

New evidence from the western Canadian Arctic Archipelago for the resubmergence of Bering Strait

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Abstract

Widespread molluscan samples were collected from raised marine sediments to date the last retreat of the NW Laurentide Ice Sheet from the western Canadian Arctic Archipelago. At the head of Mercy Bay, northern Banks Island, deglacial mud at the modern coast contains *Hiatella arctica* and *Portlandia arctica* bivalves, as well as *Cyrtodaria kurriana*, previously unreported for this area. Multiple *H. arctica* and *C. kurriana* valves from this site yield a mean age of 11.5 ¹⁴C ka BP (with 740 yr marine reservoir correction). The occurrence of *C. kurriana*, a low Arctic taxon, raises questions concerning its origin, because evidence is currently lacking for a molluscan refugium in the Arctic Ocean during the last glacial maximum. Elsewhere, the oldest late glacial age available on *C. kurriana* comes from the Laptev Sea where it is <10.3 ¹⁴C ka BP and attributed to a North Atlantic source. This is 2000 cal yr younger than the Mercy Bay samples reported here, making the Laptev Sea, ~3000 km to the west, an unlikely source. An alternate route from the North Atlantic into the Canadian Arctic Archipelago was precluded by coalescent Laurentide, Inuitian and Greenland ice east of Banks Island until ~10 ¹⁴C ka BP. We conclude that the presence of *C. kurriana* on northern Banks Island records migration from the North Pacific. This requires the resubmergence of Bering Strait by 11.5 ¹⁴C ka BP, extending previous age determinations on the reconnection of the Pacific and Arctic oceans by up to 1000 yr. This renewed ingress of Pacific water likely played an important role in re-establishing Arctic Ocean surface currents, including the evacuation of thick multi-year sea ice into the North Atlantic prior to the Younger Dryas geochron.

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Introduction

During the last glacial maximum (LGM) eustatic sea level lowering (120–130 m) exposed Bering Strait, joining Russia to North America, forming the Bering Land Bridge (Hultén, 1937; Hopkins, 1967; Hopkins et al., 1982; Harrington, 2005). The resulting land mass, Beringia (Figs. 1 and 2), constituted a salient part of the paleogeography of North America/Eurasia, contributing to the peopling of North America, the exchange of fauna and flora, and climate forcing caused by its augmented continentality (Elias, 2001; Alfimov and Berman, 2001). The resubmergence of Bering Strait is attributed to the melting of ice

sheets following the LGM (18 ¹⁴C ka BP) but the timing for this remains imprecise. Current estimates are based on radiocarbon dating of the youngest terrestrial peat preserved in cores collected at its threshold sill depth, or on marine foraminifera recording the transition from terrestrial to marine sedimentation (Elias et al., 1992; Keigwin et al., 2006). Here we report new data from the western Canadian Arctic Archipelago (CAA) that provide direct dating on the re-entry of the mollusc *Cyrtodaria kurriana* into the Arctic Ocean where it lived adjacent to the retreating margin of the NW Laurentide Ice Sheet (LIS). We propose that this re-entry provides a minimum age for the resubmergence of Bering Strait that is older than previous estimates, and has important paleoclimatic and oceanographic implications regarding the reconnection of the Pacific and Arctic oceans (Bradley and England, 2008).

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Previous records of Beringian sea level and land bridge inundation

The ages of presumed lacustrine, intertidal and near-shore sediments cored from the Bering Sea Shelf were used previously to construct relative sea level curves showing initial transgression of critical sill depths within the Strait. McManus and Creager (1984) and McManus et al. (1983) concluded that the contiguous land bridge was breached as early as 16 ¹⁴C ka BP when relative sea level reached –52 m in Bering Strait (between Seward and Chukotka peninsulas) and –46 m in Anadyr Strait (between St Lawrence Island and Chukotka Peninsula) (Fig. 2). However, McManus and Creager (1984) were careful to identify constraints on their sea level reconstruction, elaborated on by Elias et al. (1996) who noted their dependence on radiocarbon dates derived from bulk samples spanning a large thickness of core section. The bulk samples also contained coal-like fragments, rendering ¹⁴C ages uncertain. Additional uncertainties resulted from the inexact relationship between dated samples in the cores and their related relative sea levels because these were based on the interpretation of benthic foraminiferal assemblages having a depth-range variance of ~10 to 20 m (McManus and Creager, 1984).

A subsequent estimate for the resubmergence of Bering Strait is based on radiocarbon-dated terrestrial peat and organic detrital silt cored from the Bering and Chukchi seas. This reconstruction of sea level change was considered to be better constrained in the Chukchi Sea, due to its reduced potential for stormwave truncation of pre-existing sediments during transgression (Elias et al., 1996). Because the amount of erosion caused by marine transgression is unknown at these sites, the preserved, uppermost peat must provide a *maximum* age on when these sites were last emergent (Elias et al., 1992, 1996). The youngest of these dates (11.0 ¹⁴C ka BP, Beta-43953, at –50 m) is ascribed to *in situ* material from a former coastal plain, purportedly “near the top of the non-marine sequence” (Elias et al., 1992, p. 373) that contains freshwater and brackish-adapted ostracods. However, these cores from the Chukchi Sea are located 400 and 600 km north of the critical thresholds of

Herald Strait (between Lisburne and Chukotka peninsulas) and Anadyr Strait, respectively, rendering uncertain their precise application to relative sea level in Bering Strait. Subsequent coring at 17 similar sites on the Chukchi Shelf (at depths of 44 to 107 m) failed to locate beds of terrestrial macrofossils (Keigwin et al., 2006).

The most recent report concerning the resubmergence of Bering Strait utilizes a core from submarine Hope Valley, Kotzebue Sound, Alaska (Keigwin et al., 2006). Within this core, at 53 m below modern sea level, an abrupt change in $\delta^{18}\text{O}$ and $\delta^{13}\text{C}$ ratios in foraminifera (*Elphidium excavatum*) is interpreted to record a rapid increase in salinity, and together with decreasing sediment grain size (from sand to silt), Keigwin et al. (2006) infer a transition from estuarine to fully marine conditions. An AMS radiocarbon date obtained on *E. excavatum*, collected at this transition, dated 10.9 ¹⁴C ka BP (including a marine reservoir correction of 300 yr, Cook et al., 2005), or ~12 cal ka BP (cal yr; 11,261–12,371 yr; 0.996 confidence at 2 sigma; Keigwin et al., 2006; Stuiver et al., 1998). This age is consistent with previous estimates for the initial resubmergence of Bering Strait based on evidence from the Chukchi Sea (Elias et al., 1996; Hill et al., 2005). It is also consistent with sea level curves derived from Barbados and Tahiti corals that imply inundation of Bering Strait sills by this time (Bard et al., 1998). However, Keigwin et al. (2006) point out that their use of stable isotopes in foraminifera to estimate paleosalinity and water depth, together with uncertainties in the coral-based sea level reconstructions (± 5 m, Bard et al., 1998), could result in errors of up to 10 m in the Hope Valley sea level record (Keigwin et al., 2006). This would translate into an error of ~500 cal yr for the transgression based on Fairbanks’ (1989) eustatic sea level curve.

Additional records pertaining to the resubmergence of Bering Strait are provided by the remains of Pacific bowhead whales (*Balaena mysticetus*) and marine molluscs collected from glacioisostatically raised marine deposits in the western CAA (Dyke and Savelle, 2001). During the LGM, the western (Pacific) population of bowhead whales was separated from the eastern (Atlantic) stock by intervening Late Pleistocene Arctic ice sheets and by pervasive sea ice on the Arctic Ocean. The reappearance of Pacific bowheads in the western CAA was delayed until 10.2 ¹⁴C ka BP (oldest available date; Dyke and Savelle, 2001) and their return provides a minimum age for the re-opening of Bering Strait. Similarly, the bivalve *Mya truncata* is also presumed to have migrated from a northern Pacific Ocean refugium at or prior to this time (Dyke et al., 1996). A Pacific source was later attributed to *Hiattella arctica* and *Portlandia arctica* collected from deglacial sediments in the western CAA (dating 13 cal ka BP; Dyke, in Kaufman et al., 2004) due to a lack of evidence for an LGM molluscan refugium in the adjacent Arctic Ocean.

New data from the western Canadian Arctic Archipelago

During fieldwork investigating the retreat of the NW LIS, we have made widespread collections of molluscs from raised marine sediments for radiocarbon dating. On northern Banks

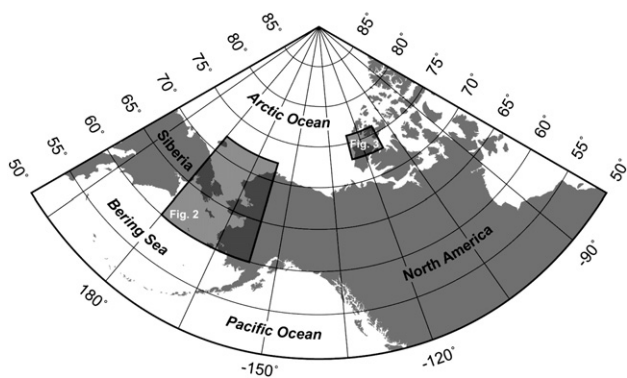


Figure 1. Northwestern North America, eastern Siberia and the western Canadian Arctic Archipelago showing the location of key sites mentioned in the text including Bering Strait and M’Clure Strait regions, insets mark locations of Figures 2 and 3.

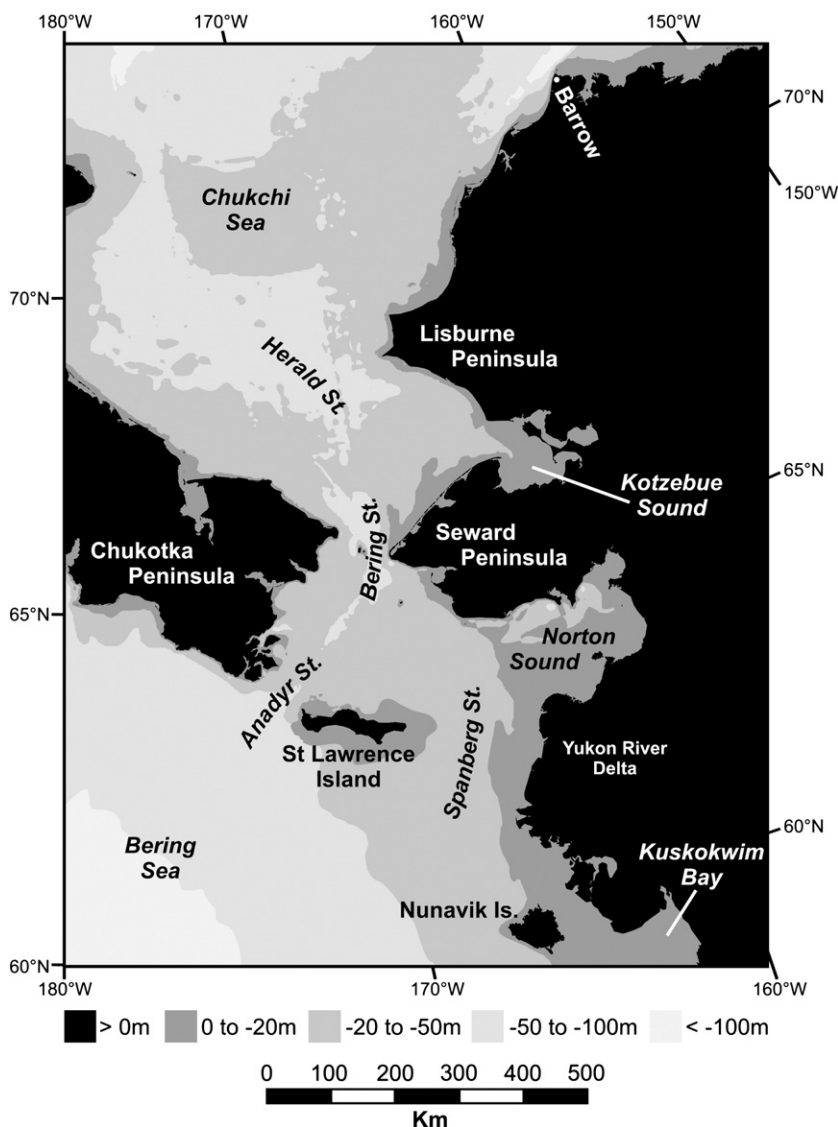


Figure 2. Modern bathymetry of Bering Strait. The 50 m isobath defines the approximate threshold for reconnection of the Bering and Chukchi seas through Bering Strait due to Late Pleistocene sea level rise. Bering Strait is an enclosed linear basin, with sills critical for Pacific–Arctic Ocean reconnection located in Anadyr and Herald straits (see inset, Fig. 1).

Island, previous reconstructions assigned the southward retreat of the LIS into the island's interior to the Thomsen Glaciation, considered to predate the last interglaciation (MIS5e, locally the Cape Collinson Interglacial; Vincent, 1982, 1983). To test this chronology, we sampled glaciomarine sediments deposited along the margin of former Thomsen ice as it retreated inland from the head of Mercy Bay, a small fiord on northern Banks Island extending southward from M'Clure Strait (Fig. 3). The deglacial marine limit at the head of the bay is marked by a prominent berm at ~48 m asl. A sand drape extends down slope from the marine limit to the coast where it overlies 1.5 m of clay that extends offshore. Three shell species occur in the clay. The first two, *H. arctica* and *P. arctica*, are widespread high Arctic species and commonly occur in deglacial sediments throughout the CAA (Dyke et al., 1996). The third, *C. kurriana* (Fig. 4), constitutes the northernmost collection of this species from late Quaternary deglacial sediments, following three decades of

widespread fieldwork investigating similar deposits throughout the Queen Elizabeth Islands to the northeast.

The unusual occurrence of *C. kurriana* immediately suggested that these deglacial sediments might be as old as originally proposed for the Thomsen Glaciation (predating MIS5e), and if so, they would be beyond the range of radiocarbon dating. However, the initial radiocarbon age (AMS) on *C. kurriana* was $12,380 \pm 110$ ^{14}C BP (TO-12496), indicating late Wisconsinan deglaciation of this site. Because of the significance of this initial age determination on *C. kurriana* to the history of the NW LIS, several additional samples from the same site were submitted for AMS dating. This included both *C. kurriana* and *H. arctica*, and for each species, multiple dates on the same individual valve were submitted to two different AMS laboratories to ensure reproducibility (Table 1). All of the resulting ages are similar, confirming the late Wisconsinan age of these deglacial sediments. These dates were then corrected for the apparent age

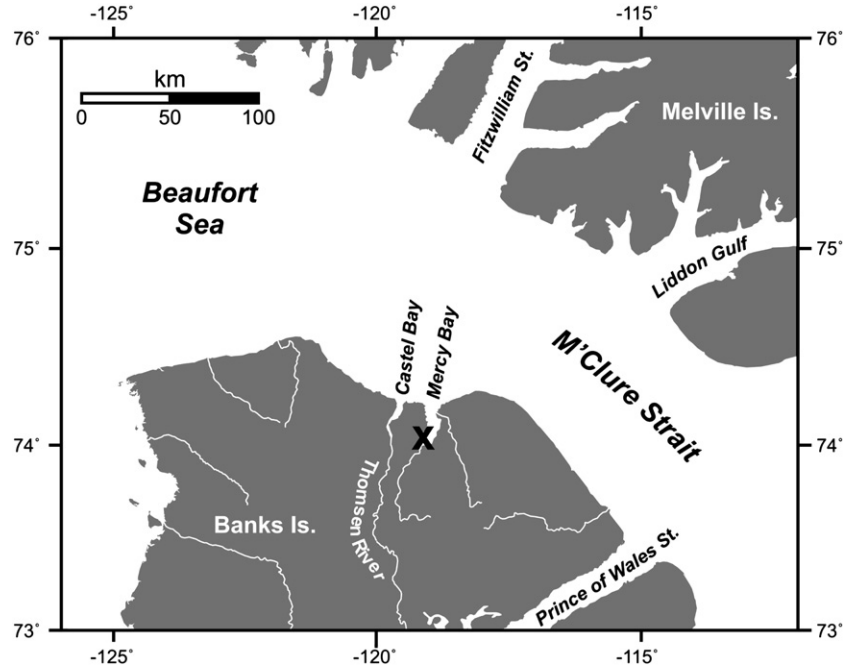


Figure 3. Northern Banks Island and M'Clure Strait, western Canadian Arctic Archipelago. X marks the molluscan site at the head of Mercy Bay on the north coast of Banks Island (see inset, Fig. 1).

of the seawater in which the shells grew (i.e., the marine reservoir effect). Recent ^{14}C dating of ~ 300 live-collected, pre-bomb molluscs from sites around Arctic North America indicates that the reservoir age for the western CAA is approximately 740 yr (Dyke et al., unpublished data). The resulting mean age of these samples is ~ 11.5 ^{14}C ka BP (reservoir-corrected), and their calibrated ages range from 13.2 to 13.4 cal ka

BP (at 2 sigma, $r > 0.95$, Calib 5.0.2; Hughen et al., 2004). Given the rarity of this species in the western CAA deglacial record, it is equally important to determine where it migrated from, especially if it originated from a refugium in the North Pacific that would require resubmergence of Bering Strait.

Discussion

Distribution and habitat of C. kurriana

The bivalve mollusc *C. kurriana* Dunker (Fig. 4; common name: Kurr propellerclam — Turgeon et al., 1988) of the family Hiatellidae is a low Arctic species of circumpolar distribution with two broad Canadian populations: an eastern one confined to the southern coast of Baffin Island and extending into northern Labrador and southwest Greenland; and a western population occupying the northern mainland coast of the Beaufort Sea, east and west of the Mackenzie Delta (Lubinsky, 1980). *C. kurriana* is a locally common suspension feeder in estuarine, deltaic and pro-deltaic environments (Ellis and Wilce, 1961; Khlebovich, 1997). It occurs in water depths of 2–50 m where it is adapted to high sedimentation, low salinity and temperatures ranging from -3 to $+6^\circ\text{C}$ (Bernard, 1983).

The reported, modern distribution of the taxon is discontinuous. While many dredge, trawl and grab-sample studies on the Beaufort and Chukchi shelves (Carey, 1979; Vilks et al., 1979; Foster et al., 1993; Feder et al., 1994) have failed to record an occurrence of the bivalve, other surveys have revealed locally abundant populations (Hulsemann, 1962; Bernard, 1979). Populations identified by Foster (1991) range semi-continuously from the north coast of Alaska ($\sim 71^\circ\text{N}$) southward through Bering Strait to Kuskokwim Bay, eastern Bering Sea ($\sim 60^\circ\text{N}$;

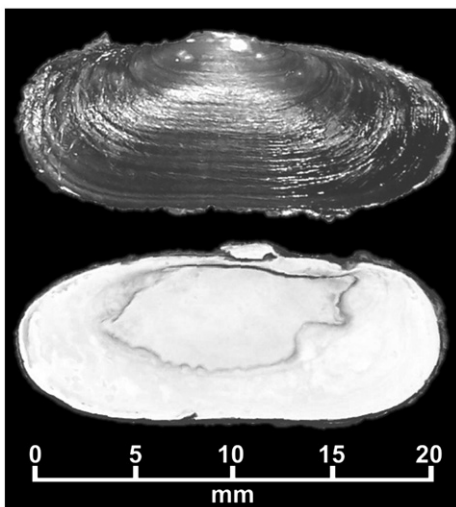


Figure 4. Right valve of *Cyrtodaria kurriana* recovered from bottomset deglacial mud in Mercy Bay, Banks Island, NWT. Preservation of specimens from the site was excellent including intact periostrica and hinge ligaments indicating that the valves were *in situ*. These samples, collected from 1.5 m asl, relate to a deglacial marine limit of approximately 48 m asl. Multiple ^{14}C AMS dates on multiple valves by two labs yielded a mean age of ~ 11.5 ^{14}C ka BP (using a marine reservoir correction of -740 yr).

Table 1
Radiocarbon (AMS) dates on molluscs from Mercy Bay deglacial bottomset clay, Banks Island, NWT

Sample number	Lab number	Bivalve species	Machine age, yr BP	Corrected age ^a , yr BP	Calibrated age ^b , yr BP to 2σ
MB-38B1-S-05	TO-12496	<i>Cyrtodaria kurriana</i>	12,380±110	11,640±110	13,280–13,730
MB-38B2-S-05	TO-12497	<i>Hiatella arctica</i>	11,970±100	11,230±100	12,930–13,280
MB-38B4-S-05	UCI-24793	<i>Cyrtodaria kurriana</i>	12,170±25	11,430±25	13,220–13,350
MB-38B5-S-05	TO-12841	<i>Cyrtodaria kurriana</i>	11,800±70	11,060±70	12,870–13,100
MB-38B6-S-05	UCI-24794	<i>Hiatella arctica</i>	12,345±30	11,605±30	13,330–13,570
MB-38B7-S-05	TO-12842	<i>Hiatella arctica</i>	11,910±100	11,170±100	12,900–13,230
MB-39-S-05	TO-12499	<i>Hiatella arctica</i>	12,220±100	11,480±100	13,140–13,560

^a Marine reservoir age correction of –740 yr (A.S. Dyke, unpublished data).

^b Calibrated using CALIB 5.1 (Stuiver and Reimer, 1993). Calibration data set: marine04 (Hughen et al., 2004).

Fig. 2). Therefore, the modern population in the Pacific Ocean appears to be confined predominantly to the Alaskan coast, north of the Aleutian Islands. The taxon's modern distribution in the western Bering Sea is unclear; however, Kuroda and Habe (1952) report records as far south as northern Japan. Elsewhere, the species is distributed eastward in the Eurasian Arctic at least to the Laptev Sea, occupying the lower reaches of Siberian estuaries (Khlebovich, 1997; Taldenkova et al., in press). Fossil records of *C. kurriana* are also known from Miocene and Pliocene sediments of northern Alaska (MacNeil, 1957) and Kamchatka Peninsula (Kafanov and Ogasawara, 2004) and from the Plio-Pleistocene Kap København Formation, North Greenland (Bennike and Böcher, 1990; Feyling-Hanssen, 1990). Other Pleistocene fossil collections of *C. kurriana* occur in pre-MIS5e deposits in NE Greenland (Funder et al., 1991; Hjort, 1981, Jensen, 1917) and in Middle Pleistocene sediments on St Lawrence Island south of the Bering Strait (Fig. 2; Hopkins et al., 1972).

Interpretation and significance of Mercy Bay samples

Several factors need to be addressed before the significance of *C. kurriana* in Mercy Bay (during deglaciation) can be determined. These include its absolute age and its preceding geographic source. The age of the *C. kurriana* collection is arguably the least contentious and it has been shown to yield concordant ¹⁴C ages by two laboratories (averaging 11.5 ka BP; Table 1). The remaining chronological question concerns the precision of these absolute ages (cal yr BP) that must include a preceding correction for the marine reservoir effect. For the Mercy Bay samples we have applied a reservoir age of 740 yr (Dyke et al., unpublished; above). It could be argued that an even larger marine reservoir age characterized the Arctic Ocean throughout MIS2 due to the glacioeustatic exclusion of Pacific water while the Arctic Ocean itself remained sealed from atmospheric CO₂ exchange by thick multi-year sea ice (Bradley and England, 2008). This would have resulted in depleted ¹⁴C input and therefore a greater reservoir age of Arctic Ocean water. This reservoir age would be further increased due to the reduced entry of Atlantic water to the Arctic Ocean during MIS2. We note that studies of late-glacial fauna in the coastal waters of the northeast Pacific Ocean indicate a reservoir correction ranging from 950±50 yr to 1200±130 yr (Hutchinson et al., 2004). This is similar to a previously proposed

correction (1.1 ka) for shells collected from glaciomarine sediments in the same area (Kovanen and Easterbrook 2002). These reservoir ages are 650 to 900 yr greater than the value applied by Keigwin et al. (2006; 300 yr) to calculate their ages on marine foraminifera attributed to the resubmergence of Bering Strait around Kotzebue Sound. Despite these uncertainties in reservoir age for the deglacial water of the western CAA, we consider the application of a reservoir correction older than 740 yr (Dyke et al. unpublished) to be arbitrary in the absence of supporting evidence.

The follow-up question concerns whether the deglacial samples of *C. kurriana* at Mercy Bay necessarily records migration from the Pacific Ocean through Bering Strait vs. other sources (Arctic or Atlantic oceans). A direct North Atlantic source through the CAA to northern Banks Island at 11.5 ¹⁴C ka BP can be ruled out because this area was fully occupied by coalescent Laurentide, Innuitian and Greenland ice until 10 ¹⁴C ka BP (Blake, 1970; Dyke et al., 2002; England et al., 2006). As for an Arctic Ocean source for *C. kurriana*, there is no documented evidence for molluscan refugia within the Arctic Ocean during the LGM (18 ¹⁴C ka BP; Kaufman et al., 2004) when its surrounding continental shelves were either exposed by glacioeustatic sea level lowering (by 120 to ≤130 m; Fairbanks, 1989; Bauch et al., 2001; Polyak et al., 2004) or covered by North American, Greenland and Eurasian ice sheets. To the contrary, available sediment cores retrieved from the Arctic Ocean that span MIS2 record intervals of minimal sedimentation that are more or less barren of fossils, supporting the existence of perennial sea ice or glacial ice shelves (Darby et al., 1997; Polyak et al., 2004, 2007; Bradley and England, 2008).

An indirect route from the North Atlantic to Banks Island for *C. kurriana* might have included eastward migration along the northern European and Russian Arctic coasts, following the so-called Northeast Passage. Although the early breakup of the marine-based Barents–Kara Sea Ice Sheet (≤15 ¹⁴C ka BP; Lubinski et al., 2001; Siegert and Dowdeswell, 2002) might have permitted such a putative, early marine migration of *C. kurriana* to Banks Island, we are unaware of any reported occurrence of this species from raised marine sediments in the Norwegian and Russian parts of the Arctic archipelago during deglaciation (Mangerud and Svendsen, 1990; Mangerud et al., 1992; Forman et al., 1997; Lubinsky, 1980). Farther east, sediment cores collected from unglaciated parts of the Laptev Sea and adjacent continental slope span water depths from 27 to

983 m. Radiocarbon dates (AMS) on 119 shell samples from these cores, after applying a mean reservoir correction of 370 ± 49 yr, document the transgression of the sea across the shelf (Bauch et al., 2001; Taldenkova et al., in press). The earliest mollusc species found in these cores (an impoverished *P. arctica*–*Thyasira gouldi* assemblage) date from 16 cal ka BP. However, the first documented occurrence of *C. kurriana* coincides with the transgression of paleovalleys on the outer shelf when relative sea level was ~ 45 m below modern. There, *C. kurriana* is first encountered, stratigraphically, 1 m above *P. arctica* that dates ~ 11.2 cal ka BP (10.3^{14}C ka BP; 520 cm depth, core PS-51/138-12, Taldenkova et al., in press). Hence, the first record of *C. kurriana* entering the Laptev Sea postdates its arrival to Banks Island (~ 13.3 cal ka BP) by 2000 yr. This is especially problematic because the Laptev Sea is >3000 km closer to *C. kurriana*'s presumed North Atlantic source. Furthermore, we are unaware of any collection of *C. kurriana* that records migration from the Laptev Sea to the Beaufort Sea where *C. kurriana* is extant. Therefore, we conclude that the most likely source for the Banks Island sample was through Bering Strait, to the south of which *C. kurriana* occurs today.

Unless new data become available that require a change in the marine reservoir age during the deglaciation of the western CAA, we accept that the ^{14}C age of both *C. kurriana* and *H. arctica* at Mercy Bay (Table 1) is $\geq 11.5^{14}\text{C}$ ka BP (≥ 13.2 – 13.4 cal ka BP). Numerous other dates on *H. arctica* collected from adjacent parts of Banks and Melville islands also cluster around 11.5^{14}C ka BP (including a 740 marine reservoir correction; England et al., submitted for publication). This places the arrival of molluscs, including *C. kurriana*, into the western CAA after meltwater pulse 1A (MWP-1A, 14.2 cal ka BP) when global eustatic sea level rise was rapidly accelerating (Fairbanks, 1989; Bard et al., 1996). Previously, Dyke et al. (1996) reported a notable diversification of the molluscan fauna (including the arrival of *M. truncata*, *Mytilus edulis*, and *Macoma balthica*) in the western CAA at 10.3^{14}C ka BP. Dyke and Savelle (2001) also reported the arrival of bowhead whales (*B. mysticetus*) in the Beaufort Sea at the same time, and attributed both lines of evidence to the initial resubmergence of Bering Strait (10.3^{14}C ka BP). However, the reported shell dates at the time (Dyke et al., 1996) were derived using a marine reservoir correction of 400 yr. These ages are equivalent to 11.2–11.7 cal ka BP if a 740 yr reservoir correction is applied. Dyke et al. (1996) also reported an earlier date (11.4^{14}C ka BP) on *M. balthica* from the coast of the Beaufort Sea (equivalent to 11.1^{14}C ka BP or 12.8–13.2 cal ka BP, using a 740 reservoir correction). Because the originally reported date on *M. balthica* coincides with a glacioeustatic sea level of -75 m (Fairbanks, 1989), Dyke et al. presumed that the 50 m sill depth of Bering Strait should have been emergent at that time. Consequently, they proposed that the *M. balthica* species could have reached the Beaufort Sea via the Eurasian shelf. However, cores collected along that proposed migration route (Laptev Sea) do not report this species between 14.4 and 11.2 cal ka BP (Taldenkova et al., in press). Therefore, we propose that *M. balthica* (if correctly dated) also arrived from the Pacific Ocean, as did

C. kurriana. This is consistent with the hypothesis of Kaufman et al. (2004) that the arrival of all shell species in the western CAA during deglaciation requires the prior resubmergence of Bering Strait in the absence of an identified molluscan refugium in the Arctic Ocean.

The Mercy Bay *C. kurriana* samples (mean age 11.5^{14}C ka BP; 13.2–13.4 cal ka BP) predate previous estimates for the resubmergence of Bering Strait based on direct stratigraphic evidence (Elias et al., 1996; Keigwin et al., 2006). This age is also older than the proposed sea level history of the Laptev Sea that places the -50 m isobath (corresponding to the approximate sill depth of Bering Strait) at only 11.1 cal ka BP (Bauch et al., 2001). The arrival of *C. kurriana* in the western CAA prior to 11.5^{14}C ka BP also indicates that relative sea level in this region was higher than currently proposed for Bering Strait by glacioeustatic reconstructions (e.g., Fairbanks, 1989). If so, this discrepancy between observed and predicted relative sea level along Bering Strait must include undocumented tectonic and/or isostatic adjustments (assuming that the reported sill depths are correct). We also emphasize that our proposed timing for the resubmergence of Bering Strait provides an improved constraint for paleoceanographic models of Arctic Ocean circulation. For example, the renewed ingress of Pacific water just prior to the Younger Dryas geochron (11 – 10^{14}C ka BP) should have contributed to the re-establishment of Arctic Ocean surface circulation, promoting evacuation of pervasive and thick landfast sea ice that developed during MIS2 into the North Atlantic (Bradley and England, 2008).

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