts. Cessation of erosion of the breach may relate to the geometry or internal structure of the moraine, the flow dynamics of the water exiting the lake, or to armoring of the breach channel by large clasts. Flow downstream may evolve into a debris flow that can increase flow volume and peak discharge by a factor of two or more (Laenen *et al.*, 1992). These complexities presently conspire against reliable deterministic models for quantitative assessment of the hazards from breakouts of moraine-dammed lakes. One is left to rely on empirical data from case studies (e.g. Costa, 1988) for rapid hazard evaluation.

If alpine glaciers continue to retreat, the threat of catastrophic releases from moraine-dammed lakes may increase. As glaciers retreat, new lakes may be expected to form. For example, several moraine-dammed proglacial lakes have formed this century in the Olympic Mountains of Washington State (Spicer, 1986). Increased runoff associated with anomalously long or warm melt seasons may increase glacier runoff and raise lake stages to levels that trigger failures. Ice-cored moraines may melt and become unstable, thereby facilitating failures.

3.4. *Rock and Ice Avalanches*

Ice and rock avalanches have long been recognized as a major hazard in alpine areas. Lately, however, there has been increased awareness of these hazards because of improved accessibility and increasing recreational use of mountainous regions (Porter and Orombelli, 1981; Grove, 1987). Eisbacher and Clague (1984) compiled an account of historic mass movements in the Alps of Europe, many of which relate to glacial activity.

Ice avalanches occur where ice or glacial masses terminate on smooth bedrock surfaces with slopes greater than 30° (Eisbacher and Clague, 1984). Failure may be facilitated by accumulations of water below the ice during periods of melting or intense rain (Heim, 1895). Rockfalls and rock avalanches occur where steep bedrock slopes or cliffs border entrenched valleys. In the Cascade Range, weathered and hydrothermally altered rocks on tall volcanoes are particularly susceptible to mass movement. During Holocene time, large avalanches from Cascade Range volcanoes have evolved into debris flows and travelled tens of kilometers from their source areas. Historic rock avalanches in the Cascades have been smaller,

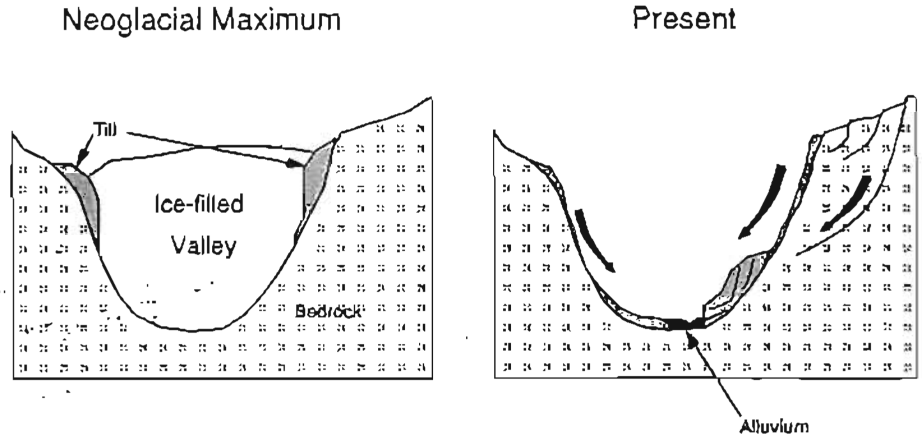

Fig. 8. Schematic cross sections of glacial valley conditions at times of maximum Neoglacial advance and present. Valleys and cirques deepened by erosion and filled with ice at maximum extent of ice advance are presently subject to mass movements of glacial deposits and valley walls as the supporting mass of ice has retreated and thinned.

but common and dangerous. For example, the Little Tahoma Peak rock avalanches of 1963 on Mt. Rainier, Washington, (Figure 4) travelled as far as 6 km and achieved velocities exceeding 100 km hr^{-1} (Crandell and Fahnestock, 1965). Similar phenomena have been lethal in more densely populated mountain environments. In 1962, an ice and rock avalanche in the Cordillera Blanca of Peru travelled 13 km and killed 4000 people. In 1970, a larger avalanche (triggered by an earthquake) travelled down the same valley and killed more than 15 000 people (Plafker and Erikson, 1978). Debris flows on Cascade Range volcanoes have also resulted from slumping of saturated glacial moraine deposits in the rapidly incising valleys. Saturation is probably a consequence of precipitation, melting stagnant ice, and glacial runoff (Walder and Driedger, 1993).

Analyses of the relation between rock and ice avalanches and glacial activity have focused on the correspondence between incidents of mass movement and periods of advancing or advanced glacier positions (Grove, 1972, 1987; Porter and Orombelli, 1981). Mass movement chronologies in glaciated basins compiled for part of Norway (Grove, 1972) and the Alps (Eisbacher and Clague, 1984) indicate that periods of rapid warming and glacier retreat also correspond with high frequencies of rock and ice avalanches. Glacier erosion can result in oversteepened valley walls that are left unsupported and unstable when the ice retreats (Figure 8). Several recent rock and ice avalanches in the Cascade Range, western Canada (J.J. Clague and S.G. Evans, GSC, oral commun., 1992) and Iceland (Sigurdsson and Williams, 1991) are undoubtedly due to glacier retreat and the resulting decrease in buttress support of steep valley walls. All of the large twentieth-century rock avalanches on the flanks of Mt. Rainier, Washington, resulted from failures of valley walls that were previously supported in part by ice (Figure 4)

(K.M. Scott, USGS, oral commun., 1991). Ice avalanches have occurred where glaciers have thinned and retreated up steep, glacially-smoothed, bedrock valleys and headwalls. More such mass movements are likely if glaciers continue to thin and retreat, and their incidence may be increased by longer and warmer melt seasons.

4. Conclusions

During the late 19th and 20th centuries, most alpine glaciers have retreated substantially from their Little Ice Age advanced positions because of warmer temperatures and, in some regions, decreased precipitation. This had led to a suite of hydrologic and geologic processes that constitute part of the geomorphic response to glacier retreat. In western North America, this geomorphic activity has significantly affected many valleys immediately downstream from areas of alpine glaciation. In areas of alpine valley development or recreational use, these processes pose hazards and have resulted in substantial loss of life and economic damage. Some hazards, such as glacier- and moraine-dammed lake outbursts, are restricted to locations that can be identified on the basis of reconnaissance mapping, but their incidence is hard to predict temporally. Other potentially catastrophic processes in areas of glacier retreat, such as ice and rock avalanches are more difficult to predict spatially as well as temporally. Other processes, such as paraglacial sedimentation, are less catastrophic, but have long-lasting effects that may be difficult to mitigate. If glaciers continue to retreat, either from natural climate variability, or human induced warming, many of the geomorphic responses and consequent hazards of glacier retreat outlined above will continue, perhaps at accelerated rates. Recognition of these hazards becomes especially important when considering present and future rates of human use of alpine environments.

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