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Paleohydrologie der St. Elias Mountains (British Columbia und Yukon) im Holozän

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Article abstract

The evolution of the Holocene paraglacial environment of the St. Elias Mountains has been dominated by hydrological variations which modify the direct glacial depositional environment and trigger instabilities in valley side glacial and talus deposits. Data from the Kaskawulsh Glacier demonstrate how discharge and sediment transport regimes vary through the season, as sediment is flushed out of the system, and a marginal to subglacial drainage change of the Grizzly Creek Glacier illustrates the effects of extraordinary events in transporting large volumes of sediment. A multiple glacier fluctuation model applied to the region produces rapid temporal changes in discharge and sediment regimes throughout the Holocene. The effect of these variations is enhanced by the occurrence of surges of many of the glaciers of the St. Elias Mountains and by sequences of glacier dammed lake formation and drainage in the region.

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HOLOCENE PALEOHYDROLOGY OF THE ST. ELIAS MOUNTAINS, BRITISH COLUMBIA AND YUKON

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ABSTRACT The evolution of the Holocene paraglacial environment of the St. Elias Mountains has been dominated by hydrological variations which modify the direct glacial depositional environment and trigger instabilities in valley side glacial and talus deposits. Data from the Kaskawulsh Glacier demonstrate how discharge and sediment transport regimes vary through the season, as sediment is flushed out of the system, and a marginal to subglacial drainage change of the Grizzly Creek Glacier illustrates the effects of extraordinary events in transporting large volumes of sediment. A multiple glacier fluctuation model applied to the region produces rapid temporal changes in discharge and sediment regimes throughout the Holocene. The effect of these variations is enhanced by the occurrence of surges of many of the glaciers of the St. Elias Mountains and by sequences of glacier dammed lake formation and drainage in the region.

RÉSUMÉ *Paléohydrologie des monts Saint-Élie (Yukon et Colombia-Britannique) à l'Holocène.* L'évolution de l'environnement paraglaciaire des monts Saint-Élie, à l'Holocène, sous le contrôle des variations du régime hydrologique qui ont à la fois modifié le milieu immédiat de dépôt de sédiments glaciaires et provoqué l'instabilité des dépôts et des éboulis sur les versants des vallées. Les données recueillies au glacier de Kaskawulsh ont permis de constater que les régimes d'écoulement et du transport des sédiments varient au cours d'une saison donnée, pendant que les sédiments sont évacués hors de l'appareil. De plus, le passage d'un drainage de type juxtaglaciaire à un drainage de type sous-glaciaire le long du glacier de Grizzly Creek illustrent bien les effets des variations excessives de volume de sédiments transportés. L'application à la région à l'étude d'un modèle de fluctuations multiples explique les changements rapides qu'ont connus les régimes d'écoulement et du transport des sédiments, survenus tout au long de l'Holocène. L'impact de ces changements a été accentué par l'avancée rapide de nombreux glaciers des monts Saint-Élie et par la formation d'une série de lacs de barrage glaciaire et de leur vidange.

ZUSAMMENFASSUNG *Paleohydrologie der St. Elias Mountains (British Columbia und Yukon) im Holozän.* Die Entwicklung der paraglazialen Umgebung der St. Elias Mountains im Holozän war von hydrologischen Variationen beherrscht, welche das direkte glaziale Ablagerungs-Milieu verändert haben und die Unstabilität der Eis- und Halden-Ablagerungen an den Talseiten ausgelöst haben. Daten vom Kaskawulsh-Gletscher zeigen, wie die Verhältnisse des Fließens und des Sedimenttransports innerhalb einer Saison variieren, während Sediment aus dem System herausgespült wird; und ein Wechsel von Rand-Entwässerung zu subglazialer Entwässerung am Gizzly Creek Gletscher illustriert die Auswirkungen von außerordentlichen Ereignissen beim Transport von großen Sediment-Volumen. Ein auf die Region angewendetes Modell multipler Gletscher-Fluktuation weist schnelle zeitliche Wechsel auf im Fließen und im Sediment-Transport während des ganzen Holozän. Die Auswirkung dieser Variationen wird durch Fluten vieler Gletscher der St. Elias Mountains verstärkt und durch Serien von durch Gletscher-Stau gebildeten Seen und ihrer Entwässerung.

INTRODUCTION

The period of adjustment between glacial and non glacial processes in sediment transport and deposition has been termed para-glacial (RYDER, 1971; CHURCH and RYDER, 1972). The processes operating during this period of adjustment produce a distinctive landscape which can be termed the paraglacial environment. Research in the last two decades has developed two important concepts of the evolution of this environment. Firstly, glacier hydrological regimes are highly variable spatially and temporally (for example ANDERSSON *et al.*, 1972). During research in the eastern St. Elias Mountains and the boundary Kluane Ranges, Yukon, and at Peyto Creek, Rocky Mountains, Alberta, hydrological events have emphasised the geomorphological importance of this variability (JOHNSON and POWER, in prep.) and the difficulty of regime prediction. Secondly, the fluctuations of glaciers through the Holocene have been extremely complex. When these two concepts are combined they indicate that the hydrological regimes of the glacierized basins of the St. Elias Mountains through the Holocene must have experienced extreme variability.

The eastern flanks of the St. Elias Mountains lie in the rain shadow of the mountains where the hydrological regimes are dominated by the snow melt and the patterns of glacier ablation. The Holocene hydrological conditions of this area were basically the Holocene glacier hydrological conditions. The hydrological regime was, therefore, a function of the Holocene glacier fluctuations. One of the major questions is the pattern of these fluctuations. From work published in Scandinavia, New Zealand and North America (BURROWS and GELLATLY, 1982; DENTON and KARLEN, 1976, 1977; KARLEN, 1979, 1982) and from field evidence in the St. Elias Mountains it is apparent that the Holocene has been a period of frequent glacier advances within periods of regional glacier expansion and retreat. These glacier advances may not have been synchronous between valleys within the region. Glacier surges have been superimposed on these fluctuations.

This paper discusses the causes of variable hydrological conditions related to glaciation and indicate that the extremes in the hydrological regimes controlled the formation of the paraglacial environment during the Holocene.

EFFECTS OF "NORMAL" GLACIER DRAINAGE REGIME FLUCTUATIONS

Even during periods of relatively stable glaciological conditions major fluctuations occur in the drainage regime which can have varying degrees of geomorphological impact. The fluctuation of the Kaskawulsh Glacier drainage between the Slims River and the Kaskawulsh River (GLACIOLOGY DIVISION. I.W.D., 1977) and a single event of drainage course change at the Grizzly Creek Glacier provides illustration at two different scales, the large valley glacier and a small remnant glacier.

The fluctuations of the drainage of the Kaskawulsh Glacier are due to internal glaciological conditions and result in a switch of the main glacier drainage between the Slims River and the Kaskawulsh River. The Slims River is the major contributor to Kluane Lake and during the periods of Kaskawulsh River dominance the level of Kluane Lake does not rise during the summer. As a consequence the regime of the Kluane River, the outflow of Kluane Lake, is altered and total discharge is reduced (Fig. 1). In addition the sediment contribution to the lake basin is reduced during these seasons. FAHNESTOCK (1969) reports fluctuations occurring between 1965 and 1968 with a prolonged period of Kaskawulsh dominance in 1967.

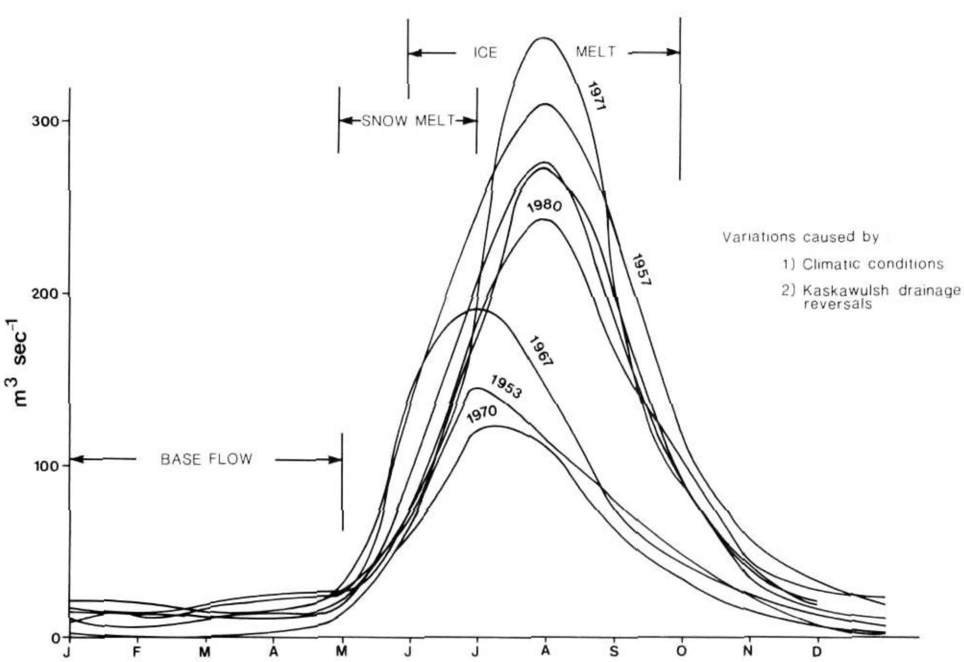

FIGURE 1. Kluane River discharge at the outlet of Kluane Lake. Representative years illustrating periods of Kaskawulsh River dominance (1953, 1967, 1970) and Slims River dominance (1957, 1971, 1980).

Débits de la rivière Kluane à l'exutoire du lac Kluane. Années représentatives des périodes d'influence de la rivière Kaskawulsh (1953, 1967 et 1970) et de la rivière Slims (1957, 1971 et 1980).

This can be seen in a deficit lake level of about 0.6 m below normal in the late summer of 1967.

The single event fluctuation at Grizzly Creek in 1976 was a diversion of the lateral meltwater stream into a subglacial course about 1 km from the terminus. The hydrograph below the glacier dropped to a minimum flow for 30 minutes while the diverted drainage built up hydrostatic pressure beneath the glacier. The release of the pressure at the glacier terminus deposited a layer of gravel averaging 1 m thickness over an area of 1,000 m^2 and sent a flood wave down valley. This flood wave caused a total reorientation of the stream below the moraine, incising a 1.6 m deep channel down the centre of the outwash plain, as compared to the previous course against the deposits on the west side of the valley.

Fluctuations of this type and magnitude are not uncommon and are a function of the pattern of opening of the glacier drainage system in the spring in response to the spring melt and changes in the flow characteristics of the glaciers. It is reasonable to hypothesise therefore that throughout the Holocene, during periods of glacier advance, stability or retreat that major changes in the drainage regime occurred.

VARIABILITY OF GLACIER SEDIMENT DISCHARGE

Highly variable patterns of suspended sediment discharge from glaciers over very short time frames have been demonstrated by ØSTREM (*e.g.* 1975). The variability at the Kaskawulsh Glacier (Fig. 2) shows similar patterns with low concentrations during snow melt conditions (June 17-18) highly variable conditions during the period of opening of glacier drainage conduits and with precipitation events (June 28-29 and June 30-July 2) and decreasing concentrations with diurnal fluctuations during the peak discharge due to ice melt (July 25-26). The variability within a season can be demonstrated schematically as in Figure 3. On a seasonal basis the suspended sediment concentrations rise rapidly after the peak of the snowmelt with the opening of englacial and subglacial drainage systems and then fall before the peak discharge due to ice melt occurs. On a daily basis the suspended sediment concentrations ranged from being in phase to out of phase with the diurnal discharge regime and fluctuated about the trend. Most of the high bed loads carried under hydrostatic pressure within glacier conduits are deposited at the glacier

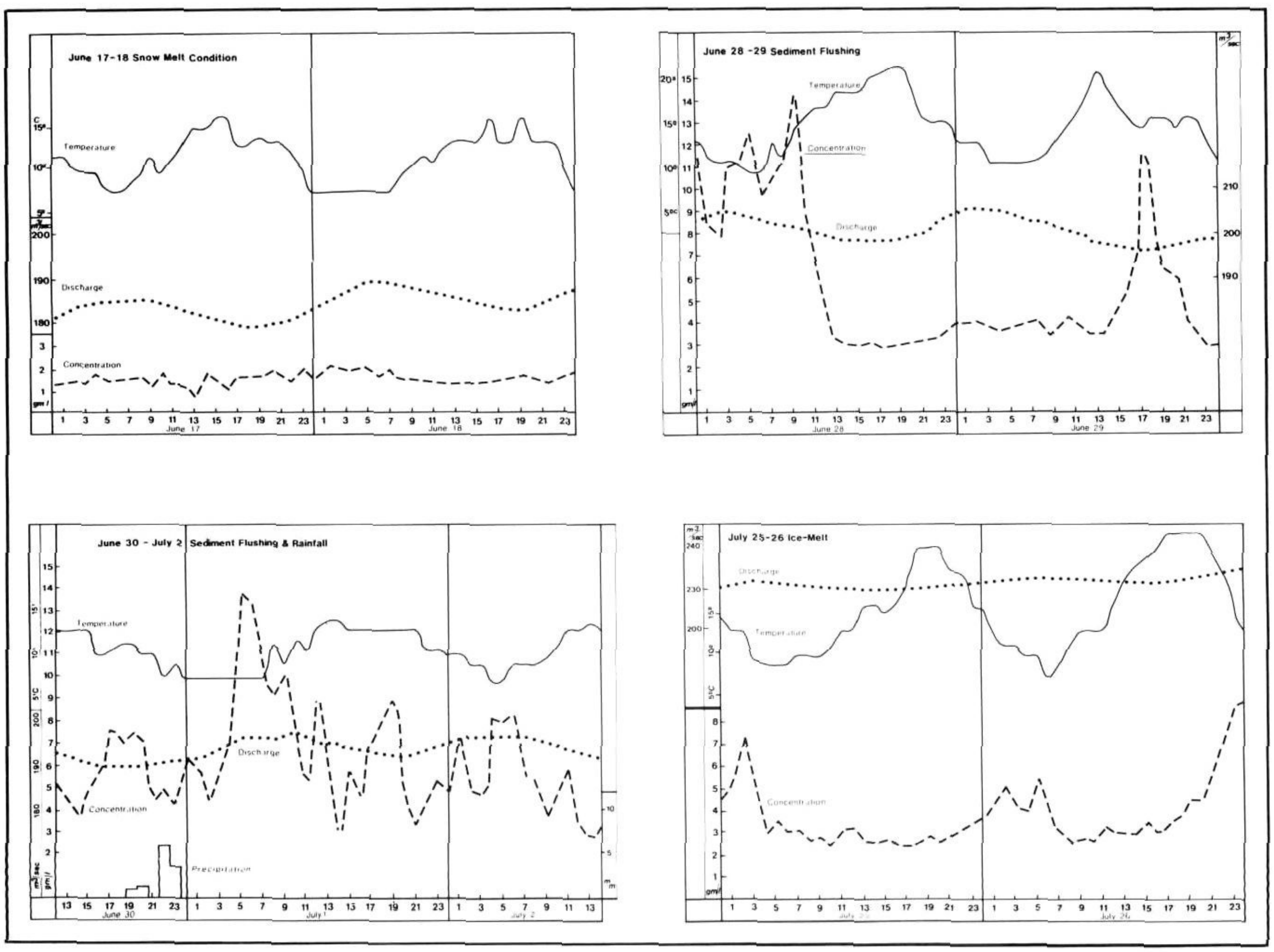

FIGURE 2. Variable regime elements of Slims River discharge (1983).

Les différentes composantes de la variabilité du régime de la rivière Slims (1983).

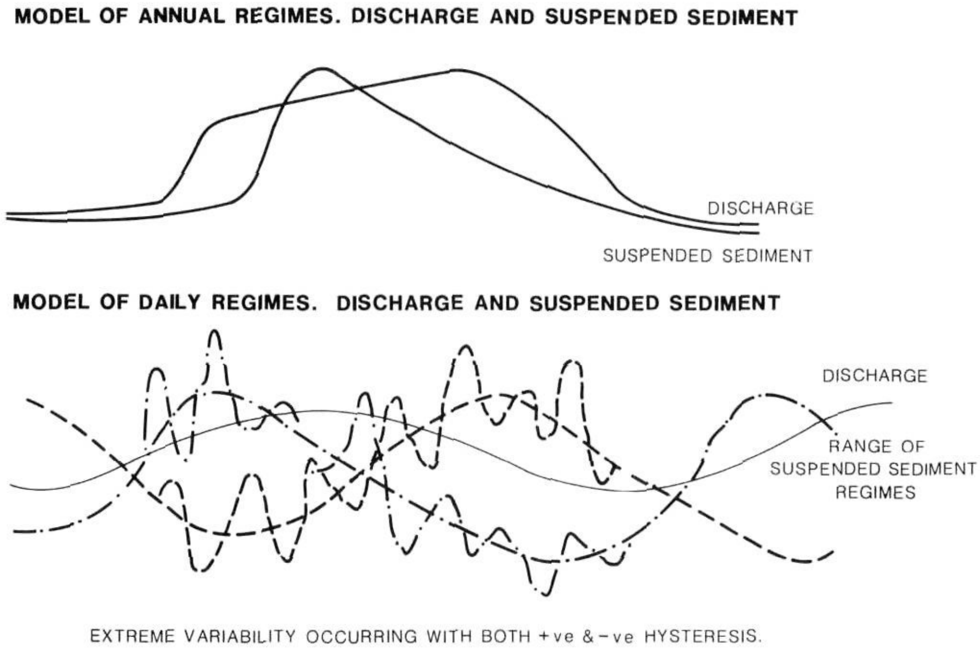

FIGURE 3. Simplified graphics of annual and daily discharge and suspended sediment regime models.

Graphiques simplifiés des modèles de régimes annuels et journaliers: le débit et les sédiments en suspension.

terminus but the suspended sediment component is transported long distances downstream and can affect geomorphological processes, ecology and water abstraction activities. The suspended sediment discharge is variable within the melt season due to changes in the routing of melt through the glacier system and the contact with sediment in the subglacial and englacial environments. It is also variable between seasons due to differences in accumulation and ablation conditions. High melt generation in one season may flush out a disproportionate amount of sediment in relation to the total in transit within the glacier system and produced by the system in any one year. The short time frame variability during conditions of gradual glacier retreat at present will be more variable with the occurrence of frequent periods of glacier advance and retreat through the Holocene. The variations in supply of sediment to the paraglacial environment have impact on the sedimentation conditions on outwash plains and in proglacial lakes.

HYDROLOGICAL CHANGES DURING GLACIER SURGES

The St. Elias Mountains have a large number of glaciers with a history of surge activity. It would seem to be a reasonable assumption that they are not just a modern phenomenon and must have occurred through the Holocene and probably throughout the history of glaciation in the region. If there is a basin morphology component in the controls on surges the glaciers which exhibit the phenomena at present may not have done so in the past and vice versa. Until the precise mechanisms of surging are determined this aspect of the glacier history will remain speculation. The impact on hydrology has been partly in the potential for damming of drainage and the formation of ice dammed lakes but more fundamentally the surge event disrupts the drainage system of the glacier causing major changes in the discharge and its regimes and having, therefore, a major role in landscape change. What are the effects of a surge on the drainage of the glacier? All the pre-existing drainage routings, englacial, subglacial and supraglacial will be destroyed and there will be no integrated drainage system during a surge. Surface lakes, damming of water within the broken ice mass and marginal drainage accumulation are visible signs of this disruption. Observations at Variegated Glacier in Alaska (KAMB *et al.*, 1985) showed a reduced discharge during the passage of the surge wave through the glacier which was followed by a massive outburst of water as the surge wave dissipated at the glacier terminus. The coincidence of this drainage outburst from the glacier with the cessation of the surge have promoted the formulation of a water layer surge generation mechanism. Whatever the relation of glacier water content to surge occurrence there is the potentiel for rapid changes in the drainage system in such parameters as portal position, subglacial course, etc., and therefore potential for geomorphological impact. Changes in erosional and depositional activity will control outwash plain development, trigger slope failures on valley sides or moraines and expose buried ice cores of the glacial deposits. Glacier surge and its accompanying drainage changes at the Donjek Glacier initiated major geomorphological changes in 1969-1970 (JOHNSON, 1972).

GLACIER DAMMED LAKES

The formation and drainage of glacier dammed lakes have had a major impact on the evolution of the area and are by far the most dramatic element of the palaeohydrological regimes. The interest in the drainage events of large glacier dammed lakes was stimulated by the Alaska Highway pipeline proposals. In addition to major lake sites in the Donjek and Alsek Valleys YOUNG (1977) identified 33 smaller lakes in the Kaskawulsh basin, a potential 75-85 ice dammed lake sites in the Donjek River catchment and 38 sites in the Klultan

Glacier basin. The number of potential ice dammed lake sites is very large and probably there were as many potential sites at other periods of the Holocene with varying extents of glacierization.

Many glacier dammed lakes drain catastrophically and the floods are capable of a large amount of geomorphological work. A report of the GLACIOLOGY DIVISION of the Inland Waters Directorate (1977) estimated the maximum instantaneous discharge or outburst of most of these small lakes. In the Klutlan Basin this ranged from 3 m^3s^{-1} to 356 m^3s^{-1}. Three of the largest lakes in this basin he estimated had discharges of 2,186 m^3s^{-1}, 2,010 m^3s^{-1} and 646 m^3s^{-1}. In the Donjek Basin he estimated peak discharges of 2,268 m^3s^{-1} for Donjek Lake and 440 m^3s^{-1} for Hazard Lake.

CLARKE'S (1970) study of the magnitudes of outburst floods from Hazard Lake (Steele Glacier) and Donjek Lake (Donjek Glacier) illustrates the problems of such calculations. He estimated 606 m^3s^{-1} from a full simulation model of Hazard Lake which compares with 696 m^3s^{-1} using a simple estimation, 554 m^3s^{-1} using the Clague Mathews formula and an estimate of 440 m^3s^{-1} by Young. For Lake Donjek the Clague Mathews formula estimates 2,994 m^3s^{-1} and Clarkes three models gave 13,210 m^3s^{-1}, 4,993 m^3s^{-1} and 1,622 m^3s^{-1}. Clarke concluded that the maximum instantaneous discharge was probably in the 3,000 m^3s^{-1} to 5,000 m^3s^{-1} range. YOUNG (1977) estimated the volume of the Donjek Lake at 162.1 x 10^6m^3.

CLAGUE and RAMPTON (1982) present the most dramatic physical evidence of the draining of Lake Alsek, dammed by the Lowell Glacier, and the extent of the lake at its maximum and at this most recent filling in the mid to late nineteenth century. The reforming of the Alsek Lake has potential impacts on settlement and transport in the region, the draining of the lake has potential impacts downstream and both of these have major influence on the geomorphology. The lake basin, shorelines and sediments dominate the upper Alsek basin and massive scoured and rippled outwash deposits dominate the lower valley.

There is a question as to whether the cause of the lakes was glacier surges, general glacier advance or a combination of the two events. The Donjek and Lowell Glaciers are both surging glaciers and during recent surges have advanced to within a few metres of closing off the river channel. To produce a sustained dam sufficient for the lake to fill completely would require a strong continued glacier advance. It is unlikely that with the current positions of the glaciers that short term surge events would be strong enough to provide a dam sufficient to allow a total filling of the lakes. The necessity to propose a surge dam has been because few glacier advances have been hypothesised for the region in recent and Neoglacial time when a number of lake filling events have occurred. The classical model of Hypsithermal glacier retreat followed by a limited Neoglacial readvance and Little Ice Age fluctuation has been steadily elaborated. DENTON and KARLEN (1977) suggested four Holocene advances and elsewhere in the cordillera a number of glacier advances in the Neoglacial period have been proposed and the definition of the Neoglacial has been pushed back to a start around 5,000 BP in Colorado (BENEDICT, 1968, 1973). BURROWS and GELLATLY (1982) have demonstrated a number of recent glacier fluctuations in New Zealand and this multifluctuation model may be applicable throughout the Holocene. It is hypothesised that damming events may have been advance events of longer duration than surges, although the latter may produce limited damming.

Glacier dammed lakes drain subglacially, supraglacially and ice marginally, all of which have implications for the hydrological regime and its geomorphological impact. Hazard Lake, dammed by the Steele Glacier, drains subglacially and this drainage has the capacity to transport large volumes of debris where it discharges under pressure from a constraining ice tunnel. The very high discharges can entrain large volumes of sediment, developing into debris flows. The combination of flood and debris flow has the capacity to travel long distances down valley performing large amounts of geomorphological activity. Subglacial drainage is also capable, given large volumes of drainage, of high rates of erosion. Rock gorges on the Donjek River at the terminus of the Donjek Glacier were carved by subglacial drainage of the Donjek Lake. Subglacial drainage has the most significant impact because marginal or supraglacial drainage does not produce rapid emptying of the lake and is not under pressure. Small channels on the valley side near the damming point of the Donjek Lake could not represent more than short periods of surface drainage overflow because their base levels are near the upper lake levels. Major drainage events must have been subglacial.

ICE CORING OF MORAINES

One of the characteristics of the post Neoglacial maximum landscape is the presence of large quantities of buried glacier ice in moraines and outwash deposits. This has been observed in a number of field sites where the author has worked in the last 15 years. The moraines of the Kaskawulsh Glacier, the moraines of the glacier at the head of the Duke Valley, the moraines and outwash of the Grizzly Creek Glacier and the moraines and outwash of the Donjek Glacier are typical sites.

The ice beneath the outwash at the terminus of the Donjek Glacier was exposed by shearing and thrusting caused by the stress of the surging of the glacier in 1969-1970. In Grizzly Creek the ice core to the outwash became exposed after a sink hole formed which channelled the glacier discharge through the moraine rather than along the subaerial channel (Fig. 4). This sinkhole experienced a sequence of blockage, pond filling and drainage events which rapidly widened the top of the sink in 1977. Revisiting the site in 1984 the sinkhole and the pond site had completely infilled with debris. The drainage had reverted totally to the subaerial channel. During the sequence of filling and drainage events the stream incised through the outwash plain, a maximum of 0.5 m of debris, into stagnant glacier ice which was $>$ 3 m in thickness. It is postulated that the whole of the valley floor is infilled with glacier ice which was covered by a thin layer of fluvially washed ablation debris during the backwasting of the ice. During this particular sequence of drainage events the resurgence of the subsurface course was through a down valley rock glacier emerging as a diffused flow along a zone about 80 m long.

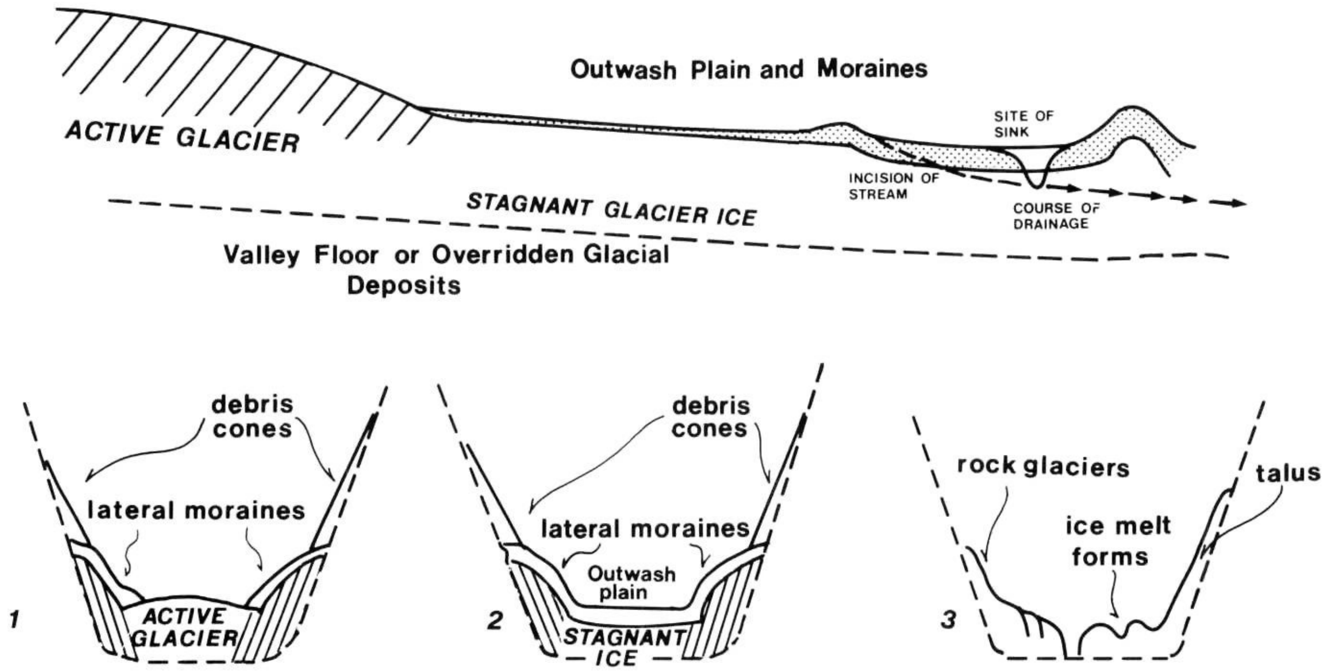

FIGURE 4. Model of evolution of glaciated valley during deglaciation. *Modèle de l'évolution d'une vallée glaciaire pendant la déglaciation.*

As the buried ice gradually melts over a long period of climatic amelioration, with periods of exposure and enhanced melt, the drainage system will continuously change and the glacier deposits will be constantly reworked. In addition the gradual melt of the ice will produce instabilities in the valley side deposits which when triggered will produce the mass movement forms common along the valley sides in the paraglacial environment (Fig. 4).

The extensive occurrence of ice beyond the active glacier terminus throughout the St. Elias will control the nature of the hydrological regimes over the next few decades or centuries as the stagnant ice controls the stream course and sediment supply to the stream.

VALLEY SEDIMENTATION PATTERNS AND HYDROLOGICAL IMPLICATIONS

RYDER (1971) concluded that "fan deposition commenced as soon as a small area became ice free during the final melting of the Pleistocene glaciers and was dependent upon a sediment supply from reworked glacial drift". The water necessary for this deposition was supplied from melting snow and ice in the basin. The sedimentary landforms in the major valleys of the St. Elias also indicate the occurrence of high flow volumes reworking glacial drift in the immediate post glaciation period. The Donjek Valley is the most dramatic site in this respect with large alluvial fans extending across the valley from, for example, the Spring and Steele valleys on the west side. Smaller fans from the east side tributaries, such as Hoge Creek, have been truncated by the constriction of the Donjek River against the east side of the valley. The dimensions of the Spring and Steele Creek fans illustrates a very dynamic stream system over a considerable time span. Current flows are not causing major modifications to fan surfaces, large areas of the fans have become stabilised and developed mature spruce vegetation communities and stream migration is primarily a reworking of existing materials rather than the addition of large volumes of new deposits. It can be concluded therefore, in agreement with RYDER (1971) and CHURCH and RYDER (1972), that the period when the fans formed must have been during strong deglaciation trends with high meltwater supply and with the availability of large volumes of material from the glacier system and from the valley sides. These conditions would be met at the end of the Pleistocene into the early Holocene.

One interesting characteristic of the Spring Creek and Steele Creek fans is the linearity of eroded faces above the Donjek River braided stream course, the cause of which is unknown. There is also no evidence on the fan surfaces of impact of floods caused by the drainage of the Donjek glacier dammed lake.

The Holocene drainage from the tributaries has been limited to smaller courses sometimes incised into the late Pleistocene Early Holocene fans but invariably transporting less sediment.

CONCLUSIONS

The hydrological conditions in the St. Elias Mountains were extremely variable throughout the Holocene. This resulted from the normal patterns of glacier discharge, which are variable spatially and temporally, the patterns of glacier advance and retreat and the further complication of glacier surging. Additional hydrological impacts are the sequences of formation and drainage of ice dammed lakes. Some of the largest lakes draining catastrophically have had major impacts on the geomorphology of the valleys. The evolution of the paraglacial environment has been dominated by these hydrological variations frequently completely modifying the direct glacial depositional environment and triggering instabilities in the valley side deposits.

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