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Short Paper

New evidence for high discharge to the Chukchi shelf since the Last Glacial Maximum

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Abstract

Using CHIRP subbottom profiling across the Chukchi shelf, offshore NW Alaska, we observed a large incised valley that measures tens of kilometers in width. The valley appears to have been repeatedly excavated during sea level lowering; however, the two most recent incisions appear to have been downcut during the last sea level rise, suggesting an increase in the volume of discharge. Modern drainage from the northwestern Alaskan margin is dominated by small, low-discharge rivers that do not appear to be large enough to have carved the offshore drainage. The renewed downcutting and incision during the deglaciation and consequent base level rise implies there must have been an additional source of discharge. Paleoprecipitation during deglaciation is predicted to be at least 10% less than modern precipitation and thus cannot account for the higher discharge to the shelf. Glacial meltwater is the most likely source for the increased discharge.

Keywords: Chukchi Sea; Incised valleys; Sea level; Meltwater discharge

Channel sequences preserved on continental shelves provide important information about past base level change and paleodischarge. In most coastal fluvial valleys, downcutting results from a base level lowering, such as relative sea level fall, while deposition and infilling of the valley occurs during sea level rise as the system regrades (Posamentier and Vail, 1988; Dalrymple et al., 1994). Alternatively, climate change may result in increased discharge or reduced sediment load, creating incision in the absence of base level change (Schumm et al., 1987). CHIRP subbottom data collected on the Chukchi shelf off NW Alaska reveal a large buried channel system within an incised valley, which is at least 24 km wide and 50 m deep. Below we discuss the valley stratigraphy in terms of multiple incisions, some of which appear to require increased discharge during deglaciation. If correct, this research has important implications for the paleoclimate during deglaciation (wetter) or requires more continental glaciation than previously proposed.

Results

The incised valley is located in a bathymetric low between the Herald and Hanna Banks (~50 m water depth), and extends for at least 90 km across the shelf (Fig. 1). Regionally, the valley cuts across steeply dipping, folded and faulted reflectors interpreted to be Cretaceous strata, tilted as a result of thrusting along the Herald Bank (see Fig. 19 of Phillips et al., 1988). Six distinct and regionally extensive erosional surfaces that separate depositional sequences are identified within the incised valley.

The oldest incision, termed Valley Incision 0 (VI-0), truncates the underlying Cretaceous strata on the northeastern side of the incised valley, downcutting at least 50 m (Figs. 2, 3). A second incision surface, Valley Incision I (VI-1) downcuts acoustically transparent sediment above VI-0 (Unit 0) and coalesces with VI-0 to the southeast (Figs. 2, 3). Together these two incision

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surfaces define the extent of the incised valley. The sediment in Unit 1, overlying reflector VI-1, is acoustically laminated, continuous over long distances, and locally drapes the underlying topography (Figs. 2, 3). Unit 1 in turn is, truncated and downcut by another incision surface, Valley Incision II (VI-2) (Figs. 2, 3). Infill above VI-2, termed Unit 2, shows complex stratal geometry characteristic of fluvial cut-and-fill structures (e.g., cutbanks, and lateral accreting sets; Figs. 2E, 3).

Incision I-3 delineates a channel or valley that is ∼4.5 km wide with 45 m of relief (Fig. 2). Reflectors in Unit 3 overlying I-3 are much higher amplitude and more laminated than adjacent Units 1 and 2. Unit 3 strata also exhibit slight thickening toward the basin depocenter. VBC03 (8.66 m) sampled Unit 3 strata overlying I-3 and recovered blocky sands and interbedded sands and silty clay containing marine shells and foraminifera (Fig. 1). An articulated bivalve mollusk from the base of Unit 3 yielded a radiocarbon age of 12,300±65 ^{14}C yr BP (∼13,500 cal yr BP). Reflector I-4 represents a subsequent episode of erosional truncation that also results in large relief (∼20 m) on the unconformity (Fig. 2). Unit 4 fill is locally truncated near the valley walls by reflector FS, a flooding surface observed only in the I-4 channel. Note infill Units 3, 4 and 5 exhibit a similar acoustic character.

A feature approximately 2 km wide and at least 15 m high (Constructional Mound; Fig. 2), adjacent to I-3/I-4, exhibits downlap to the southwest along two different surfaces and is elevated above Unit 2. The uppermost reflectors within CM show minor truncation on the NE side. The CM feature is present in multiple subbottom profiles across the incised valley (Fig. 1B) and shows a three-dimensional morphology in orthogonal Boomer subbottom profiles that intersect at CM. Reflector TS truncates strata along nearly the entire cross section of the valley, (Transgressive Surface; Fig. 2). TS is interrupted by small, discrete, v-shaped downcutting events, labeled IS, in the NE. Unit 6 fill above TS appears to drape the underlying strata across the length of the acquired profiles (Fig. 2).

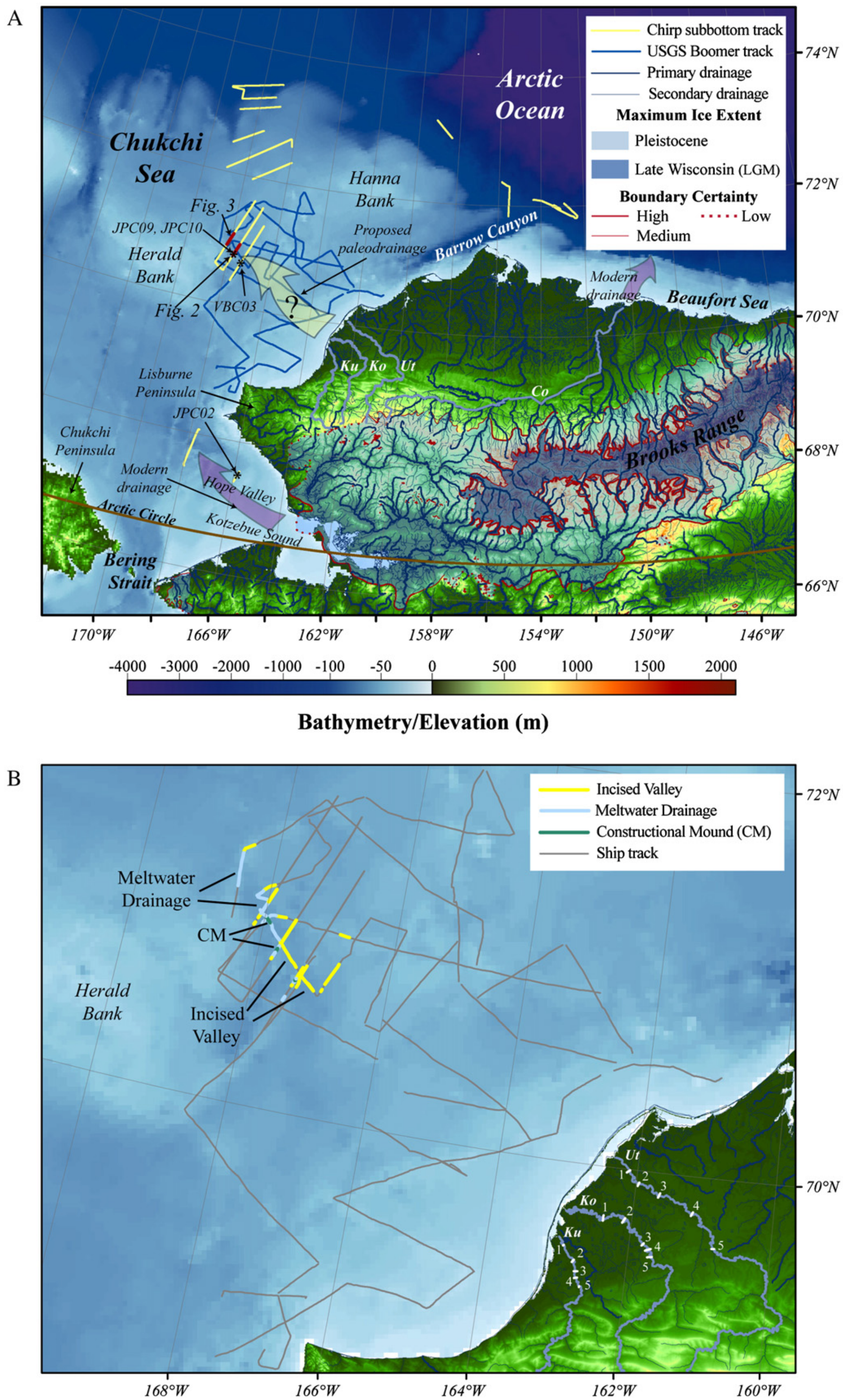
Two piston cores, JPC 09 (8.81 m) and JPC10 (8.13 m) acquired in the incised valley, recovered Units 4 and 6 above I-4 and the NE edge of the CM feature below I-4 (Figs. 1, 2D). Both cores show similar facies, with ∼4 m of silty clay at the top (Unit 6), grading into interbedded silty clay and sand (Unit 4), overlying 2–3 m of well sorted fine sand and fine sand with silty clay rip up clasts at the base of the core on the boundary between the CM feature and Unit 2 (JPC09) and within CM (JPC10; Fig. 2D). JPC 09 recovered an additional layer of small rip-up clasts near the base of Unit 4. In both cores, marine shells and foraminifera were observed only in Unit 6. Radiocarbon dating on paired bivalves in JPC10 yielded an average sedimentation rate of ∼1.45 m/kyr prior to ∼8 ka, with a very low sedimentation rate after ∼8 ka. The oldest date in JPC10 is 10,200 ^{14}C yr BP (∼10,770 cal yr BP), near the base of Unit 6.

Discussion

Several interpretations may explain the stratal geometry observed in our CHIRP subbottom data, four of which are outlined in Table 1; however, these interpretations are speculative due to the limited core sample information. All scenarios propose similar explanations for the formation of VI-0, VI-1 and VI-2, but we explore alternative scenarios for the formation of I-3 and I-4. Options 1 and 2 predict stratal geometries and chronologies inconsistent with the observations, and thus are discarded. In Option 1, I-4 would correspond to Marine Isotope Stage (MIS) 2, I-3 to MIS 6, and VI-2, VI-1 and VI-0 to successively older glacial periods. This scenario fails to account for the much narrower widths of I-3 and I-4 compared with VI-0, VI-1 or VI-2 and markedly different infill character of Unit 3 and 4 relative to Unit 0, 1, and 2. Given the MIS 2 glaciation is believed to have been limited, restricted primarily to alpine regions, and MIS 6 glaciation was far more regionally extensive, it is difficult to explain why the channel dimensions and relief are similar for I-3 and I-4, yet appear markedly different from the older incisions (e.g., VI-0, VI-1, VI-2). Finally, radiocarbon dating of a marine shell in VBC03 indicates that the basal section of Unit 3 was deposited during the Allerød warm period (∼13,500 cal yr BP), which postdates the LGM (MIS 2; ∼21,000 cal yr BP). In Option 2, I-3 and I-4 represent the last phase of localized channel incision within VI-1 and VI-2 valleys, respectively; however, erosion associated with I-3 downcuts and truncates Unit 2 sediment, suggesting formation of I-3 must be younger than VI-2. Therefore I-3 cannot be an open channel associated with valley VI-1. While controversy exists regarding the extent and volume of Arctic continental glaciation during the Last Glacial Maximum (LGM) (e.g., Brigham-Grette et al., 2004; Grosswald and Hughes, 2004 and references therein), both Options 3 and 4 require a greater extent of glaciation in NW Alaska than previously recognized. Our preferred scenario, Option 4, as described below, requires the least amount of ice buildup, making it simpler to reconcile the new evidence with existing Arctic studies.

Figure 1. (A) Location map showing SIO SUBSCAN CHIRP subbottom data (1–6 kHz signal, 50 ms sweep) acquired on the Chukchi margin aboard the USCGC Healy in 2002 as well USGS Boomer subbottom data collected by Phillips et al. (1988). The locations of Figures 2 and 3 subbottom profiles and piston cores discussed in the text are labeled. Abbreviations: Ku—Kukpowruk River, Ko—Kokolik River, Ut—Utukok River, Co—Colville River. The primary modern drainage in northern Alaska flows NNE through the Colville River, while the southern Brooks Range drains through Hope Valley, as denoted by the purple arrows. The smaller rivers on the NW margin discussed in the text are highlighted and the proposed paleodrainage direction is shown by the yellow arrow. Also shown is the previously interpreted maximum ice extent for the Pleistocene and late Wisconsin (LGM) glaciations (Manley and Kaufman, 2002). High-certainty boundaries have well-defined chronologies, while low-certainty boundaries may encompass areas lacking significant field or remotely sensed studies. Note that ice extent is uncertain along the NW Brooks Range foothills that compose the headwaters of the Kukpowruk, Kokolik, and Utukok Rivers. (B) Interpreted channel map showing CHIRP and Boomer subbottom crossings of the incised valley (VI-0, VI-1, VI-2), meltwater drainage (I-3, I-4), and the constructional mound (CM) feature. Note the meltwater drainage appears to reexcavate portions of VI-0, VI-1 and VI-2. Relatively small northwest-trending channels were also observed in the region between the incised valley and the northwestern Alaskan margin. No channels were observed between the Lisburne Peninsula and Herald Bank. Correlation of channels across the inner shelf is difficult because of the poor data quality and azimuth of the Boomer profiles being parallel to the channel trend. The location of floodplain profiles across the northwestern rivers shown in Figure 4 are also highlighted and labeled.

Three regional valley incisions, reflectors VI-0, VI-1 and VI-2 (Figs. 2, 3), are observed in the CHIRP subbottom data, which suggest three events of lowered sea level and valley excavation. Reflector VI-0 appears to represent the oldest valley incision. The transparent acoustic character of Unit 0 fill makes it difficult to interpret the depositional environment, yet the lack of characteristic fluvial structure suggests this may be a marine or estuarine deposit. Downcutting associated with the formation



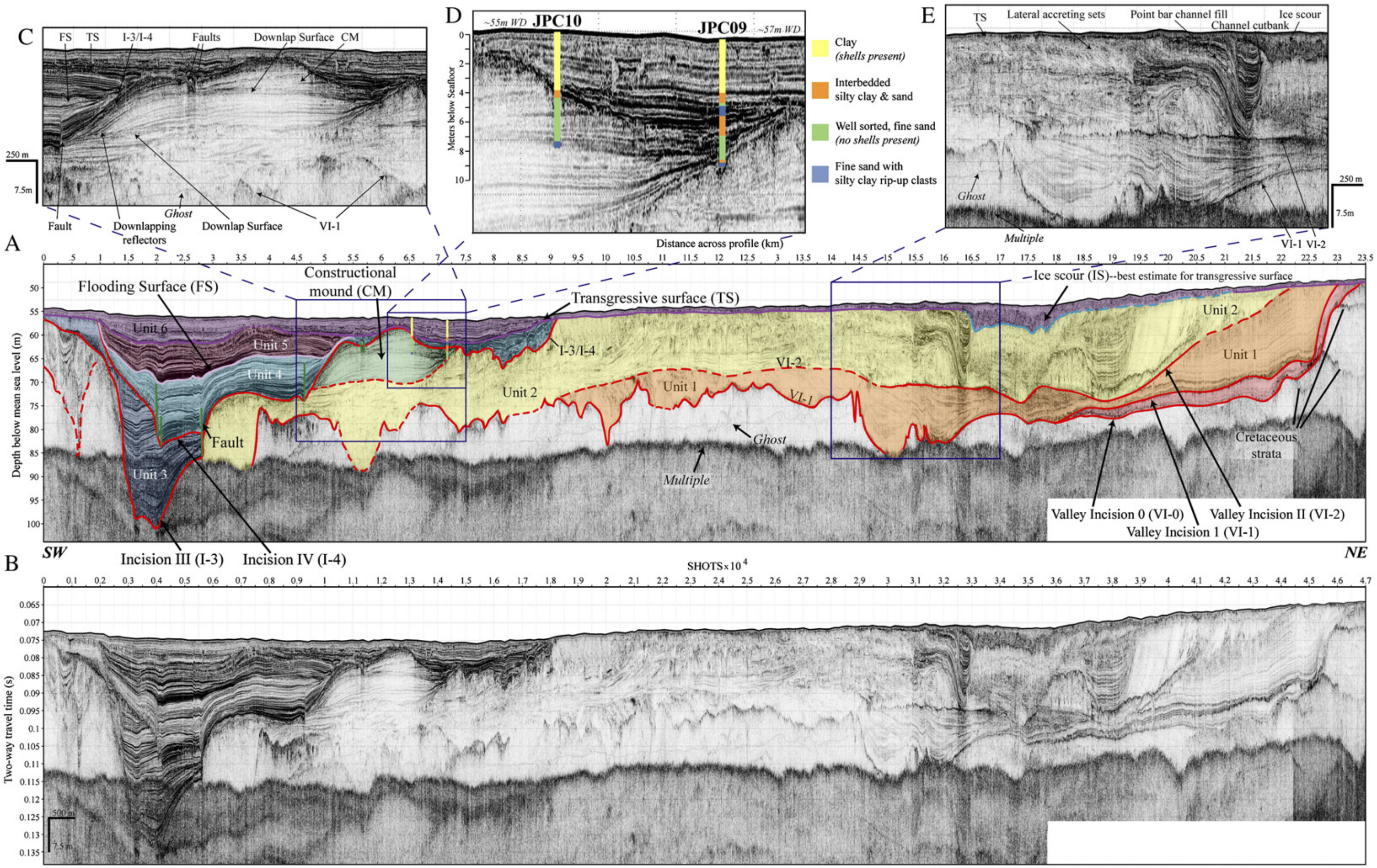


Figure 2. CHIRP subbottom profile across the incised valley (Line 2, see Figure 1 for location). (A) Interpreted profile with the reflectors color coded as follows: red—Valley Incision 0 (VI-0), Valley Incision I (VI-1), Valley Incision II (VI-2), Incision III (I-3) and Incision IV (I-4); light purple — Flooding surface (FS); dark purple—most recent transgressive surface (TS); blue—most recent ice scour (IS), also the best estimate for TS in that area; green—post-depositional faulting. CM indicates a constructional mound feature. Sedimentary units are also labeled. The dimensions of the I-3/I-4 valleys were measured between shotpoints ~2000 and ~18000. (B) Same profile as 2a, with no interpretation (C) Constructional mound (CM). Downlapping reflectors indicate build up of positive relief. (D) Sedimentary facies of piston cores JPC09 and JPC10 in the incised valley. Both cores have a similar stratigraphy of well sorted fine sand with silty clay rip-up clasts in the base, grading upward into interbedded sand and silty clay, with silty marine clay at the top. JPC09 was collected ~60 m to the NW of the profile. JPC10 was collected ~15 m to the SE. The core positions have been projected orthogonally onto the subbottom profile to represent the most accurate correlation of sediment facies. (E) Characteristic fluvial cut-and-fill stratigraphy. Unit 2 displays lateral accreting sets as well as fluvial point bar deposition on the SW bank, with cutbank erosion on the opposite side.

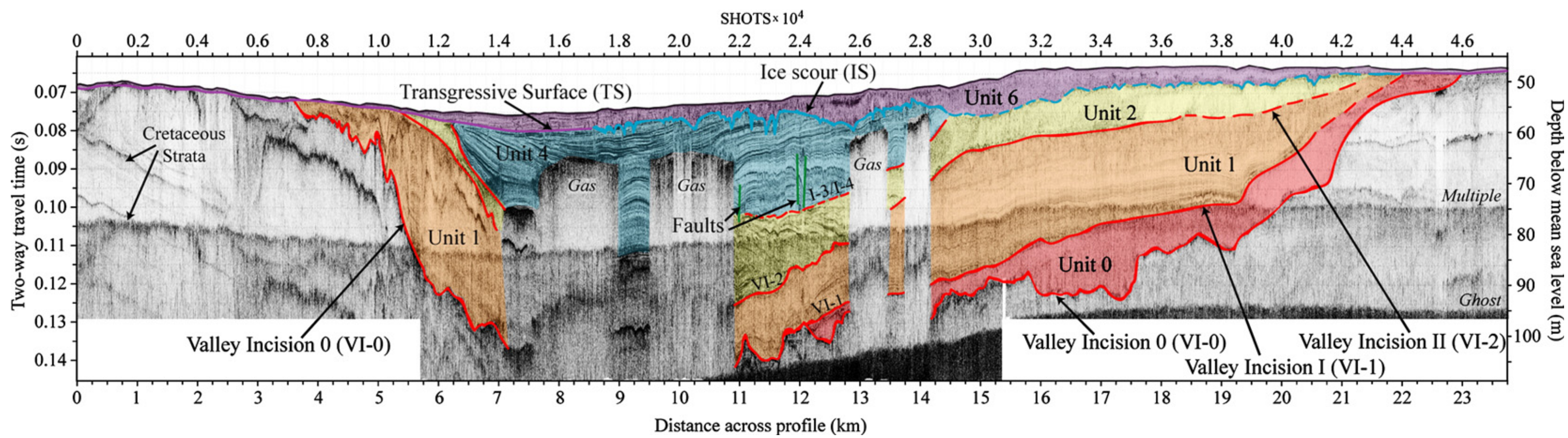


Figure 3. CHIRP subbottom profile across the incised valley (Line 3, see Figure 1 for location). Bottom: uninterpreted profile. Top: Interpreted profile with the reflectors color coded as follows: red—Valley Incision 0 (VI-0), Valley Incision I (VI-1), Valley Incision II (VI-2), Incision III (I-3) and Incision IV (I-4); light purple—flooding surface (FS); dark purple—most recent transgressive surface (TS); blue—most recent ice scour (IS), also the best estimate for TS in that area. Sedimentary units are also labeled. Gas in the shallow sediment results in acoustic wipeouts that obscure deeper reflectors.

of VI-1 appears to have removed most of Unit 0 infill. Unit 1 infill shows some geometric evidence of fluvial cross-cutting at the base of the deposit (Fig. 2E), but it mantles the underlying topography across most of the valley (Figs. 2, 3). The parallel, draping reflectors in the upper part of the package are suggestive of hemipelagic deposition, typical in estuarine or marine environments. Downcutting and truncation of Unit 1 across the width of the valley, indicated by reflector VI-2, is consistent with a third sea level fall and fluvial incision reexcavating Unit 1 valley fill. Unit 2 represents fluvial-dominated sedimentation as indicated by internal channel geometry interpreted to record cut-and-fill structures (Figs. 2E, 3) as the channel migrates within the valley, the details of which are beyond the scope of this paper. A fourth regional reflector (TS), interpreted as the most recent transgressive surface, is observed across the entire valley. TS locally truncates the upper sediments and is mantled by marine deposits of Unit 6 (Figs. 2, 3).

The ages of the proposed sea-level cycles remain uncertain. Without deep core information, the simplest explanation appears to be that the sea level cycles represented by VI-1 and VI-2 correlate to the Illinoian (MIS 6) and Wisconsin (MIS 2) glaciations, respectively. VI-0 would then correspond to an older glaciation, perhaps MIS 12, a similar period of rapid sea level lowering associated with a glacial maximum. This interpretation is consistent with the 6 m of negative relief observed at the seafloor above the incised valley, as well as the relatively thin sediment cover in Unit 6 above the most recent transgressive surface, TS (Fig. 2).

Reflectors I-3 and I-4 exhibit large downcutting relief with highly reflective sediment fill (Units 3, 4, 5) that appears to be deposited in an estuarine or marine environment (Fig. 3). Blocky sands and interbedded sands and silty clays with marine assemblages recovered from Unit 3 (VBC03; Fig. 1) are consistent with the observed stratal geometry. Reflectors I-3 and I-4 coalesce to the NE and Unit 4 onlaps Unit 2 (Fig. 2), indicating the incisions must be younger than VI-2. I-3 and I-4 may have been incised by fluvial processes; however, the lack of concomitant fluvial deposition in Units 3, 4, and 5 indicates this segment of the channel was predominantly undergoing erosion and sediment bypass. Note the different acoustic character of Units 1 and 2 versus Units 3, 4, and 5. For example, in Unit 2, faint lateral accreting sets appear to grade into a high-amplitude point bar (Fig. 2E). These dipping sequences exhibit greatest thickness at the rollover point, thinning both updip and downdip, and are adjacent to a small, infilled channel; such relationships are not observed within Unit 3, 4 and 5 fills. I-3 and I-4 appear to be younger than VI-2; if the proposed timing of VI-2 (MIS 2) is correct, this suggests I-3 and I-4 occurred during a period of sea level rise following the LGM. This interpretation is consistent with the age determination for the base of Unit 3 (~13,500 cal yr BP). Sequence stratigraphic models commonly dictate that fluvial erosion and downcutting will develop during base level lowering as a result of relative sea level fall, while sediment infill accumulates as fluvial systems regrade with the base level rise (Christie-Blick and Driscoll, 1995). In the absence of base level lowering, channel incision may result from increase in discharge, a decrease in sediment supply, or a combination of both. Sedimentation rates in both the incised valley (JPC10) and Hope Valley (JPC02; Keigwin et al., 2006) appear to have been relatively high during the most recent transgression and dropped dramatically ~7000 cal yr BP. Given these constraints, our preferred interpretation is that the incision resulted from increased discharge in response to meltwater runoff during deglaciation. High discharge events would scour the upper reaches of the channel, transporting the sediment farther offshore, hence the lack of fluvial fill observed in the subbottom data (Fig. 2).

The marine shell dated at 13,500 cal yr BP in Unit 3 is 1.24 m above I-3. Using the sedimentation rate determined from JPC10 implies I-3 was formed 14,300 cal yr BP, which coincides with Meltwater Pulse 1A (Fairbanks, 1989). Thus we speculate I-3 was incised by meltwater discharge during post-LGM warming, with the open channel subsequently infilled by estuarine to marine sediment (Unit 3; Fig. 2). I-4 may represent a second phase of meltwater discharge (e.g., MWP1B; Fairbanks, 1989) following a climatic cooling (e.g., Younger Dryas). Unit 4 and 5 infills are interpreted to be of marine origin and reflector FS may represent a period of rapid sea level rise. This explanation is consistent with Unit 5 sediment collected in JPC09/JPC10, which shows interbedded silty clay and fine sand, grading into silty marine clay of Unit 6. While possible that the formation of

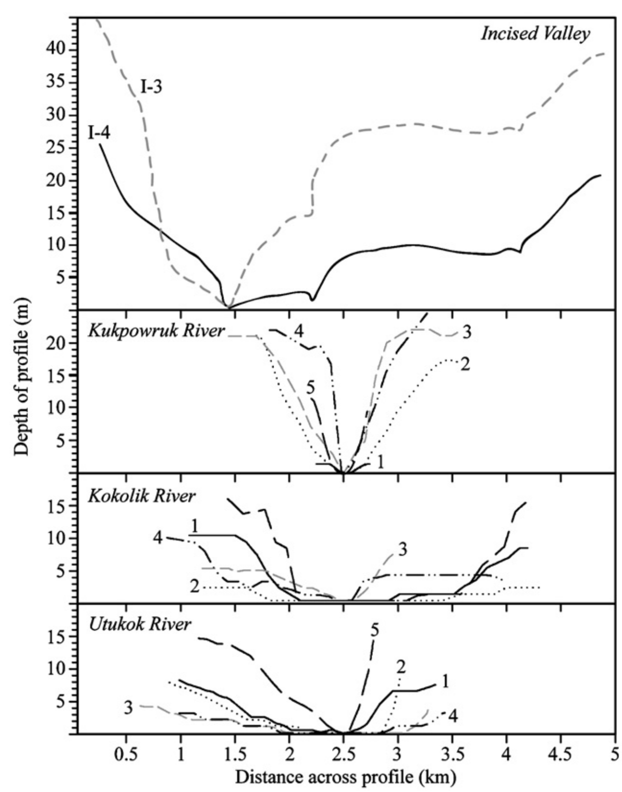
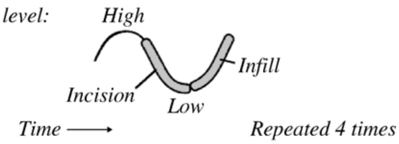
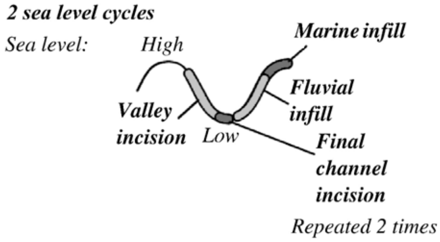
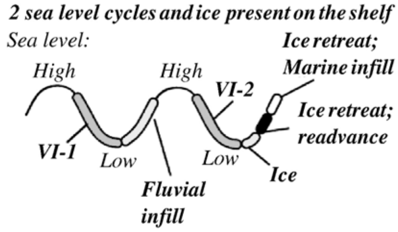
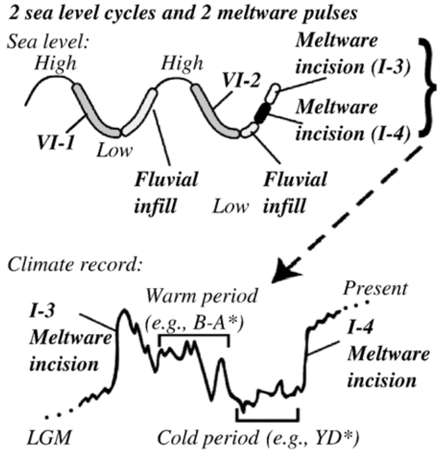


Figure 4. Midshelf Chukchi paleo-valley cross section profiles represented by the I-3 and I-4 reflectors compared with valley cross section profiles for three upstream dominant northwestern rivers that represent the principle source area for discharge. The cross section profiles of the rivers were measured from a 100 m resolution DEM of northern Alaska (Manley, 2001). The river profile locations are shown in Figure 1B. Note the I-3 and I-4 valleys are much wider than the corresponding river valleys onshore.

Table 1

	Options	Description	Concerns
1	***4 sea level cycles*** 	Each incision (VI-1, VI-2, I-3, I-4) repesents a separate sea level cycle: fluvial incision during sea level fall; infill as sea level begins to rise	I-3 and I-4 do not appear to have fluvial infill Expect pluvial conditions following peak glaciation
2	***2 sea level cycles*** 	*Sea level cycle 1:* a. VI-1 fluvial incision; fluvial infill b. I-3 represents the last channel location during valley incision; marine infill as sea level rises *Sea level cycle 2:* a. VI-2 fluvial incision; fluvial infill b. I-4 represents the last channel location during valley incision; marine infill as sea level rises	I-3 appears to be younger than VI-2 indicating that it can not be associated with the VI-1 SL cycle I-3 and I-4 do not appear to have any fluvial infill prior to marine incursion
3	***2 sea level cycles and ice present on the shelf*** 	*Sea level cycle 1:* VI-1 fluvial incision; fluvial infill *Sea level cycle 2:* a. VI-2 fluvial incision; fluvial infill b. Grounded ice shelf advances shelf and incises I-3 c. Ice retreats; I-3: glacial lacustrine or marginal marine infill d. Shelf ice readvances; I-4 incised e. Ice retreats; I-4: glacial lacustrine and marine infill	CM then is an ice contact feature (e.g. esker or lateral moraine) formed in association with I-4 ice advance. Requires shelf glaciation sourced from the Alaskan margin Expect more local sediment deformation with ice advance
4	***2 sea level cycles and 2 meltware pulses*** 	*Sea level cycle 1:* VI-1 fluvial incision; fluvial infill *Sea level cycle 2:* a. VI-2 fluvial incision; fluvial infill b. I-3 incised by pulses of glacial meltwater as climate warms c. Climate cools (e.g., Younger Dryas); glacial meltwater diminishes d. I-3; Low infilled with lacustrine sediment e. Climate warms and I-4: incised by pulses of glacial meltwater; marine infill as sea level rises *B-A = Bølling-Allerød, YD = Younger Dryas	Suggests there are two major discharge events, which are triggered by climatic variations rather than sea level The fills above I-3 and I-4 appear very similar, but I-3 infill may be glacial lacustrine, while I-4 infill is marine

I-3 and I-4 represent individual bankfull channels, it is more likely that these two erosional surfaces represent valleys carved by high-discharge, incising channels.

The depositional structure (CM; Figs. 2, 3) exhibits downlap along multiple surfaces, suggesting a constructional feature rather than an erosional remnant. Note the geometry of CM is different from Unit 2 fluvial fill (e.g., lateral accreting sets). While it is difficult to trace the basal sequences of Unit 4 across the fault on the eastern edge of the channel and determine the relative age of CM, our preferred hypothesis is that the feature was formed after the I-3 incision since there is only minor truncation of CM. The three-dimensional stratal geometry and sediment facies (i.e., well-sorted fine sand with no marine shells or microfossils) of CM is consistent with a fluvial origin (e.g., bar or braided island; Fig. 3). The large size (2 km wide, 15 m high) implies a high-volume discharge. Similar fluvial bars with large dimensions scaled to the magnitude of discharge have been observed in glacial outburst floods (Marren, 2005). This scenario is also consistent with the presence of silty clay rip-up clasts on the upper downlap surface of the CM feature (JPC 10; Fig. 2). The presence of CM in several subbottom profiles across the shelf (Fig. 1B) suggests multiple bars or braided islands along the length of the incised valley.

Previous researchers have suggested primary drainage across the Chukchi shelf may have been derived from the Hope Valley to the south (McManus et al., 1983); however, truncation of dipping Cretaceous strata indicates the uplift of Herald Bank, a structural drainage divide, predated channel formation (Phillips et al., 1988). While United States Geological Survey Boomer subbottom data collected in the region (Fig. 1) also provide evidence of numerous small paleochannels between the NW Alaskan margin and our study area, there is no evidence of paleochannels between the Herald Bank and Lisburne Peninsula (Phillips et al., 1988). This evidence precludes flow around Herald Bank from either Hope Valley or other rivers to the south and west as the potential source of the discharge and implies the drainage must be from the northwest Alaskan margin (Figs. 1, 2).

Currently, only small, low-discharge rivers drain the western portion of Alaska's North Slope (Fig. 1); however, these rivers have steep banks and incised channel morphologies cut into the Brooks Range foothills, suggesting they may have been carved by much stronger flows in the past. Profiles across portions of the Kokolik, Kukpowruk and Utukokok Rivers on the coastal plain show broad floodplain valleys (Fig. 4). The active flow occupies a small channel surrounded by meander cutoffs and oxbow lakes while the remaining floodplain is heavily sedimented with fluvial deposits. Note the valley dimensions of these northwestern rivers are less than half the size of the valleys defined by I-3 and I-4 on the midshelf (Fig. 4), and a key point is that the I-3/I-4 valleys do not contain any fluvial sediment, unlike their onshore counterparts. Infilling of the onshore channels may have occurred after the maximum flooding, when the rate of sea level rise diminished. Note for comparison, the individual paleochannels preserved in the fluvial sediments of Unit 2 are greater than 500 m across and 8–9 m deep (Fig. 2E), about twice the size of the bankfull channel dimensions observed along the northwestern rivers (Childers et al., 1979).

The formation of I-3 and I-4 during the last sea level rise suggests that there must have been an additional source of flow, either in the form of more pluvial conditions immediately following peak glaciation or glacial meltwater. Pollen records indicate higher moisture levels after 10,000 ^{14}C yr BP with a Holocene peak around 6000 ^{14}C yr BP (Edwards et al., 2001; Mann et al., 2002). Paleoprecipitation for this period, however, is estimated to be at least 10% less than the modern (Edwards et al., 2001). Given modern discharge observed across the North Slope of Alaska is insufficient to carve the I-3/I-4 valleys, these observations require another source for the increased discharge. We propose that the increased discharge resulted from meltwater runoff during deglaciation. Meltwater would have originated from the Alaskan margin, implying a greater extent of continental glaciation than previously recognized (Fig. 1). Pluvial conditions during deglaciation may have increased glacial water storage and perhaps glacial readvances, as well as augmented glacial meltwater discharge. This explanation is consistent with evidence from piston cores JPC10 and JPC02 (Hope Valley), which indicates a dramatic decrease in sedimentation in the last ~7 kyr (Keigwin et al., 2006).

Much of the argument for limited glaciation in northern Alaska during the LGM has been centered on evidence for relatively arid conditions, which would limit moisture required for significant ice buildup (e.g., Brigham-Grette, 2001 and references within). These conclusions are commonly based on paleoclimate proxies from the eastern and central Brooks Range; however, some studies suggest that spatial climatic variability in the region may be significant (Mock and Anderson, 1997; Edwards et al., 2001). LGM ice buildup in the southwestern Brooks Range dammed montane rivers, resulting in Glacial Lake Noatak that eventually drained to the south during deglaciation (Hamilton, 2001). It appears plausible that similar glacial conditions may have also existed 15–20 km to the north across the northwestern river headwaters. Our offshore data provide evidence for increased drainage during deglaciation that appears to have drained from the northwestern Alaskan margin. Nevertheless, in the absence of onshore field-based studies in this region, it is difficult to make any definitive assertions about the implied ice extent and source of the increased discharge. We are not arguing for a large ice sheet across the region, but rather suggesting there may have been more extensive alpine glaciation during the LGM than previously recognized.

Conclusions

The large, northwest-trending valley on the Chukchi shelf shows evidence of fluvial downcutting during multiple periods of lowered sea level. The stratal geometry, absence of fluvial fill following the two most recent incisions (I-3/I-4), and age constraints indicate these incisions may have been formed by episodes of high discharge. The modern flow from northwestern Alaskan rivers does not appear to be sufficient to carve these offshore valleys, and paleoprecipitation during deglaciation is predicted to be at least 10% less than modern. Therefore the inferred magnitude of discharge needed to carve the I-3/I-4 valleys requires an additional input, most likely from pulses of glacial meltwater since the Last Glacial Maximum. The meltwater pulses that incised I-3 and I-4 are most likely short-term events, as suggested by the age at the base of Unit 3 infill being ~13,500 cal yr BP with the overlying post-transgressive marine sediment being ~10,770 cal yr BP. The proposed timing of I-3 and I-4, carved by a high volume of discharge during a period of sea level rise, suggests that in glacially dominated landscapes, incision on the shelf can be caused by brief pulses of meltwater discharge. Therefore, renewed events of incision on glaciated margins do not always correlate with base level falls and caution needs to be exerted when interpreting channel formation. Additionally, our results suggest more climate variability and a greater extent of continental glaciation during the LGM than previously proposed.

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References

Brigham-Grette, J., 2001. New perspectives on Beringian Quaternary paleogeography, stratigraphy and glacial history. Quaternary Science Reviews 20, 15–24.

Brigham-Grette, J., Lozhkin, A.V., Anderson, P.M., Glushkova, O.Y., 2004. Paleoenvironmental conditions in western Beringia before and during the Last Glacial Maximum. In: Madsen, D.B. (Ed.), Entering America: Northeast Asia and Beringia before the Last Glacial Maximum. University of Utah Press, Salt Lake City, pp. 29–61.

Childers, J.M., Kernodle, D.R., Loeffler, R.M., 1979. Hydrologic reconnaissance of western Arctic Alaska, 1976 and 1977. U.S. Geological Survey Open-File Report 79–699.

Christie-Blick, N., Driscoll, N.W., 1995. Sequence Stratigraphy. Annual Review of Earth and Planetary Sciences 25, 451–478.

Dalrymple, R.W., Boyd, R., Zaitlin, B.A., 1994. Incised-valley systems: Origin and sedimentary sequences. Society for Sedimentary Geology Special 51.

Edwards, M.E., Mock, C.J., Finney, B.P., Barber, V.A., Bartlein, P.J., 2001. Potential analogues for paleoclimatic variations in eastern interior Alaska during the past 14,000 yr: atmospheric-circulation controls of regional temperature and moisture responses. Quaternary Science Reviews 20, 189–202.

Fairbanks, R.G., 1989. A 17,000-year glacio-eustatic sea level record; influence of glacial melting rates on the Younger Dryas event and deep-ocean circulation. Nature 342, 637–642.

Grosswald, M.G., Hughes, T.J., 2004. Chlorine-36 and ^{14}C chronology support a limited last glacial maximum across central Chukotka, northeastern Siberia, and no Beringian ice sheet; discussion. Quaternary Research 62, 223–226.

Hamilton, T.D., 2001. Quaternary, glacial, lacustrine, and fluvial interactions in the western Noatak Basin. Quaternary Science Reviews 20, 371–391.

Keigwin, L.D., Donnelly, J.P., Cook, M.S., Driscoll, N.W., Brigham-Grette, J., 2006. Rapid sea-level rise and Holocene climate in the Chukchi Sea. Geology 34, 861–864.

Manley, W.F., Kaufman, D.S., 2002. Alaska PaleoGlacier Atlas. Institute of Arctic and Alpine Research (INSTAAR), University of Colorado, http://instaar.colorado.edu/QGISL/ak_paleoglacier_atlas, v. 1.

Manley, W.F., 2001. Alaska North Slope 100 m Digital Elevation Model (DEM). National Snow and Ice Data Center. Digital media, Boulder, CO.

Mann, D.H., Peteet, D.M., Reanier, R.E., Kunz, M.L., 2002. Response of an arctic landscape to Lateglacial and early Holocene climatic changes: the importance of moisture. Quaternary Science Reviews 21, 997–1021.

Marren, P.M., 2005. Magnitude and frequency in proglacial rivers: a geomorphological and sedimentological perspective. Earth-Science Reviews 70, 203–251.

McManus, D.A., Creager, J.S., Echols, R.J., Holmes, M.L., 1983. The Holocene transgression of the flank of Beringia: Chukchi valley to Chukchi estuary to Chukchi Sea. In: Masters, P.M., Flemming, N.C. (Eds.), Quaternary coastlines and marine archaeology: towards the prehistory of land bridges and continental shelves. Academic Press, London, pp. 365–388.

Mock, C.J., Anderson, P.M., 1997. Some perspectives on the late Quaternary paleoclimate of Beringia. In: Isaacs, C.M., Tharp, V.L. (Eds.), Proceedings of the thirteenth annual Pacific climate (PACLIM) workshop.

Posamentier, H.W., Vail, P.R., 1988. Sea-level changes: an integrated approach. Society of Economic Paleontologists and Mineralogists Special Publication 42, 125–154.

Phillips, R.L., Barnes, P., Huner, R.E., Reiss, T.E., Rearic, D.M., 1988. Geologic investigations in the Chukchi Sea, 1984, NOAA ship SURVEYOR cruise. U.S. Geological Survey Open-File Report 88-25.

Schumm, S.A., Mosley, M.P., Weaver, W.E., 1987. Experimental fluvial geomorphology. Wiley, New York. 413 pp.