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Catastrophic discharge of fluvial sediment to the ocean: evidence of Jøkulhlaups events in the Alsek Sea Valley, southeast Alaska (USA)

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Abstract Periodic, catastrophic sediment discharges (Jøkulhlaups) from neoglacial lake Alsek have resulted in a thick (more than 80 m) distal wedge of late Holocene sediment in the Alsek Sea Valley on the continental shelf off southeastern Alaska. Individual events are calculated to have discharged as much as 1.3 to 2.5 $\times$ 10^9 of sediment, roughly equivalent to the combined annual discharge from all North American rivers. However, the estimated total sediment discharge from Jøkulhlaups into the sea valley over the last 3000-4000 years, about 24 $\times$ 10^9 t, gives an annual mean of only about 6-8 $\times$ 10^6 t, considerably less than the sediment load predicted for a drainage basin the size of the Alsek River. Jøkulhlaups events in the Alsek system may be as important in changing an along-shelf transport system to one in which sediment transport is predominantly cross-shelf, as in the actual discharge of sediment itself.

INTRODUCTION

Catastrophic floods are particularly important events in small river basins that are too small to modulate varying rainfalls in the way larger basins can. Thus, for instance, peak discharge in small rivers in semiarid mountainous basins during infrequent rain storms can be orders of magnitude greater that normal flow. One of the best cited examples is the Santa Clara River, near Los Angeles, California. Normal sediment discharge averages about 0.01 to 0.1 $\times$ 10^6 t year^{-1}, but during El Niño-related rainstorms, the flooded Santa Clara can transport as much as 20 $\times$ 10^6 t in 24 h and 50 $\times$ 10^6 t in a year (see Meade *et al.*, 1990).

By virtue of their size, large river basins seldom exhibit significantly greater sediment discharges during even peak events – heavy rainfall in one part of the basin is often modulated by normal rainfall over the rest of the basin. Maximum and minimum annual discharges of large rivers seldom vary by more than an order of magnitude, rather than the orders of magnitude seen for the Santa Clara (Fig. 1). This principle

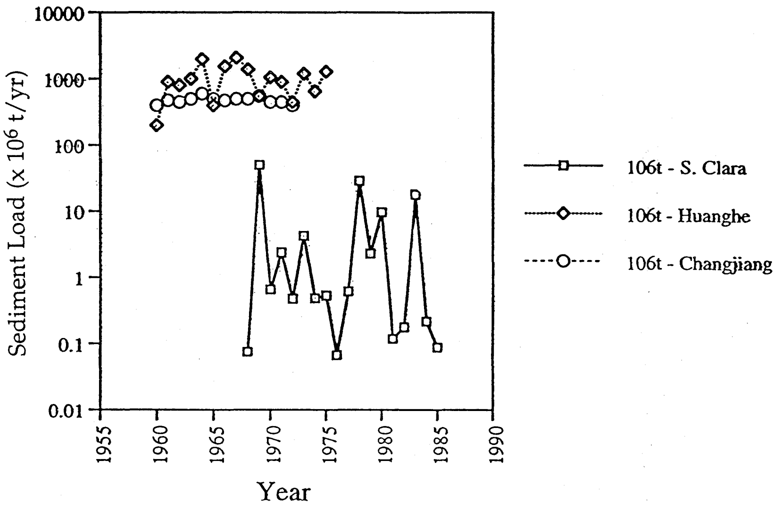

Fig. 1 Interannual comparison of the annual sediment loads of the Santa Clara, Changjiang (Yangtze River) and Huanghe (Yellow River). Sediment discharge from the small Santa Clara (drainage basin area 4100 km^2) varies by more than 4 orders of magnitude, largely in response to el Niño-related floods, whereas the larger Changjiang and Huanghe basins can modulate peak events within their sub-basins. The greater annual variation of the Huanghe is related to the greater episodicity of rainfall within its drainage basin.

extends beyond simply rainfall – the volcanic eruption of Mount St Helens in 1981, for example, resulted in a major flood of the Cowlitz River (a tributary of the Columbia River in western Washington), and sediment loads increased by several orders of magnitude (literally overnight) in response to the wide spread melting of mountain ice (Hubbell *et al.*, 1983). However, the effects of the eruption only resulted in a factor of three increase in the annual sediment load of the Columbia River over the following three years (Meade & Parker, 1985).

In his comprehensive review of paleofloods, Baker (1994) discussed a number of events during the late Quaternary that caused catastrophic flooding of major rivers. Many of these resulted from shifts in climate or changes in drainage patterns. The most dramatic events resulted from the draining of proglacial lakes, such as Glacial Lake Missoula in the northwestern USA, 12 to 17 ka BP, where the estimated peak discharge was 10^7 m^3 s^{-1}, nearly two orders of magnitude greater than the Amazon River. Said another way, during this peak discharge the Columbia River, through which Glacial Lake Missoula discharged, accounted for as much as 90-95% of the total terrestrial water reaching the global ocean!

Catastrophic floods related to abrupt draining of glacial lakes have been noted in a number of modern arctic and subarctic areas, most notably in Iceland, where thermal activity periodically melts glaciers, releasing water trapped in subglacial or (less commonly) proglacial lakes. These glacier-related floods (the Icelandic term, *Jøkulhlaups*) can cause discharges 3 to 4 orders of magnitude greater than normal flow. Because Icelandic rivers often carry glacially-eroded sediment, the sedimentological impact of these Jøkulhlaups may be even greater. The interested reader is referred to a review paper by Bjørnsson (1992).

Glacier-related floods have also been noted in North America. For instance, for five months in 1986, the advance of Hubbard Glacier closed off Russell Fjord, an arm of Yakutat Bay in southeast Alaska. The retreat and subsequent reopening of the fjord released more than 5 km^3 of water, resulting in the erosion of a 7.5 km-long channel in Yakutat Bay; the channel subsequently was covered by 1-2 m of sediment generated by the flood (Cowan *et al.*, in press).

In this paper we discuss a series of Jøkulhlaups that also have occurred in southeastern Alaska, but, in contrast to the Russell Fjord event, these have involved the damming of a major river. Because the events happened 100 km inland (in contrast to the Russell Fjord floods, which essentially occurred at the land-sea boundary), our study documents the distal effects of these Jøkulhlaups.

Study area

In discussing the Alsek Jøkulhlaups, we describe both the source of the events and the site of the distal sedimentation – the Alsek Sea Valley. The Alsek River (drainage area 28 000 km^2) drains the St Elias Mountains of the Yukon Territory (western Canada) and Alaska. Based on the algorithms predicated on drainage-basin elevation and drainage-

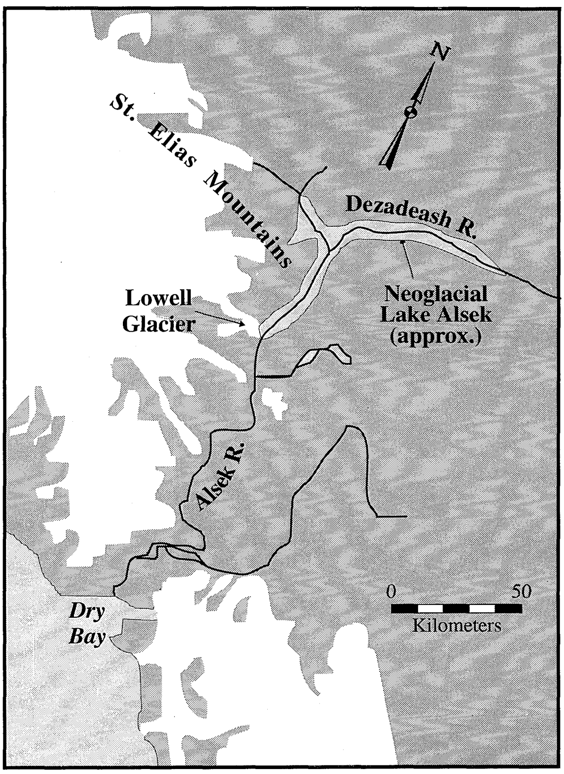

Fig. 2 The Lower Alsek River, Yukon Territory and Alaska, showing the probable extent of Glacial Lake Alsek resulting from the advance of Lowell Glacier.

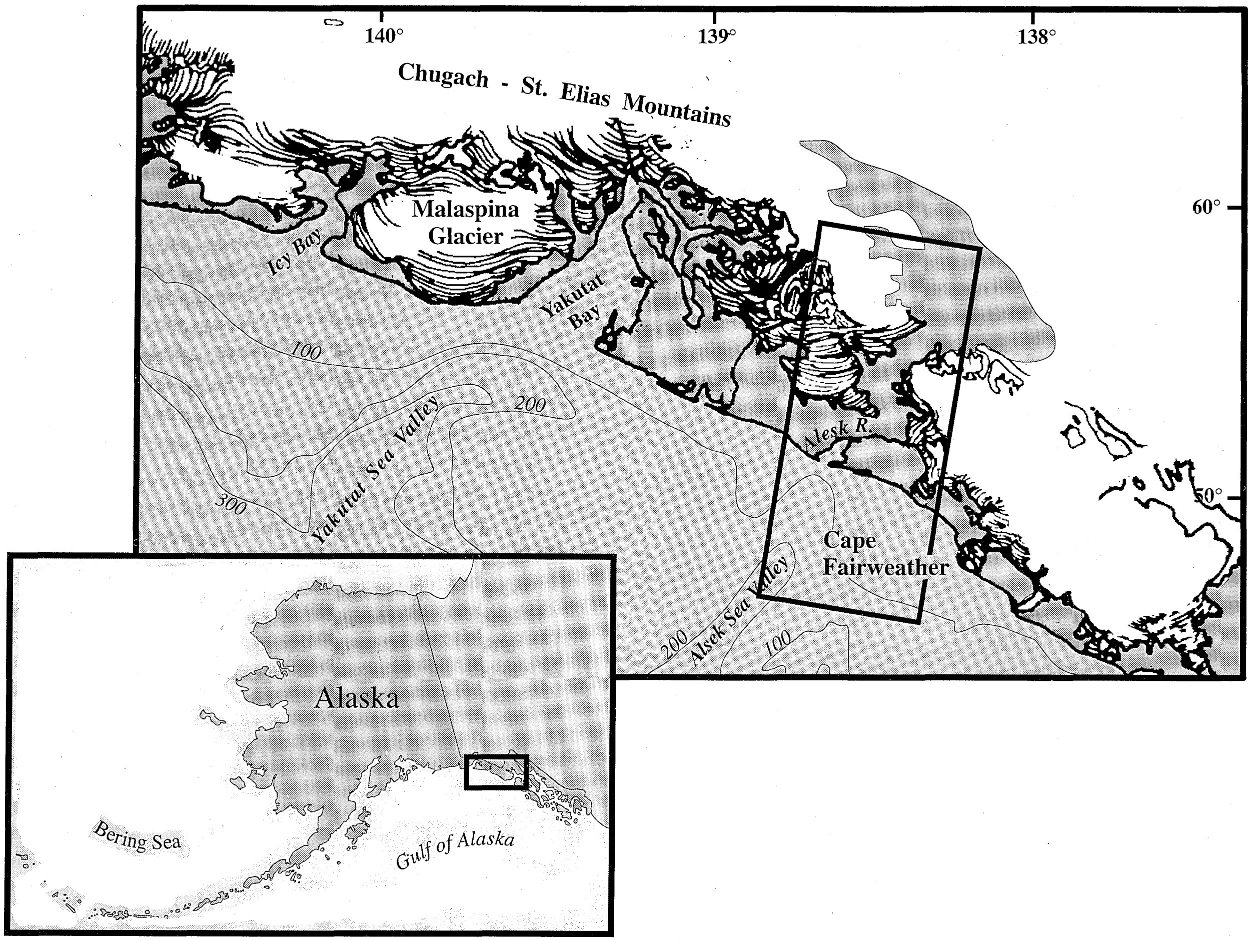

Fig. 3 Coastal Alaska, including the Alsek Sea Valley. Water depths in metres.

basin area (Milliman & Syvitski, 1992) as well as the measured loads of the Skena and Klinikilm rivers in British Columbia and the Susitna, Copper, Chilikat, Speel and Sustina rivers in southeastern Alaska (Milliman *et al.*, 1995), the sediment load of the Alsek is predicted to be about 30-40 $\times$ 10^6 t year^{-1}.

Over the past three thousand years, however, periodic advance of the Lowell Glacier across the Alsek River valley formed an iced-dammed Neoglacial Lake Alsek (Fig. 2). Based on elevated beaches, wave-cut benches and driftwood deposits, Clague & Rampton (1982) estimated that at its maximum the lake was 100 km long and 200 m deep. Glacial retreats caused catastrophic discharges (Jøkulhlaups), the latest ones, according to C-14 dating and historic records, occurring since the mid-nineteenth century. Based on the dimensions of the dammed lake and the constrictions through which the breached lake flowed, peak discharges may have surpassed 10^5 m^3 s^{-1}, approximately the same magnitude as the Amazon River. Relict dunes as high as 4 m (Clague & Rampton, 1982, their Fig. 7) testify to the severity of these events, but the total sediment discharged by each Jøkulhlaups is not known.

The mouth of the Alsek River reaches the Gulf of Alaska at Dry Bay, an estuary that over the past several hundred years has nearly filled with fluvial sediment (B. Molnia, 1995, oral communication). Seaward of Dry Bay the 5-km wide inner shelf gives way to the Alsek Sea Valley, one of a number of cross-shelf valleys that characterize the Gulf of Alaska (Fig. 3). The sea valley trends to the south-southwest, widening to as much as 20 km. The relief of the sea valley seldom exceeds 50 m relative to the adjacent shelf. The central part of the valley tends to be flat, with an average axis gradient of 4 m km^{-1}. A subtle outer shelf sill may form the seaward boundary of the sea valley.

The Alaskan Current flows west along the outer shelf and the Alaska Coastal Current flows west on the inner shelf. At an average velocity of 8 to 10 cm s^{-1}, the coastal current entrains a substantial amount of suspended sediment entering from local rivers and transports it westward (Feely *et al.*, 1978). The high sediment load of coastal rivers draining the Alaskan rivers is deposited along the inner shelf as a thick lens of Holocene mud (Molnia, 1989).

METHODS

The Alsek Sea Valley was surveyed in 1994 using a Huntec Deep-Towed System (DTS) and in 1995 using a water gun system. During the two cruises, a total of six 20 $\times$ 30 cm box cores (each about 40 cm long) and 13 $\times$ 13 cm kasten cores (about 100-150 cm long) and an additional three cores from adjacent shelf were obtained (Fig. 4).

The Huntec DTS is a deep-towed boomer that gives up to 100 m of seismic penetration, often with a resolution finer than 1 m. For the 1994 cruise, we used the DTS at 375 J, a tow depth of about 100 m, and a filter setting of 700 to 2500 Hz; firing rate was 1 s. The seismic system used in 1995 was a 20 cu inch water gun fired at 8 s intervals; final playback was at 250 to 1500 Hz. This more powerful system lacked the vertical resolution of the Huntec DTS, but its records penetrated the entire Holocene sequence except where prevented by multiple returns.

We also used geophysical data collected for the Mineral Management Service (MMS) in 1979 as part of a pre-lease block sale survey. These data, including 3.5 kHz echo-soundings, a 400 J minisparker, and a 20 kJ single-channel sparker, were run in

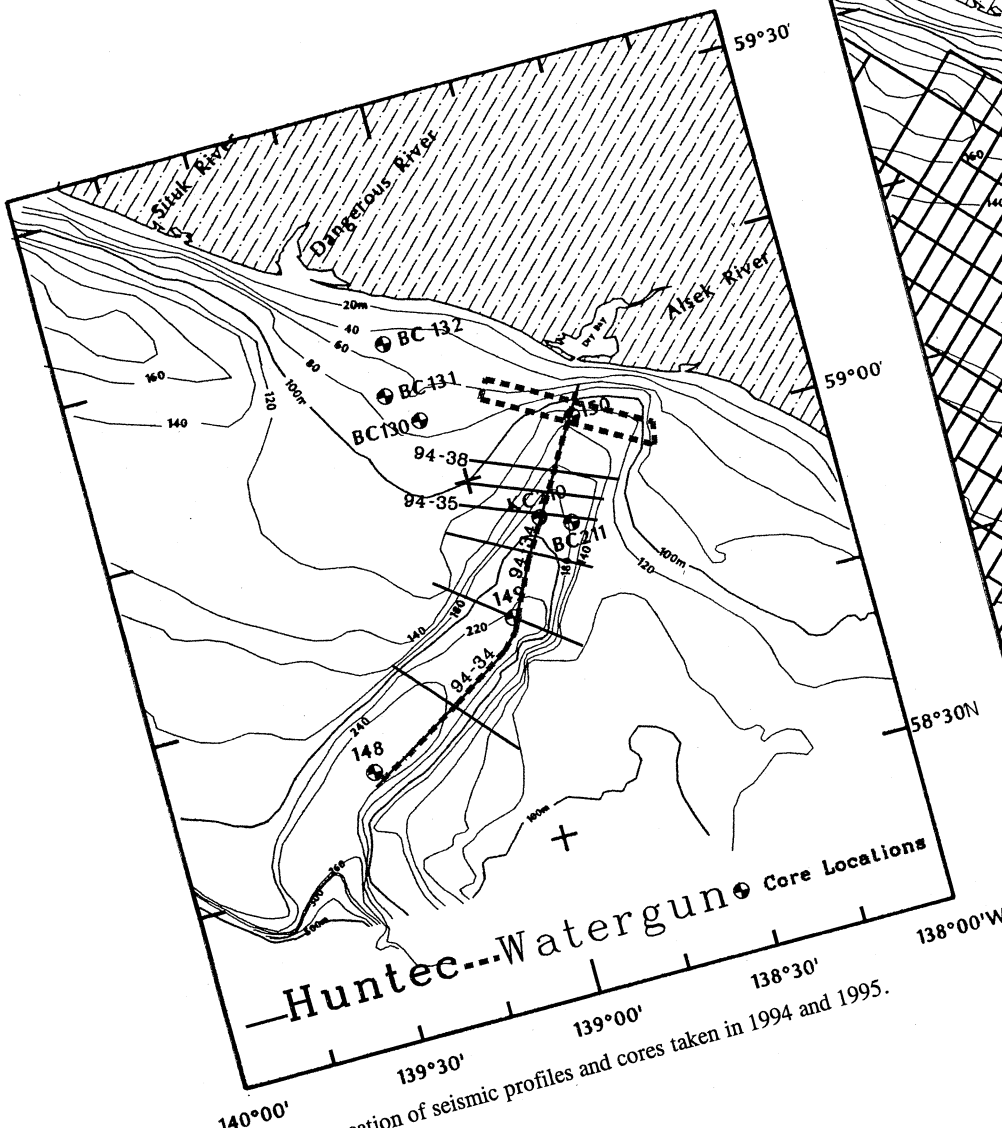

Fig. 4 Location of seismic profiles and cores taken in 1994 and 1995.

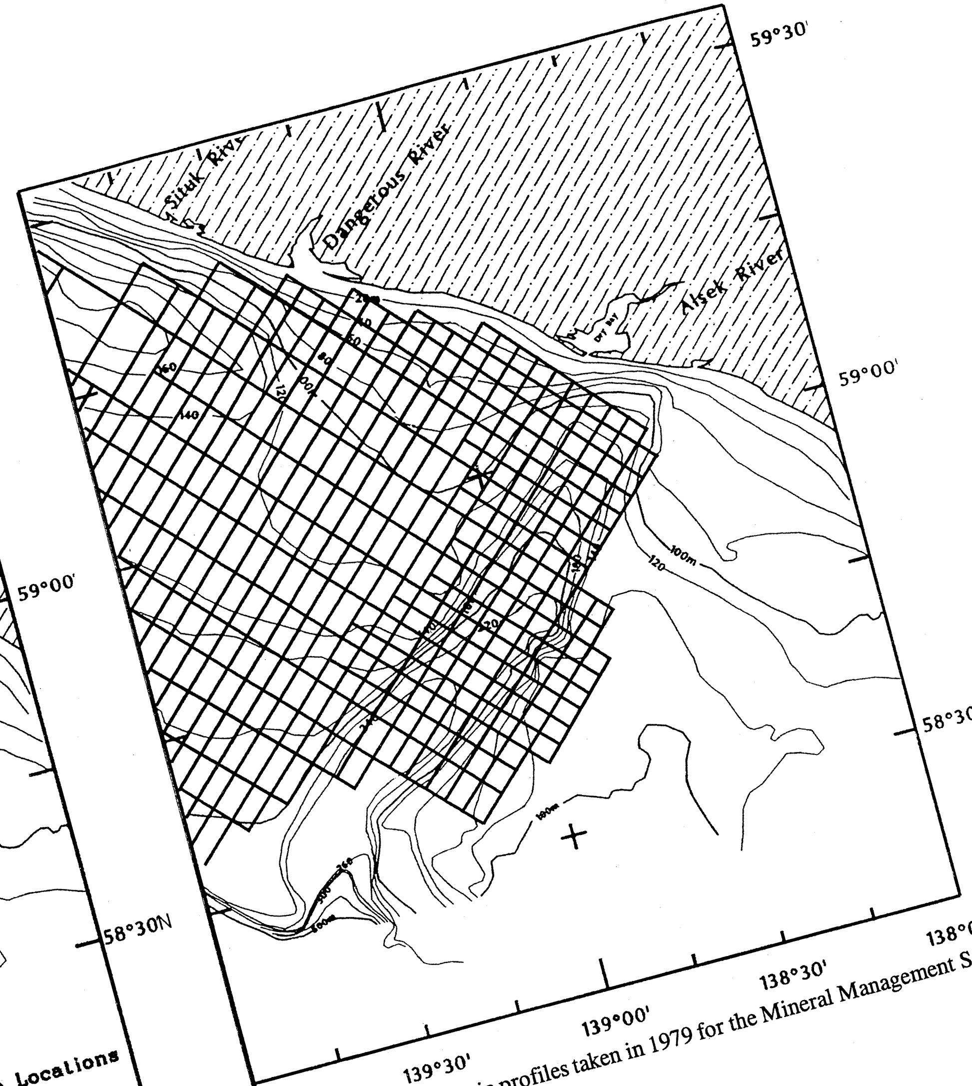

Fig. 5 Location of seismic profiles taken in 1979 for the Mineral Management Service.

a 3-km wide grid, covering most of the inner and middle shelf (Fig. 5). Because of their relatively poor resolution, however, these data were used primarily to trace the extent of reflectors defined by the better quality 1994 and 1995 seismic data.

Coring operations in the Alsek Sea Valley region were hindered by highly consolidated sediment, and cores longer than 150 cm were impossible to obtain. At a number of mid-shelf locations, in fact, no cores were recovered despite numerous attempts. Once on deck, the box and kasten cores were subsampled for X-radiography, benthic ecology, radiochemistry (^{210}Pb, ^{14}C), and additional sedimentary properties. Calcium carbonate shells were picked for subsequent ^{14}C dating, as the limit of ^{210}Pb geochronology is only five half-lives ($T_{1/2}$ = 22.3 years) or 120 years.

RESULTS

Our seismic profiles in the sea valley show the same sediment sequence defined by Carlson & Molnia (1978) for the shelf in general: an erosional acoustic basement overlain by an acoustically homogenous layer assumed (by Carlson & Molnia) to be late Pleistocene glacial and glacial marine sediments. Over this layer lies a Holocene layer of periglacial and fluvial sediment, which Carlson & Molnia defined as having well-developed internal stratification. In the Alsek Sea Valley, the stratification of this upper layer, which we have termed the yellow layer, is well-defined, particularly as seen on the Huntec DTS profiles (Figs 6-8). It overlies an acoustically clear layer that outcrops on the sides of the sea valley (see below). The yellow layer wedges from more than 80 m thickness (Fig. 9) on the inner shelf valley to less than 5 m over much of the outer shelf valley. Moreover, whereas the underlying layer conforms to the sub-bottom topography, individual strata within the yellow layer are parallel with the present sea bottom (e.g. Figs 7, 8).

Closer inspection of the yellow layer shows that it is composed of more than 20 individual layers. In the inner shelf these layers are as thick as 7-8 m, but they tend to

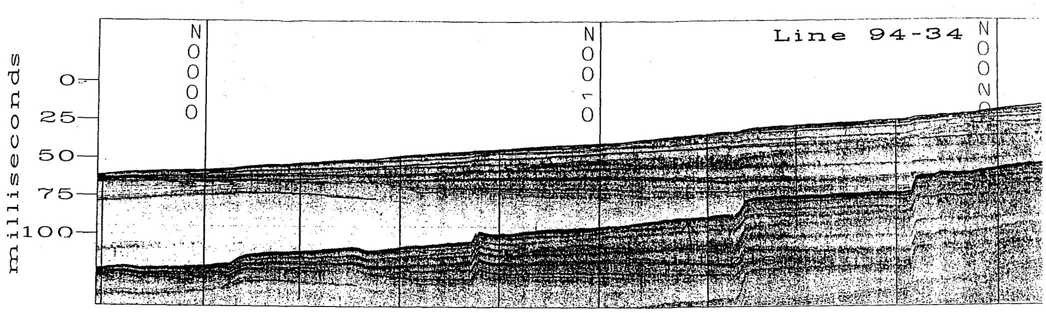

Fig. 6 Cross-shelf Huntec seismic profile (Line 94-34) along the axis of the Alsek Sea Valley (location in Fig. 4) showing the shoreward (right) thickening of the acoustically laminated distal Jøkulhlaups layers. Hourly navigational fixes are roughly equivalent to 7 km h^{-1}, the approximate speed of the survey ship. The vertical scale (in ms) indicates sea-valley relief and sediment thickness rather than depth from the sea surface. Assuming a velocity of sound of 1560 m s^{-1}, a two-way travel time of 25 ms equals approximately 20 m sediment thickness.

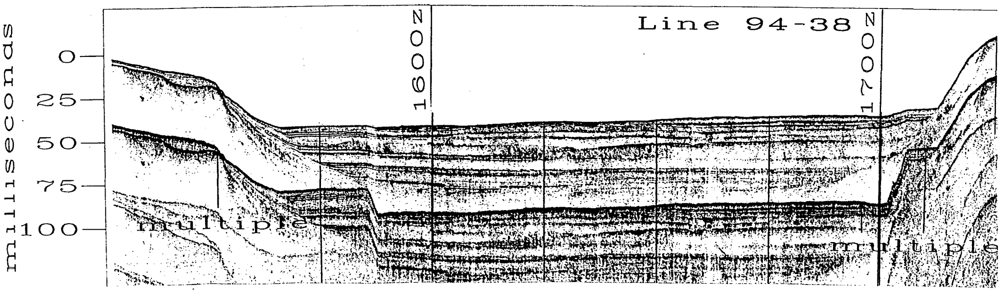

Fig. 7 Cross-valley Huntec seismic profile (Line 94-38) in the inner shelf portion of the Alsek Sea Valley (location in Fig. 4) showing the relatively thick individual distal Jøkulhlaups layers. Scales same as in Fig. 6.

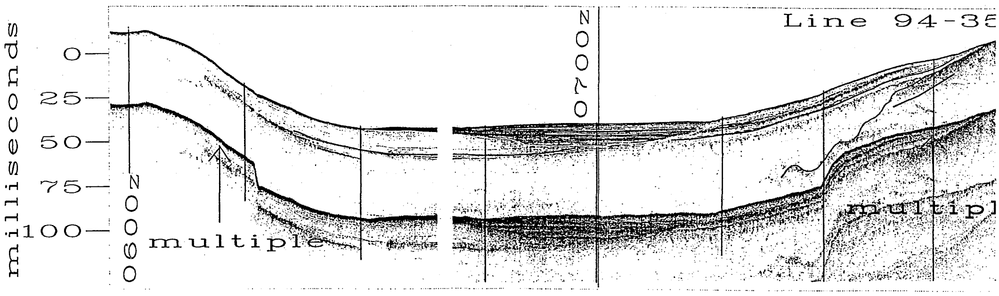

Fig. 8 Cross-valley Huntec seismic profile (Line 94-35) on the mid shelf portion of the Alsek Sea Valley (location in Fig. 4) showing the thinner distal laminated Jøkulhlaups layers overlying the acoustically clear glacial marine layer; compare with Fig. 7. Scales same as in Fig. 6.

be discontinuous, giving the sea floor an uneven, hummocky appearance. The Huntec DTS profiles indicate that the individual layers thin to less than 1 m on the mid and outer shelf, but they are continuous; the resultant seafloor is extremely flat (Fig. 8). It is this yellow layer that we have considered to represent the Alsek Jøkulhlaups deposits.

The supposed Jøkulhlaups sequence lies discontinuously over an acoustically clear layer (glacial marine sequence). Locally the clear layer is faintly laminated, and in the central axis of the valley it appears to be eroded (Fig. 10), suggesting that the first Jøkulhlaups event(s) was(were) erosive not depositional. Perhaps these early Jøkulhlaups events emanated from coastal mountains, in contrast to subsequent events that occurred 100 km inland.

X-radiographs of box and kasten cores collected along the valley axis show both biogenic and physical structures. The surfaces of all cores are heavily bioturbated and mottled to a depth of about 20-30 cm, with distinct burrows 1 to 12 mm in diameter. Below the surface bioturbated zone, all cores have a laminated interval, which has a maximum thickness of 12 cm inshore (BC 150; Fig. 11) and thins offshore. The bottom of the laminated zone is marked by a sharp contact, below which are found bioturbated sediments.

Lead-210 profiles show a 5-cm thick surface mixed layer, underlain by exponential decrease in activity to supported values of 0.9-1 dpm g^{-1} by 30 cm (Fig. 12). Steady-state sediment accumulation rates calculated from excess activities are less than 1 mm $year^{-1}$ for both KC 149 and KC 150.

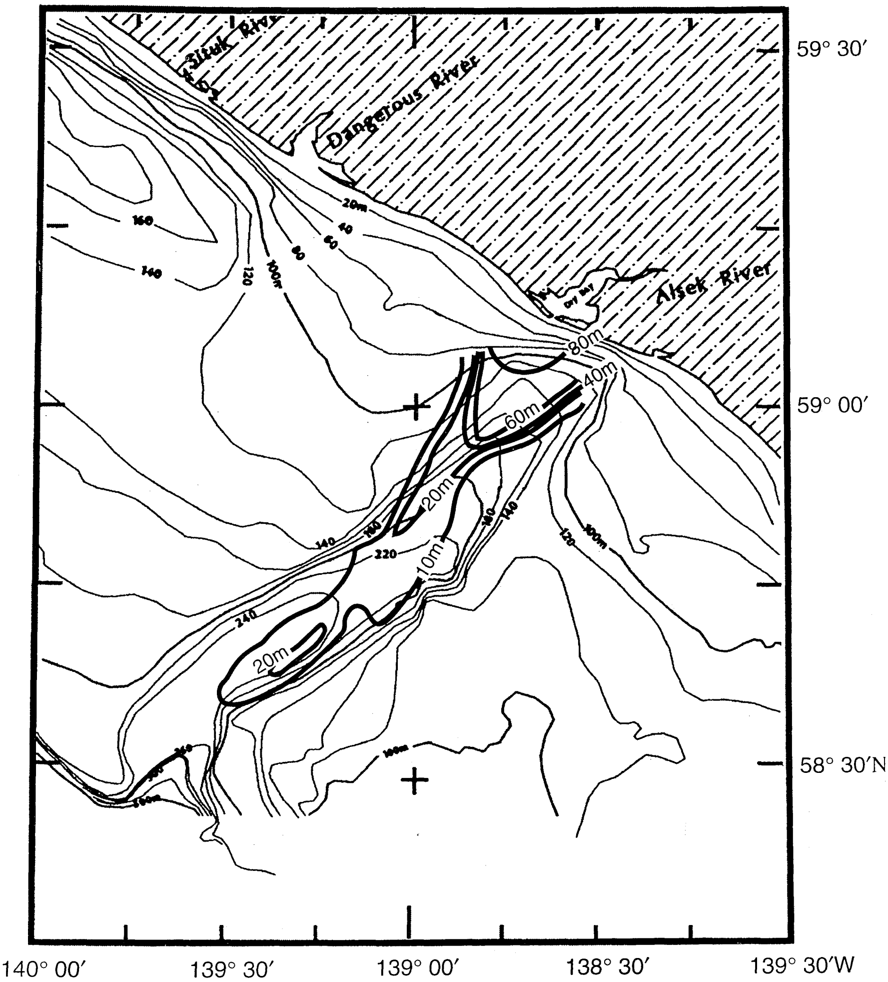

Fig. 9 Thickness (m) of Jøkulhlaups-related sediments in the Alsek Sea Valley, assuming a two-way travel time of 1560 m s^{-1} Although the 0 and 5 m isopleths are not shown, they lie very near the 10 m isopleth. N.B. These isopachs are preliminary; reinterpretation of digitally processed seismic data may change their configuration.

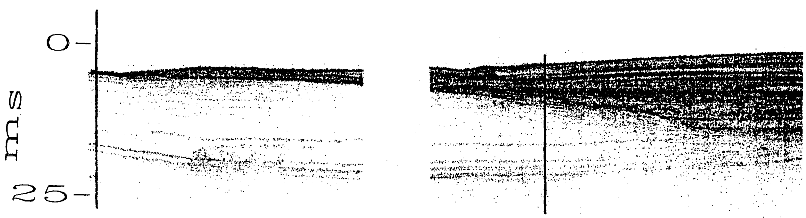

Fig. 10 Close-up of the laminated Jøkulhlaups sequence (right) in profile 94-35 (see Fig. 8) overlying the acoustically clear layer. This finely laminated sequence, presumably glacial marine in origin, may have been eroded by the draining of a glacial lake located near the coast (see text). Distance between vertical lines is approximately 1.7 km.

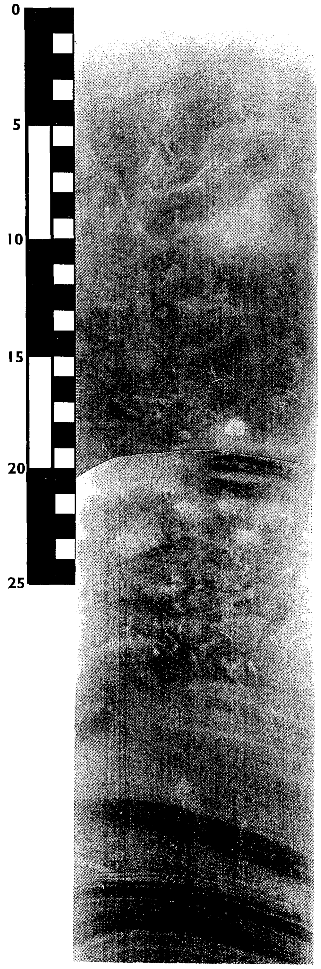

Fig. 11 X-radiograph of a box core (BC 150) taken near the head of the Alsek Sea Valley (location in Fig. 4). Note the bioturbated upper section (about 30 m thick) and the laminated lower layers, which presumably represent the last Jøkulhlaups event.

DISCUSSION

Despite its proximity to the river mouth, the inner shelf off the Alsek River has relatively little Holocene sediment cover, generally less than 10-20 m. Where, then, has the sediment discharged from this large river accumulated? Based on historic records over the past several hundred years, much of the sediment load appears to have filled in the Alsek estuary (B. Molnia, 1995, oral communication); the remainder, presumably, has been transported westward along the inner shelf by the Coastal Current. Given the probable sediment load of the Alsek and the westward drift of the Alaskan Coastal Current, one would expect significant sediment accumulation west of the river mouth, but seismic profiles show little modern sediment cover; perhaps some sediment has been transported into the Yakutat Sea Valley, 100 km to the west.

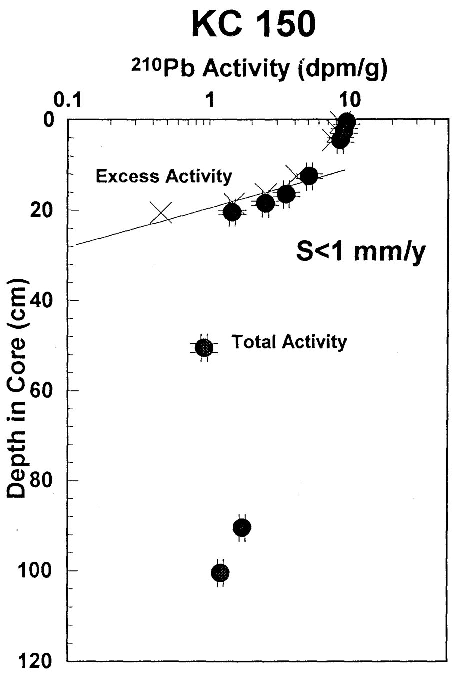

Fig. 12 The depth distribution of ^{210}Pb activity in kasten core (KC 150) taken at the same location as BC 150. Note that excess activity extends only to about 20-25 cm, meaning that the laminated section seen in Fig. 12 is older than 120 years (5 half-lives of ^{210}Pb).

The modern offshore depocentre for Alsek River sediment appears to be the Alsek Sea Valley. Huntec DTS profiles show that the sediment in the sea valley is highly deformed, suggesting rapid influx and subsequent slope failure. The rough, uneven morphology of layers near the head of the sea valley implies slumping; Schwab & Lee (1989) have suggested that this irregular topography reflects earthquake activity in the area, but we speculate that the layered nature of the sea valley sediment sequence reflects periodic, catastrophic influxes of sediment associated with the Jøkulhlaups events resulting from the draining of Neoglacial Lake Alsek. The smooth, continuous nature of the layers in the mid and outer shelf portion of the sea valley suggests that transportation and distal deposition occurs as a series of hyperpycnal flows generated by the slope failures at the head of the sea valley.

Evidence from X-radiographs and ^{210}Pb geochronology indicates that modern sedimentation in the sea valley alternates between slow steady-state accumulation (< 1 mm year^{-1}) punctuated by sudden cm-to perhaps m-scale inputs. The bioturbated and mottled sediment is characteristic of slow, steady-state accumulation, which is corroborated by the ^{210}Pb profiles. The presence of physical sedimentary structures and lack of bioturbation in the laminated interval would indicate rapid deposition of material. The laminated intervals found in all cores at 20-30 cm was deposited over 100 years ago, as indicated by the absence of excess ^{210}Pb, which would agree with an earlier supposition that the last major Jøkulhlaups event occurred in the middle of the last century.

The thickness and continuity of individual layers in the Alsek Sea Valley identified on Huntec DTS profiles allow us to calculate the total volume of individual layers. The thickest layers have sediment volumes of 1.1 to 2.1 $\times$ 10^9 m^3; assuming a dry density of 1.2, this amounts to 1.3 to 2.5 $\times$ 10^9 t $year^{-1}$, equivalent to the combined annual discharge of all the rivers draining North America (Milliman & Meade, 1983)! The total sediment volume of the Jøkulhlaups sequence in the sea valley amounts to 20 $\times$ $10^9 m^3$ or 24 $\times$ 10^9 t. Assuming that the Jøkulhlaups events noted in the Alsek River Valley began about 3000-4000 years ago (Clague & Rampton, 1982), this sediment volume represents a mean discharge of only about 6-8 $\times$ 10^6 t $year^{-1}$, even though the individual episodic inputs were far greater than this.

As we estimate that the Alsek has a sediment load of about 30-40 $\times$ 10^6 t $year^{-1}$, we question where the remainder of the Jøkulhlaups sediment has been deposited, or did most events transport less sediment than the Alsek sediment load pro-rated over the interval between events? We have no idea as to the amount of sediment deposited landward of the sea valley, but it may well be equal to or greater than that deposited in the sea valley. Whether the amount deposited landward or transported westward (by the Alaskan Coastal Current) can account for the "missing" 15-25 10^6 t $year^{-1}$ is, however, uncertain. We can conclude, nevertheless, that an equally important effect of Neoglacial Lake Alsek Jøkulhlaups may have been the transforming of a fluvial-coastal system, in which sediment mostly accumulated within the estuary or was transported along shelf, to one in which the sediment was transported cross-shelf.

The apparent sill on the outer shelf may prevent any sediment from escaping onto the slope, and seismic profiles on the Alsek outer shelf and upper slope show no evidence of modern sediment accumulation. Thus, as configured, the Alsek Sea Valley appears to act as a shelf basin rather than a conduit to the deep sea.

CONCLUDING REMARKS

The thick late Holocene sequence in the Alsek Sea Valley represents the distal portion of a series of hyperpycnal flows initiated by periodic Jøkulhlaups events caused by the draining of Neoglacial Lake Alsek, some 100 km inland. While individual events may have deposited as much as 2.5 $\times$ 10^9 t of sediment, this may represent less sediment delivery than if the Alsek River had discharged in a non-Jøkulhlaups mode over the intervening period between Jøkulhlaups. These Jøkulhlaups-related flows, however, appear to offer a mechanism by which sediment can escape from the Alaska Coastal Current-dominated regime on the inner shelf (which transports sediment along shore) to the outer shelf. Escape to the slope, however, is prevented by a possible outer shelf sill. Additional ^{14}C dates must be obtained to add more chronological significance to the stratigraphic sequences.

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