Rapid sea-level rise and Holocene climate in the Chukchi Sea

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ABSTRACT

Three new sediment cores from the Chukchi Sea preserve a record of local paleoenvironment, sedimentation, and flooding of the Chukchi Shelf (~−50 m) by glacial-eustatic sea-level rise. Radiocarbon dates on foraminifera provide the first marine evidence that the sea invaded Hope Valley (southern Chukchi Sea, −53 m) as early as 12 ka. The lack of significant sediment accumulation since ca. 7 ka in Hope Valley, southeastern Chukchi Shelf, is consistent with decreased sediment supply and fluvial discharge to the shelf as deglaciation of Alaska concluded. Abundant benthic foraminifera from a site west of Barrow Canyon indicate that surface waters were more productive 4–6 ka, and this productivity varied on centennial time scales. An offshore companion to this core contains a 20 m record of the Holocene. These results show that carefully selected core sites from the western Arctic Ocean can have a temporal resolution equal to the best cores from other regions, and that these sites can be exploited for high-resolution studies of the paleoenvironment.

Keywords: sea level, Chukchi Sea, Holocene, Bering Strait, foraminifera.

INTRODUCTION

The Chukchi Sea overlies part of the broad circum-Arctic continental shelf that was exposed when sea level fell during the Last Glacial Maximum (LGM). Understanding the history of sea level and climate in the Chukchi Sea is important because when sea level was low the climate was more continental across a vast region, and when sea level is high the flow of North Pacific water through Bering Strait (sill depth 50 m) affects the fresh water and nutrient balance of the Arctic (Aagaard and Carmack, 1989; Woodgate and Aagaard, 2005). It has been traditionally thought that humans (and other fauna) populated the Americas by migrating across the exposed continental shelf prior to flooding of the strait; however, this view has been challenged by evidence for a maritime route (Dalton, 2003; Sarnthein et al., 2006). Previous work, based mostly on terrestrial organic macrofossils identified as peat, suggests that Bering Strait was flooded ca. 11,000 yr B.P. (Elias et al., 1992, 1996).

During summer 2002, we surveyed and cored many locations in the Bering (Cook et al., 2005) and Chukchi Seas (Hill et al., 2005) to study climate and sea level. Hill et al. (2005) showed that the large mismatch between the size of buried channels on the shelf and modern discharge, and their formation during sea-level rise, indicates there must have been a significant increase in fluvial discharge during deglaciation. This might indicate the presence of significant continental ice in Alaska during the LGM. Here we report on sedimentological, geochemical, and paleontological results from shelf and slope locations in the Chukchi Sea. Hope Valley crosses the Chukchi Shelf and has a bathymetric expression in the nearshore regions of Kotzebue Sound (Fig. 1). It most likely drained a portion of the continent, yet it does not connect to the offshore drainage network described by Hill et al. (2005). Our slope sites are near Barrow Canyon off Point Barrow, Alaska, a major conduit for dense briny waters that are produced on the shelf during winter, and sediment that is resuspended by autumn and early winter storms (Weingartner et al., 1998). Our sediment cores from Hope Valley (HLY0204 01GGC/02JPC, 45 m) and the shallow site near Barrow Canyon (HLY0205 19GGC, 369 m) contain high-resolution records of Holocene climate, sea-level change, and the history of sediment source and sink for the Chukchi Shelf. Preliminary results from the deeper slope (HLY0205 15/16JPC, ~1300 m) indicate the potential for very high resolution paleoclimate studies in the Chukchi Sea.

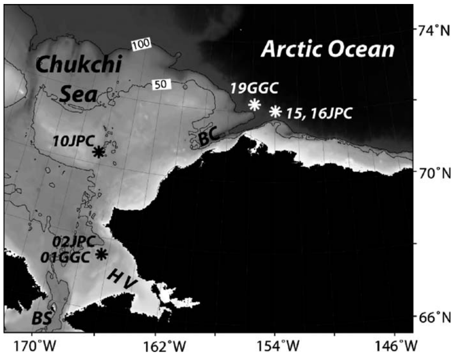

Figure 1. Chukchi Sea and surrounding regions with core locations discussed in this paper. HV—Hope Valley, BC—Barrow Canyon, BS—Bering Strait.

METHODS

Cores were sampled at 10 cm spacing for identifying the foraminiferal fauna, for dating, and for stable isotopes using methods described by Cook et al. (2005). Abundance peaks in benthic foraminifera were sampled at 1–2 cm spacing for ^{14}C dating using standard methods at the National Ocean Sciences Accelerator Mass Spectrometer facility at Woods Hole. Radiocarbon dates were calibrated to calendar years using CALIB v.5.x (Stuiver et al., 1998). Samples were taken at 1–10 cm spacing from 02JPC for grain-size measurements using a Beckman Coulter LS13320 laser diffraction particle size analyzer.

Geology; October 2006; v. 34; no. 10; p. 861–864; doi: 10.1130/G22712.1; 4 figures.

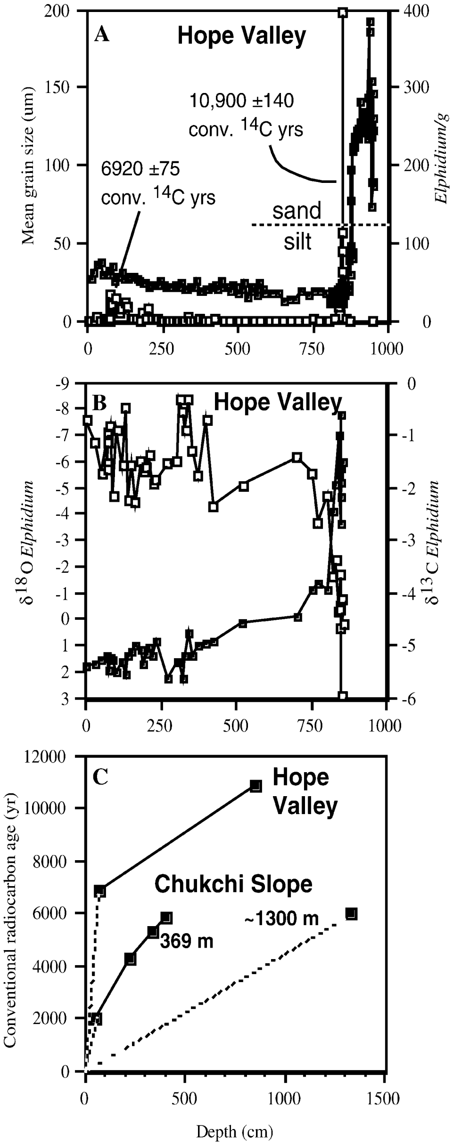

Figure 2. Paleontological and sedimentological (A), stable isotope (B), and sedimentation rate (C) evidence for sea-level change on Chukchi Shelf. In Hope Valley, sharp contact at ~850 cm marks transition in grain size (solid squares) from sandy layer that contains terrestrial plant fragments to overlying marine silt (A). Abundance peak in benthic foram *Elphidium* (open squares) dates to ca. 12 ka (calibrated). Large increase in δ^{18}O (solid squares) and decrease in δ^{13}C (open squares) of this genus indicate sudden change from nearshore brackish conditions to open marine conditions in just few centuries (B). Declining rate of sedimentation during late Holocene in both Hope Valley and on upper slope near Barrow Canyon (C) is consistent with decreased fluvial supply of sediment to Chukchi shelf. In contrast, sedimentation in deeper water off Barrow Canyon may reflect different sediment transport processes, but with only one date we can only estimate minimum Holocene rate of sedimentation of 220 cm k.y.$^{-1}$.

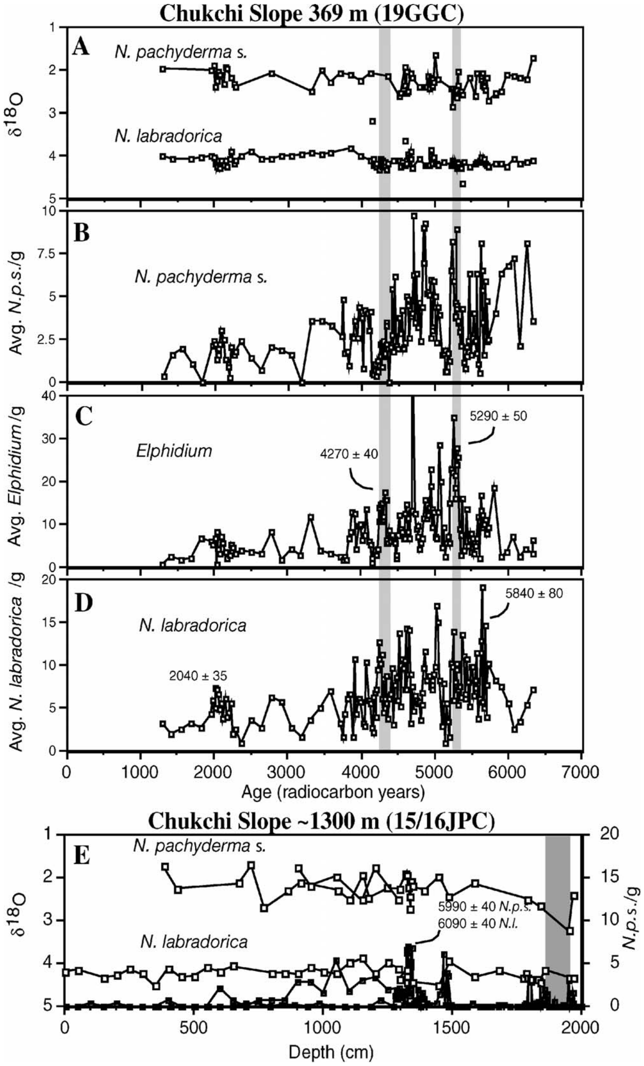

Figure 3. Stable isotope ratios and faunal counts on upper slope near Barrow Canyon (A–D) and at mid-slope location (E), and positions of ^{14}C dates (in conventional yr B.P.). As described in text, these changes may indicate centennial-scale changes in sea-surface temperature, sea ice extent, and flow of surface waters through Bering Strait. Shaded bars in A–D illustrate coherent changes in abundance patterns of foraminifera, and in E illustrate interval of ice-rafted sand and clumps of mixed lithology. N.p.s.—*Neogloboquadrina pachyderma* sinistral.

RESULTS

All data will be archived at the World Data Center for Paleoclimatology (Boulder, Colorado). In each of the cores reported on here, the Holocene section is mostly featureless clay and silt. This suggests high accumulation rates without major redeposition events. Hope Valley core 02JPC contains ~850 cm of silt overlying a unit of fine sand (Fig. 2A). *Elphidium excavatum* dominates the foraminiferal fauna, but this species is abundant only at about the 70 cm and 850 cm levels. These peaks in abundance were sampled for accelerator mass spectrometry (AMS) dating, which indicates that the silty unit was deposited beginning ca. 10,900 ± 140 ^{14}C yr B.P. (at 845.5 cm; depth of sample below mean sea level = 53.5 m). The upper peak of *E. excavatum* abundance dates from 6920 ± 75 yr (at 69.5 cm). (Unless otherwise noted, all dates are in conventional ^{14}C yr.) A companion gravity core (01GGC) from the same depth ~2 km away contains small peaks in *E. excavatum* abundance at ~200 cm, indicating that the piston core may have overpenetrated by ~1 m. Oxygen and carbon isotope ratios of *E. excavatum* reveal that profound environmental changes were associated with the lithologic change at 850 cm in 02JPC (Fig. 2B). At the abundance peak of this species the δ^{18}O was nearly −8.0‰, and assuming a linear sedimentation rate, the δ^{18}O increased by 7‰ within ~200 yr. Increasing δ^{18}O continued to the core top, but most of the remaining change occurred before 8 ka.

At several hundred meters deeper than Hope Valley, on the northwest side of Barrow Canyon, core 19GGC has a more diverse foraminiferal fauna through its 471 cm length. The fauna include the planktonic species *Neogloboquadrina pachyderma* sinistral as well as the benthic foraminifera *E. excavatum*, *Nonionella labradorica*, *Cassidulina*, and *Islandiella*. On average, these benthic genera compose >95% of the benthic fauna. Oxygen isotope ratios of *N. pachyderma* and *N. labradorica* display little long-term variability through the core, but the abundance of all foraminifera decreases from maxima before 4 ka to the core top (Fig. 3 shows only the abundance of *N. pachyderma* s., *Elphidium*, and *N.*

labradorica). AMS dating of four abundance peaks in *E. excavatum* and *N. labradorica* confirms that the core represents the late Holocene. There is good evidence of centennial-scale variability in the fauna between 4 and 6 ka, and some of that variability appears coherent. For example, all species reach maxima in abundance ca. 4.3 ka and ca. 5.3 ka, and foraminifera are uniformly rare ca. 5.2 ka. At 15/16JPC, $\sim$1000 m deeper than 19GGC, there may be similar variability in the abundance of *N. pachyderm*a s. Where sampled closely, between 1300 and 1500 cm, we find peaks in this species at $\sim$1320 (6.0 ka) and $\sim$1450 cm. These and other faunal changes near Barrow Canyon are not linked in any obvious way to the δ^{18}O record of either planktonic or benthic foraminifera.

DISCUSSION

The temporal resolution of faunal and stable isotope results discussed here is significantly greater than anything published previously from the Chukchi Sea. Typical Arctic sediments in offshore regions are thought to accumulate at $\sim$1 cm k.y.$^{-1}$, but Andrews and Dunhill (2004) described an upper slope site far to the east in the Beaufort Sea that has a rate of $\sim$130 cm k.y.$^{-1}$. A Chukchi Shelf edge core with moderate accumulation (10 cm k.y.$^{-1}$) was described by Darby et al. (2001) and de Vernal et al. (2005), but accumulation at Hope Valley, and slope locations near Barrow Canyon, can be more than 20 times greater (Fig. 3). Although we provide only one new data point for sea-level reconstruction, this is the first case where the evidence for flooding of Chukchi Shelf has been directly dated. A marine date is important because it gives a minimum age of transgression.

Sea Level

The history of Beringia sea level, and specifically that of Bering Strait, has been of interest for decades (Hopkins, 1967). Traditionally, authors used geological markers for shallow water in core samples (e.g., nearshore foraminiferal faunas or peat), coupled with ^{14}C dates on organic material (McManus and Creager, 1984; Elias et al., 1992, 1996). With the advent of AMS dating, it is possible to directly date terrestrial organic material that is usually disseminated in cores and requires wet sieving and floating to concentrate it (Elias et al., 1992). Thus, there remains some doubt that these pieces of organic material are in situ. In the Chukchi Sea, we specifically tried to core sequences with terrestrial macrofossils, yet of 17 sites cored in water depths between 44 and 107 m, none contained any beds of terrestrial macrofossils. However, in general our core sites were in deeper water and farther offshore than those of Elias et al. (1992).

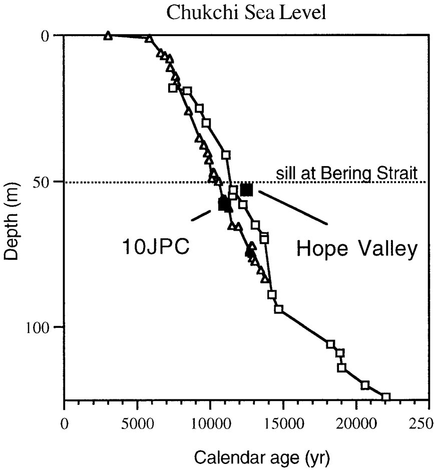

Figure 4. New sea-level data from Chukchi Sea (in calibrated yr) plotted with latest U series dates on corals (Bard et al., 1998) from Barbados (open squares) and Tahiti (open triangles). Point from 10JPC is minimum age-depth estimate because underlying terrigenous sediments were not recovered (Hill et al., 2005), whereas Hope Valley point is maximum estimate because it immediately overlies terrigenous sediments.

In Hope Valley, the dramatic increase in δ^{18}O of *E. excavatum* must reflect increased salinity, bearing in mind that the isotope effect of temperature is $\sim$0.25‰ °C^{-1}, and the sea-level effect was ~ -1.0‰ (Fig. 2B). The increase in δ^{13}C is consistent with a change from estuarine to open ocean conditions, as is the abrupt decrease in grain size (Fig. 2A). These three lines of evidence indicate flooding of the region by marine waters ca. 12 ka (calibrated) (11,261–12,371 yr; 0.996 relative area at 2σ), assuming a ΔR of 300 yr as in the Bering Sea (Cook et al., 2005). Although ΔR might have been larger, leading to a younger date for opening Bering Strait, we assume that as the -50 m isobath was flooded, it was Bering Sea water that invaded Chukchi Shelf (Fig. 1).

The record from Hope Valley is remarkably similar to the results reported by Polyak et al. (2003) from the Russian Arctic near Novaya Zemlya. At their shallower site ($\sim$35 m), δ^{18}O of *E. excavatum* increased rapidly by 8‰ ca. 8 ka as the shoreline migrated landward. Our one point cannot define a sea-level curve, but it is consistent with both a ^{14}C-dated marine mollusc from a core farther offshore (10JPC) from 55 m (Hill et al., 2005), and with the estimate from Elias et al. (1996) that Bering Strait was flooded by 11 ka. These new data show that relative sea level ca. 12 ka (calibrated) in Beringia probably did not differ significantly from the secular record defined by Barbados and Tahiti corals (Bard et al., 1998) (Fig. 4). There are several uncertainties in this simple analysis; e.g., the corals might have lived in water as deep as 5 m, the mollusc date provides only a minimum age for marine incursion, and the water depth of $\sim$53 m inferred for the *Elphidium* spike is a maximum depth. Because the uncertainties in the coral-based sea-level reconstructions are $\sim$5 m, and the foraminiferal data may be similar, isostatic rebound of as much as 10 m after 12 ka (calibrated) is possible. This uncertainty needs to be constrained by minimum depths based on dated terrestrial deposits. However, we conclude that Bering Strait and most of Chukchi Shelf was flooded by 12 ka (calibrated), at least 1 k.y. before previously thought, and that any isostatic rebound from nearby continental ice (Hill et al., 2005) was probably within the uncertainties of the data in Figure 4 ($<$10 m).

Sediment Balance on Chukchi Shelf

The sedimentary successions in Hope Valley and on the slope near Barrow Canyon record completely different processes on Chukchi Shelf. Although all three sites have high sedimentation rates, Hope Valley is probably not a site of active flow and sedimentation today (Fig. 2C), whereas from 11 ka to ca. 7 ka the average sedimentation rate was $\sim$220 cm k.y.$^{-1}$. It is unusual for greatest sediment accumulation to occur during sea-level rise (Christie-Blick and Driscoll, 1995), but it is consistent with the scenario described by Hill et al. (2005). The very high sedimentation rates during deglaciation may be evidence of both a source of sediment on land and a large fresh water supply to carry it seaward (glacial ice according to Hill et al., 2005). High riverine discharge might have been maintained until ca. 7 ka by moister climate in northeast Alaska during the early Holocene (Mann et al., 2002).

While Hope Valley was nearly nondepositional, sites near Barrow Canyon were actively accumulating because Barrow Canyon drains the Chukchi Shelf. Much of this drainage today is independent of fluvial input. Instead, it is driven by brine rejection during sea ice formation (Weingartner et al., 1998), so as long as there has been sea ice there has been a mechanism for exporting sediment from the shelf. An additional export mechanism for fine-grained sediments is the flow of turbid water associated with storm-driven resuspension. Our ^{14}C dates from 19GGC show an average sedimentation rate of $\sim$100 cm k.y.$^{-1}$ prior to ca. 4 ka, with a subsequent decrease to $\sim$60 cm k.y.$^{-1}$ until ca. 2 ka, and even lower than that to present but not nearly as low as in Hope Valley. The declining rate of sedimentation since the middle Holocene may be related to the reduced sediment supply to the shelf since 7 ka if results at Hope Valley prove to be typical at other sites on the Chukchi

Shelf. However, less sea ice during middle Holocene warmth (6–2.5 ka, according to de Vernal et al., 2005) may have led to less brine rejection, but it also might have facilitated more resuspension of sediment by storms. This process could account for higher accumulation rates earlier in the Holocene off Barrow Canyon.

Climate

Neither benthic nor planktonic $\delta^{18}O$ show much evidence of climate change in Barrow Canyon or farther offshore, yet the abundance of foraminifera is higher in the middle Holocene than later, and there is good evidence of systematic change on century time scales (Fig. 3). The exact timing of century-scale events cannot be addressed further without closer AMS dates on planktonic foraminifera. Foraminiferal abundance could be driven by dissolution, but where present, the foraminifera are generally well preserved, and the more solution-susceptible *N. pachyderma* s. undergoes abundance changes similar to more robust benthic genera such as *Elphidium*. Abundance changes on the slope could also reflect transport from the shelf, but there are no planktonic foraminifera on the shelf, and *Elphidium* is the dominant benthic genus. Instead it is more likely that the variability reflects either production of calcareous microfossils or their dissolution. Bulk density of 19GGC gradually decreases ~10% from bottom to top (~1.7 to ~1.5 g cm^{-3}), as sedimentation rates decrease (Fig. 2C). Because foraminiferal abundances are maximum deeper in the core, their accumulation rate must have been higher. Because we have argued above against preservational artifacts and transport of foraminifera, we conclude that biological production near Barrow Canyon was probably higher before 4 ka than after. Higher biological productivity during the middle Holocene is most easily explained by reduced sea ice (de Vernal et al., 2005) and a longer growing season, although we cannot rule out greater transport of nutrient-rich Pacific water through Bering Strait at that time. If middle Holocene warmth reduced sea ice extent, it may have increased the salinity of the sea surface enough to maintain relatively constant $\delta^{18}O$. Salinity would have also increased as a consequence of decreased runoff to the Chukchi Sea. Alternatively, warming may have been insufficient to raise sea-surface temperature enough to decrease the $\delta^{18}O$ of *N. pachyderma*, especially if this species lives in the marginal ice zone or in a subsurface habitat. Unfortunately, there are no quantitative data on the distribution of planktonic foraminifera in Chukchi Sea waters, although zoologists have observed more foraminifera in plankton tows from the warm summer 2004 than the colder summer 2002 (Sharon Smith, December 2005, personal commun. to Keigwin).

CONCLUSIONS

The first time-series results from very high deposition rate cores from the Chukchi Sea show the potential for developing ocean and climate histories for this region. Our geochemical, micropaleontological, and sedimentological study shows the following. (1) Bering Strait was probably flooded between ca. 11 and 12 ka, and that since that time there has been little isostatic rebound. At present this conclusion is based on a large increase in $\delta^{18}O$ in *E. excavatum* and one AMS date on this species that gives a minimum date of marine incursion at ~53 m; more dates of both terrestrial and marine carbon from cores at different water depths are required to develop a more complete history of relative sea level. (2) Very little sediment probably accumulates on the Chukchi Shelf today, compared to before ca. 7 ka, when there was greater terrigenous sediment input. (3) Higher biological productivity probably accounts for higher foraminiferal abundance near Barrow Canyon before ca. 4 ka. It is not known if this resulted from warmer surface waters (less sea ice), or greater nutrient supply from Bering Strait.

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