

The Bering Strait, Rapid Climate Change, and Land Bridge Paleoeecology

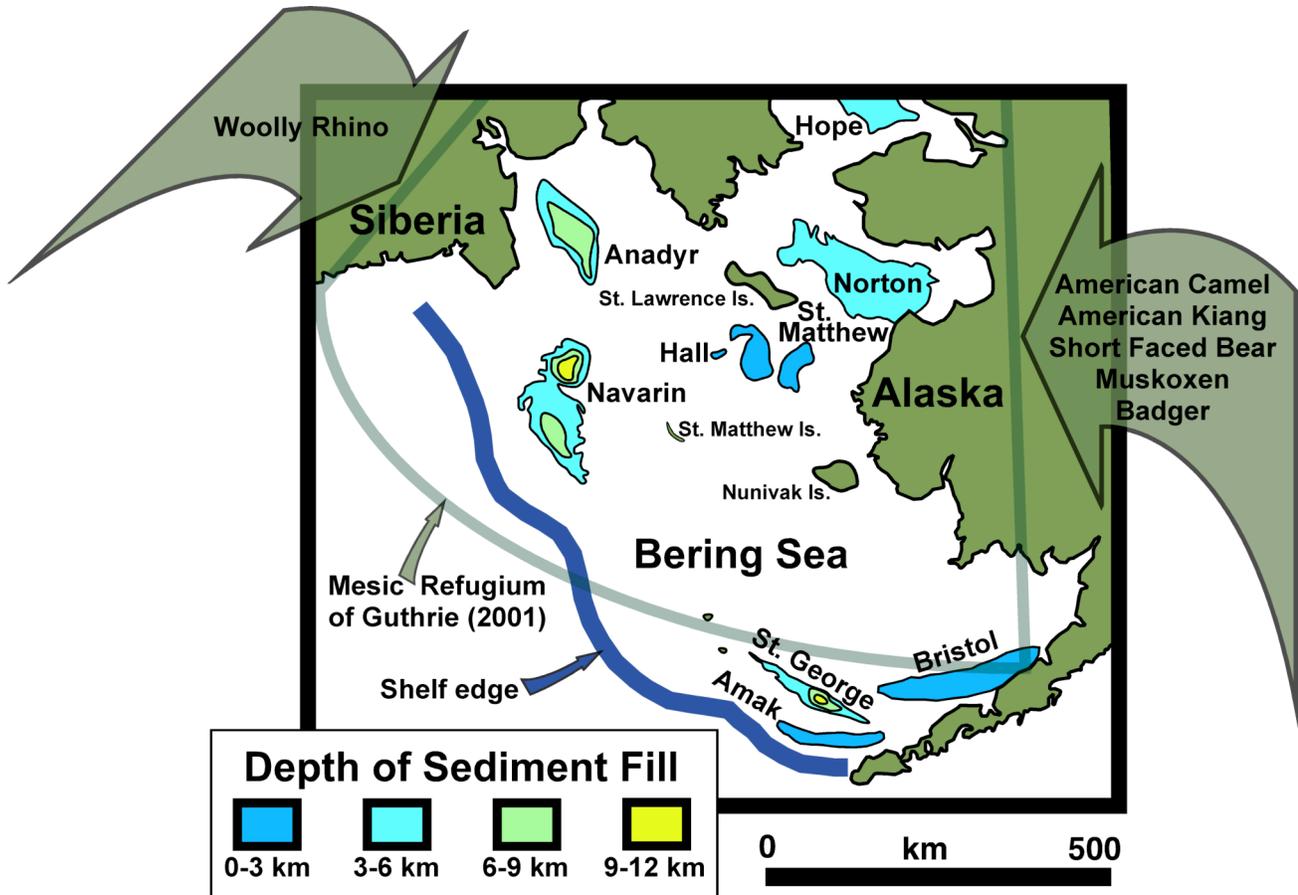


Figure 1: Distribution of Bering Shelf basins showing depth of sediment fill (after Worrall, 1991). Steppe-adapted mammals that failed to cross the Bering Land Bridge (arrows) may have been prevented from doing so by a mesic refugium (trapezoid) with a greater proportion of tundra vegetation (data from Guthrie, 2001).

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Introduction

The Bering Strait connects the Pacific and Atlantic oceans via the Arctic Ocean. This important oceanic gateway is currently a mere 50 meters deep. During low sea level stands it is emergent, forming the Bering Land Bridge connection between North America and Asia. This is the only area on Earth where the circulation between ocean basins has been blocked and a migration corridor between continental landmasses has been opened by falling sea levels of the Pliocene and Pleistocene epochs, yet scientific drilling for the purpose of paleoclimate analysis has never been conducted in the Bering Strait region. In order to address unresolved questions regarding global ocean circulation and rapid climate changes, and to permit reconstruction of the flora, fauna, and climate of the Bering Land Bridge, basinal features that contain both marine and terrestrial lacustrine sediment must be targeted.

Seismic surveys have identified eight basins in the Bering Sea that contain thick (up to 12 km) sediment sequences; a ninth, Hope Basin, is located in the southern Chukchi Sea immediately north of the Bering Strait (Fig. 1). Each of these basins contains several kilometers of seismically layered, Tertiary and Quaternary sediment (Scholl et al., 1987; Worrall, 1991; Klemperer et al., 2002) that likely include extensive non-marine sequences. Test wells in Norton Basin, immediately south of the Bering Strait, and in the more distal Navarin Basin (Fig. 1), reveal the presence of nonmarine sediment, including coal (Turner 1983a, 1983b; Turner et al., 1985). Similar nonmarine depositional units have been recovered north of the Bering Strait by coastal drilling in Kotzebue Basin (Tolson, 1987), a substructure of the larger, offshore Hope Basin. Representative seismic sections for Norton and Hope basins are displayed in Figures 2 and 3 (see pages 5 and 6).

Whereas Norton and Hope basins are most proximal to the Bering Strait, constituent records of Pleistocene and Holocene transgressions and regressions from any of the nine basins (Fig. 1) would serve to constrain temporal estimates of the opening and closing of the Bering Strait and assess its impact on Northern Hemisphere and global climate changes at orbital (20k – 400k), oceanic (hundreds to thousands of years), and anthropogenic (seasonal to millennial) time scales. Ultimately, the results of a Bering Sea coring program will further understanding of “Environmental Change, Processes, and Effects”, one of the three themes set forth in the International Ocean Drilling Project (IODP) Initial Science Plan.

Significance of the Bering Strait / Bering Land Bridge

Marine and Terrestrial Geography

Beringia is the name given to northeastern Asia, northwestern North America, and the land connection between the two regions, commonly known as the Bering Land Bridge. Historically, speculation regarding a connection between the two continents dates to the late 16th century. Centuries later, researchers noted a relationship between fluctuations in sea level and glacial advances and retreats, inspiring the concept of a dry land connection between Asia and North America. In the 1930s, the similarity of modern northeast Asian and northwestern North American floras led Hultén (1937) to propose the name “Beringia” for the land bridge. By this definition, Beringia is a Pleistocene concept.

As the land mass connecting North America and Asia and the oceanic gateway between the Arctic and North Pacific, Beringia served a critical pathway/barrier to terrestrial dispersal of plants and animals and to the mixing of Northern Hemisphere oceans for at least the past 100 Myr. As such, it had profound effects on both biogeography and paleoceanography. Pleistocene Beringia experienced the largest shifts in marine and terrestrial geography in the northern hemisphere, and these fluctuations imposed biogeographic filters between the old and new worlds, and between the North Pacific, Arctic, and North Atlantic oceans.

Cretaceous Connections

Hopkins (1967, 1996) argued that the concept of “Beringia” should be extended back in time to the mid- to early Tertiary based on floral similarities between Asia and North America. Evidence of an emergent Bering Strait during the Tertiary is provided by the presence of distinct Atlantic and Pacific mollusk and marine mammal faunas and by migration of terrestrial faunas between the old and new worlds. In addition to the land connection between these two modern continents, attributes of Beringia include: a bidirectional pattern of faunal exchange, complex vegetative zones, gregarious keystone vertebrate herbivore species, year round populations of resident vertebrates, and a paradox between the abundance of extinct fossil vertebrates and the presumed availability of forage (Hopkins, 1967, 1996; O’Neill, 2004). Each of these relevant attributes of the Beringian ecosystem extends the concept of Beringia originally proposed by Hultén (1937).

Tectonic reconstructions and striking parallels between taxon-free patterns in Cretaceous and Quaternary faunas and floras suggest that a generalized concept of Beringia can be extended back in time to the Cretaceous (Fiorillo, in press). A significant shift in emphasis of defining variables occurs with this extension. Climate, in the form of meteorological phenomena, and geologic history are important variables in the previously recognized definition of Beringian. Extension into the Cretaceous implies that Beringia is rooted in its tectonic history, rather than its climatic history. In other words, the geographic configuration produced by tectonic activity is the defining parameter for Beringia.

Coring of Cretaceous sediment beneath the Bering Sea has the potential to provide important new insights regarding climate in the early stages of Beringia, the Cretaceous vegetation of Beringia, and the complexity of vegetative zones. As more data are gathered regarding the dietary preferences and requirements of particular dinosaur groups, reconstruction of Cretaceous vegetative zones will offer innovative new insights into the details of faunal exchange between Asia and North America in the Cretaceous, facilitating comparison with the record of Quaternary exchange. Prospective drilling sites for Cretaceous records have been identified in Hope Basin, where Tertiary and older Beringian units underlie the southern Chukchi Sea in the vicinity of the Bering Strait (Figs. 2 and 3).

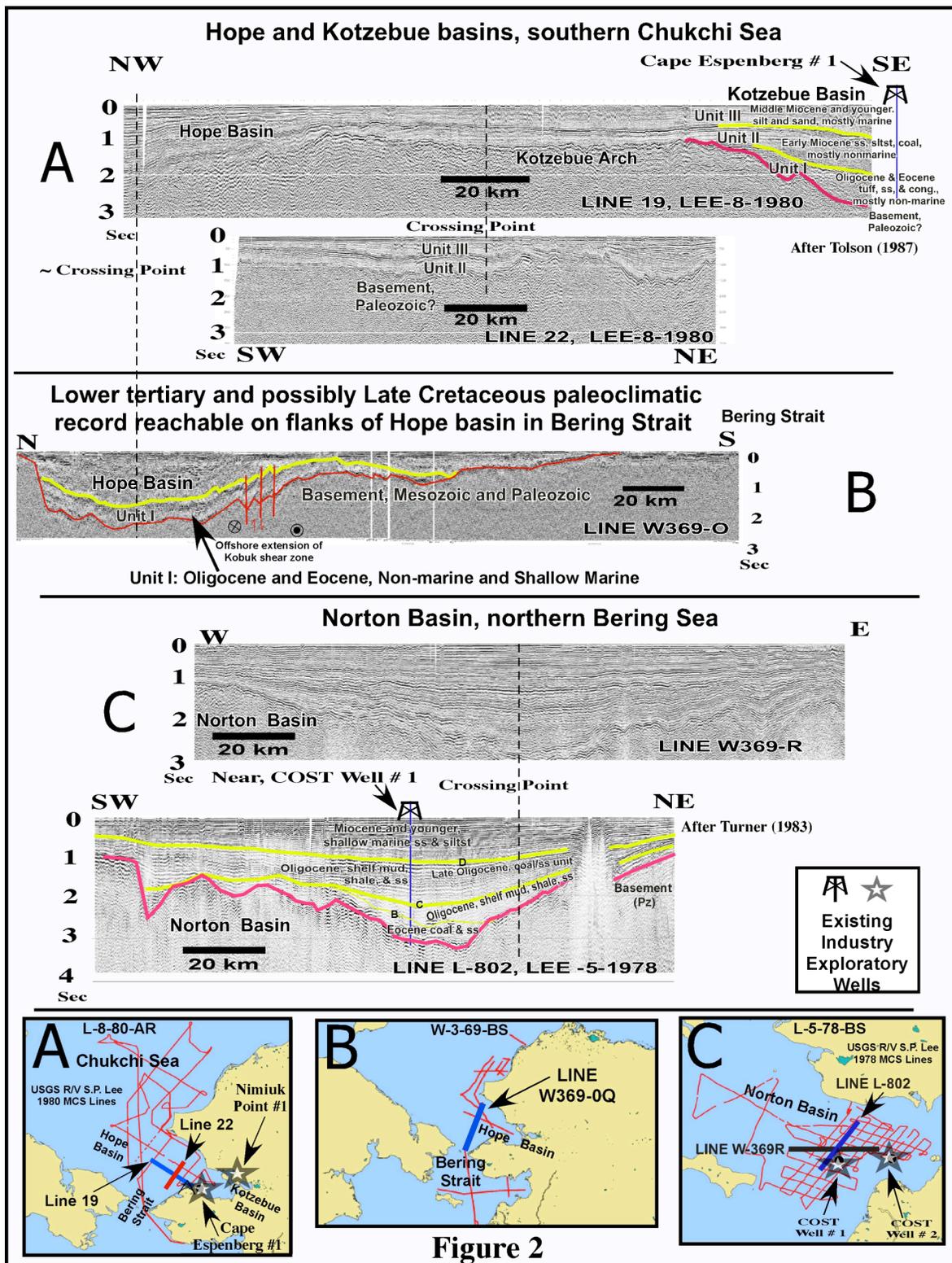
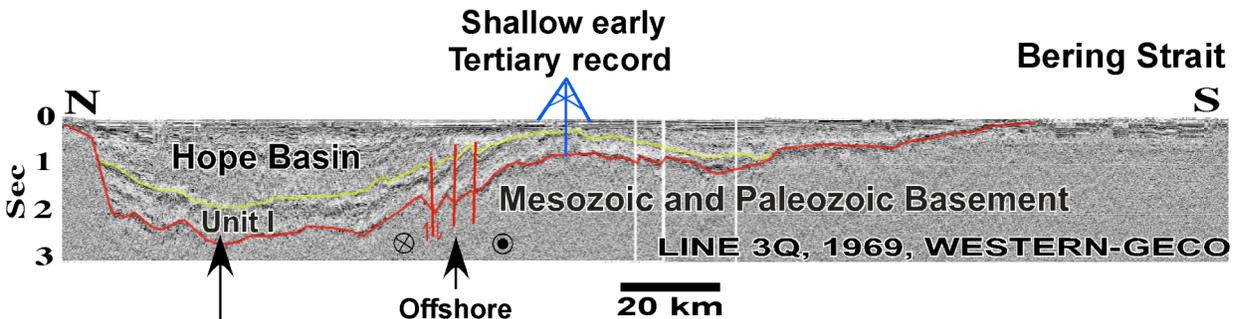


Figure 2: Representative seismic sections for Norton and Hope basins (following page), showing locations of existing industry exploration wells. Annotated stratigraphic information is based on offshore drilling in Norton Basin (Turner, 1983a,b) and offshore drilling in Kotzebue Basin (Tolson, 1987), a substructure of the larger Hope Basin.

Lower Tertiary and possibly Late Cretaceous sedimentary record recoverable on flanks of Hope Basin



Unit I:
Oligocene and Eocene tuff, sandstone, conglomerate, and coal. Lacustrine, non-marine, and shallow marine.

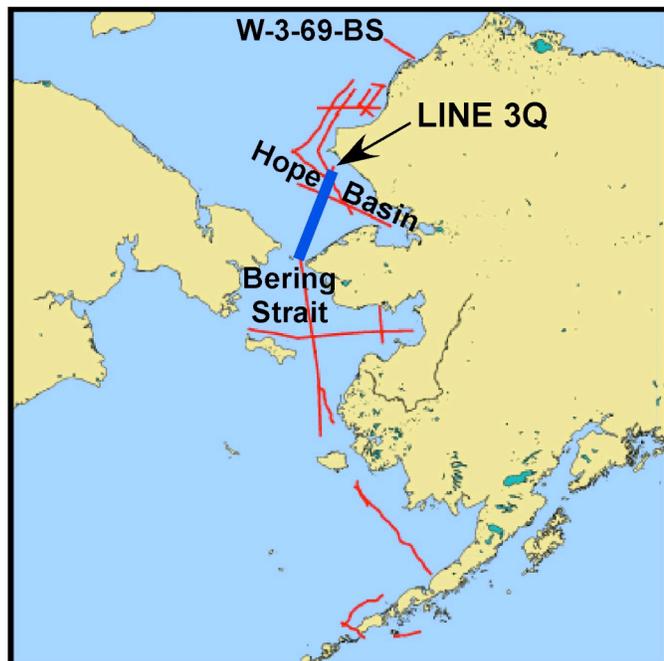


Figure 3: Representative seismic section from Hope Basin showing location of obtainable Tertiary and older sediment (blue well) where units rise and thin over the Kotzebue Arch. Annotated stratigraphic information is from Tolson (1987).

Mesic Refugium and Filter Bridge

The Bering Land Bridge served as a migration corridor for plants, animals, and humans that passed between Eurasia and North America during the Quaternary period. A sedimentary record of marine transgressions and regressions within the Bering Strait region that includes intercalated terrestrial lacustrine sediment would thus have the potential to resolve crucial questions regarding Bering Land Bridge paleoecology.

Biogeographic distributions of several Pleistocene mammal species, including the Asian woolly rhino and the American camel, short faced bear, muskoxen, and badger, end at the Bering Strait region (Fig. 1). In addition, several plant species that are rare in the strait region are distributed only on one side or the other (Murray, 1981). Apparently a barrier prevented further dispersal of these northern plant and animal species, leading to the concept of the Bering Strait region as a filter bridge (Guthrie, 2001).

Regional changes in Beringian climate and vegetation since the last glacial maximum have been reconstructed on the basis of millennial-scale analyses (e.g. Anderson and Brubaker, 1993; Ager, 1983; Ager and Brubaker, 1985; Barnosky et al., 1987; Kutzbach et al., 1998), but few continuous records from eastern Beringia extend beyond the Holocene. Cores of extant lakes in the Yukon Territory and Alaskan interior record basal ages of 15,000 years or younger (Ager, 1983; Anderson and Brubaker, 1994). However, extant lakes on the Alaskan margin of the Bering Strait were continuously present during the last glacial maximum (LGM) (Colinvaux, 1964; Anderson and Brubaker, 1994), indicating that moisture availability increased in the vicinity of the emergent lowlands of the strait (Guthrie, 2001). If it is true that the age and duration of lakes is greater in the Bering Strait region, then the Bering Sea shelf is likely to house lacustrine sediment deposited during glacial maxima.

Palynological reconstructions of relatively mesic conditions in the Bering Strait region (Anderson and Brubaker, 1994) are supported by the presence of tundra-adapted beetles in west Alaska (Elias, 1992; Elias et al., 1996) and LGM macrofossil mosses from a buried surface on the Seward Peninsula (Goetches and Birks, 2001). The mirror image of this moisture gradient existed on the Asian side of the strait (Anderson and Lozhkin, 2001). Consequently, Guthrie (2001) has proposed that, due to maritime cloud cover, the lowlands of the Bering Strait operated as a refugium for mesic-adapted species and an ecological barrier to steppe-adapted species (Fig. 1). This is an elegant hypothesis that eliminates the need for a mosaic vegetation model (Schweger, 1982) to explain the mix of steppe and tundra elements and explicates the biogeographic distributions of both arid-adapted mammals of the steppe belt and mesic-adapted plants of the Bering Strait region.

The question of whether the Bering Land Bridge served as a glacial refugium for boreal taxa has received new impetus from recent mapping work (Brubaker et al., 2005; Williams et al., 2004). Consistent, but low (< 5%) pollen frequencies of boreal taxa from early Holocene Beringia provide strong evidence that some taxa may have survived on the land bridge during the last glaciation. It seems likely that several of these taxa may have survived on the southern margin of the land bridge, where moisture was more abundant (i.e., Guthrie's "mesic buckle"). However, a conclusive test of Guthrie's (2001) mesic refugium theory requires reconstruction of the climate and ecology of the Bering Strait lowlands. This can only be accomplished by collection of terrestrial sediment from the Beringian shelf.

Human Migrations

Although theories about early human migration imply the use of subaerial continental shelves, the archaeological record, particularly that relevant to coastal adaptations and the use of boating technology, is likely to be seriously underrepresented due to the rapidly changing sea-level history of shelf environments (Erlandson, 2002). Whereas ongoing research strives to map the worldwide sea-level history and shelf environment of the last glacial cycle (LGC) (e.g. IGCP Project 464), many regions exist where data and/or research are insufficient to provide a meaningful history. The Beringian shelf is one such region.

The relevance of the Beringian continental shelf to human migration has been and continues to be a topic of significant research and debate. Limited and disparate data have resulted in contradictory interpretations by paleoecologists and paleontologists on both sides of Beringia and generated the "productivity paradox", in which late

Pleistocene megafauna seemed to thrive on the limited biomass productivity of tundra vegetation (see Hopkins et al., 1982). The sea-level history is uncertain and varies both through time and across the region. Although global eustatic sea-level curves continue to be developed and refined (e.g. Lambeck et al., 2002; Cutler et al., 2003), they remain limited in their regional application. These curves are especially problematic in high-latitude regions where glacio-isostatic responses result in disparate sea-level curves for locally proximal sites (e.g., Hetherington and Barrie, 2004; Hetherington et al., 2004). Furthermore, the Bering Strait region is characterized by tectonic activity, in particular crustal extension (Mackey et al., 1997). Rifting and crustal subsidence in the late Miocene led to the late Cenozoic opening of the Bering Strait (Marincovich and Glandenkov, 1999, 2001; Glandenkov and Glandenkov, 1994), probably as a far-field tectonic consequence of the collision of the Yakutat block with the eastern end of the Alaska subduction zone (Mackey et al., 1977; Scholl and Redfield, 2006). Hence far-field plate boundary driven processes could also have modulated the flooding history of the Bering Strait.

Despite ongoing research, there currently exists little substantive evidence regarding the environment, history of exposure, and inundation of Beringia. In addition to far-field tectonics and changes in sea level, the Beringian shelf was affected by changes in sea-ice cover (e.g. Vavrus, 1999) and shifts in land surface albedo resulting from fluctuating snow cover (Bonan et al., 1992; Foley et al., 1994; Berger, 2001). Acquisition of these data is critical to ascertaining the role of the region in initiating and perhaps constraining human migration, and hence its role in the peopling of the Americas.

Global Climate Change

Millennial-scale climate events and abrupt changes in ocean circulation cannot be fully understood nor adequately modeled until intervals of emergence of the Bering Land Bridge are accurately dated and the effects of circulation from the Pacific to the North Atlantic through the Bering Strait are quantified. Climate records from the last glacial cycle (125,000 – 10,000 years ago) reveal large-amplitude, millennial-scale oscillations known as Dansgaard/Oeschger (D/O) cycles and Heinrich events (Bond et al., 1993; Labeyrie, 2000). To explain these oscillations, Broecker et al. (1985) suggest that discharge of icebergs into the north Atlantic results in a freshwater anomaly that suppresses formation of North Atlantic Deep Water (NADW), abruptly returning northern Atlantic climates to their glacial state. Broecker's (1987a) ocean "conveyor belt" balances the freshwater budget of the North Atlantic by exiting NADW and its fresher return flow, but this model fails to incorporate the freshwater pathway from the Pacific to the Atlantic via the Bering Strait (Wijffels et al., 1992).

Studies of global ocean circulation have demonstrated a net flux of relatively fresh water (~1ppm less saline than North Atlantic water) from the North Pacific to the North Atlantic through the Bering Strait (Stigebrandt, 1984; Wijffels et al., 1992) at a rate of 0.8 Sverdrups per year (McRoy, pers. commun., 2004). Today, this flux of less saline Pacific water accounts for nearly one-third of the total freshwater input to the Arctic Ocean, half that provided by riverine inputs (Brigham-Grette et al., 2003). Freshening of the North Pacific and Bering Sea via glacial runoff and riverine inputs into the westward flowing Alaska Stream likely began during the late Miocene, when entrance of the Yakutat block into the eastern end of the Alaska Trench led to the onset of mountain

building in the Gulf of Alaska (Scholl et al., 2003). The rising Yakutat orogen interrupted the eastward flow of atmospheric moisture moving across the North Pacific onto the North American continent. Mountain systems of southeastern Alaska are thus drenched with an annual rainfall of 150-200 inches (~4-5 meters), the bulk of which returns to the North Pacific via the Alaska Stream, which spills into the Bering Sea through passes between the Aleutian Islands (Fig. 4) (Scholl et al., 2005).

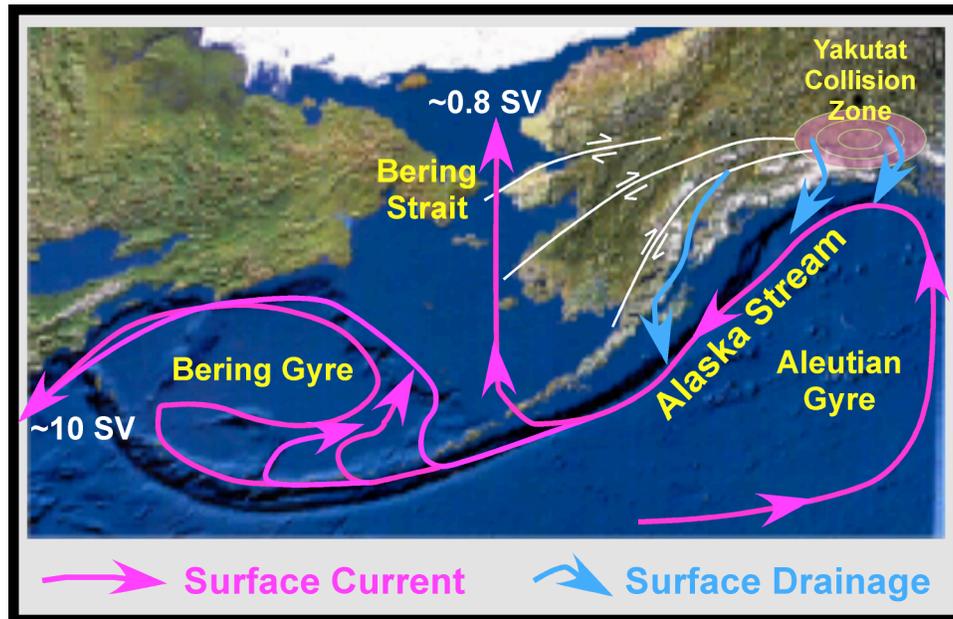


Figure 4: Circulation of surface water in the northern Pacific and Bering Strait, showing transport of freshwater runoff from the Gulf of Alaska to the Bering Sea via the Alaska Stream.

Models indicate that increased flow of fresher North Pacific water through the submerged Bering Strait can lead to suppression of NADW formation (Shaffer and Bendtsen, 1994). Whereas the simulations of Shaffer and Bendtsen (1994) indicate that decreased flow through the Bering Strait does not necessarily cause NADW formation to resume, Wijffels et al. (1992) suggest that cutoff of the Bering Strait freshwater pathway during intervals of low sea level may have provided a negative feedback to glaciation by allowing North Atlantic salinities to increase, thus strengthening thermohaline circulation. Conversely, Stigebrandt (1981) notes that pack ice in the Arctic Ocean is secured by inflow of low-salinity Pacific water. Significant reduction of this flow during glacial periods would promote disappearance of Arctic pack ice, possibly triggering growth of northern glaciers (Stigebrandt, 1984).

Opening and closing of the Bering Strait may also have profound implications for climatic stability and the duration of climatic perturbations induced by freshening of the north Atlantic. Shaffer and Bendtsen (1994) conclude that higher sea levels led to greater flow through the Bering Strait during the last interglacial period, heightening sensitivity of thermohaline circulation to fluctuations in the hydrologic cycle. Increased flow through the Bering Strait may thus promote rapid Northern Hemisphere cooling during warm, interglacial periods and explain the climatic variability of the last interglacial

relative to the Holocene (Shaffer and Bendtsen, 1994). However, the analytical ocean model of De Boer and Nof (2004) indicates that perturbations in NADW are quickly damped out during interglacial periods, when the Bering Strait is open. Closure of the Bering Strait during glacial periods traps freshwater anomalies in the Atlantic, prolonging climate oscillations.

The opening and closing of the Bering Strait, which is controlled both by global eustatic and regional tectonic processes, clearly has global climatic implications with regard to the cause and the duration of glacial and interglacial climatic oscillations. Yet the numerous and sometimes contradictory models cannot be adequately tested because an accurate chronology of the emergence and submergence of the strait is lacking. Reconstructions of the sea level history and salinity of the Bering Strait, including the exact timing of the opening and closing of the land bridge, the rates of associated sea level changes, and the arrival of orogenically delivered freshened surface water are essential to understanding its role as a trigger, pacemaker, or benign observer of northern hemisphere climate changes.

Explosive Volcanism

Tephra ejected from volcanoes in the Aleutian Islands, Wrangell Mountains, and Kamchatka is present in terrestrial sediment throughout Beringia. Identification and dating of new and previously recognized tephra units from terrestrial or marine sediment of the Bering Strait will further enhance understanding of the chronology of Quaternary eruptions and their role in rapid global climate changes. Correlation of volcanic eruptions recorded in Greenland ice cores with episodes of global cooling indicates that explosive volcanism has the potential to impact global climate on annual to decadal time scales. Whereas the source areas of many eruptions represented by elevated acidity levels in Greenland ice are not known (Zielenski et al., 1994), volcanic glass and tephra recovered from the North Pacific (Ocean Drilling Leg 145) record an increase in explosive volcanism in the Kamchatka-Kurile and Aleutian arcs during the Late Pliocene (Prueher and Rea, 1998, 2001a, 2001b). Comparison of mass accumulation rates of volcanic glass and ice-rafted debris (IRD) reveals a marked increase in flux of volcanic glass throughout the North Pacific at 2.65 Ma, just prior to an increase in the flux of IRD (Prueher and Rea, 2001b). Subsequent episodes of volcanism are recorded during the Pleistocene (Prueher and Rea, 2001a). These data suggest that Late Pliocene cooling and, ultimately, Northern Hemisphere glaciation may have been triggered by explosive eruptions of North Pacific volcanoes (Prueher and Rea, 1998, 2001b).

The Bering Strait region lies in the path of ash clouds produced by explosive eruption of volcanoes in the Kamchatka-Kurile volcanic arc and, to a lesser degree, the Aleutian arc and Wrangell-St. Elias mountains (to view animated time series of ash dispersal for three decades of North Pacific eruptions, visit the Puff volcanic ash tracking model website at <http://puff.images.alaska.edu/30yrseries.shtml>). Geochemical characterization of tephra from Bering Sea cores could enhance records of the frequency, magnitude, and timing of volcanic eruptions in Alaska and Kamchatka and permit correlation of ash deposits with records of IRD, SST, sea-ice extent, and/or terrestrial vegetation. Furthermore, geochemical characterization of volcanic ash deposits has the potential to provide precise correlations between terrestrial and marine deposits throughout Beringia and the Bering Sea.

Key Scientific Questions

Paleoecology

- ◆ How did the Bering Land Bridge serve as a biological filter for terrestrial animals, plants, and humans? Were climate and ecology of the central lowlands sufficiently different to prevent some animals and plants from crossing during times of emergence?
- ◆ Would lowland regions have been a suitable or desirable habitat for humans?
- ◆ Did the Bering Land Bridge serve as a glacial refugium for boreal taxa such as spruce, alder, and birch?
- ◆ Is there evidence of a N-S climate gradient during the LGM and/or earlier intervals of emergence?
- ◆ How long has the uniquely Beringian ecological structure been in place? How, and how long, do animal guilds survive at these latitudes?
- ◆ How does recycling/pedogenesis of marine sediment affect productivity, vegetation cover, and loess accumulation on the exposed land bridge?

Global Paleoclimate

- ◆ What is the effect of an open Bering Strait on NADW formation?
- ◆ Does an open Bering Strait promote, moderate, or terminate northern hemisphere glaciation?
- ◆ Does an open Bering Strait accelerate or deter sea-ice formation in the Bering Sea?
- ◆ What is the role of sea ice in high latitude and global climate change?
- ◆ When did the strait open following the LGM?
- ◆ When did previous intervals of emergence occur?
- ◆ Is there a relationship between water depth in the strait and initiation/termination of global climate changes (e.g. Pliocene cooling)?
- ◆ Is there a relationship between explosive eruptions in the Aleutian Islands, Wrangell Mountains, and/or Kamchatka, intervals of rapid global cooling or drought, and dust and sulfur in the Greenland ice cores?

Paleoceanography

- ◆ Was the Late Miocene opening of the Bering Strait a far field effect of Yakutat orogenesis in southeast Alaska?
- ◆ Has salinity of the North Pacific changed over time? Did collision of the Yakutat Block in the Miocene alter the salinity of surface water flowing through the Bering Strait into the Arctic Ocean?
- ◆ When were water depths in the Bering Strait deep enough to allow net export of water to the Arctic Ocean, once northward flow was initiated after closure of the Panama Strait?
- ◆ When was sea ice present in the Bering Strait?

- ◆ What is the sea surface temperature (SST) history of water in the open Bering Strait?
- ◆ How does migration of various marine animals (diatoms, mollusks, whales) through the Bering Strait relate to water depth? Can appearance of these animals be considered a proxy for paleo-water depth? Are migration rates slow or geologically instantaneous?

Targets and Platforms

Primarily as a consequence of exploratory studies for offshore metal and energy resources, a large library of seismic reflection profiles exists for the Chukchi and Bering Seas, in particular for shelf basins (Fig. 2). These include Hope and Norton basins immediately north and south, respectively, of the strait, and more distal basins, such as Anadyr, Hall-St. Matthew, Navarin, St. George, and Bristol basins on the Bering Sea shelf. The locations of most of these seismic lines can be viewed at these two web sites:

- 1) <http://walrus.wr.usgs.gov/infobank/programs/html/regions2html/regions.html>.
- 2) <http://walrus.wr.usgs.gov/NAMSS/>

Most of the pre-1970 library of seismic data consists of analog (paper) single-channel (SCS) records gathered by the USGS and academia, principally the University of Washington. Beginning in the late 1960s, digital multichannel (MCS) data were collected by industry and later, in the mid 1970s, by the USGS. In 2005 the USGS began to acquire multichannel data gathered by industry over Bering and Chukchi shelf basins. This information, including example reflection profiles, is being placed in the public record (see web site # 2, above).

Workshop participants concur that, by virtue of proximity to the Bering Strait, sedimentary records from Hope and Norton basins have the greatest potential to answer questions regarding the paleoecology and timing of emergence of the Bering Land Bridge. However, some distal Bering Sea shelf basins have a greater depth of sediment fill (e.g. Navarin and St. George basins, see Fig. 1). These basins could provide longer records of Cretaceous terrestrial paleoecology and more complete records of Plio-Pleistocene marine sediment and proxies, facilitating calibration of discontinuous marine sections from Hope and Norton basins. Furthermore, collection of records from *both* proximal basins *and* basins on the shelf edge would permit estimation of the rates of sea level change during emergence and submergence of the strait and delimit tectonic evolution of the Bering Sea. Finally, shelf edge basins lie in the path of proposed human coastal migration routes and thus stand to provide crucial information regarding intervals of emergence and ice cover.

Norton and Hope Basins

Based on seismic data and test wells, Pleistocene basin-fill sequences in Norton and Hope basins are estimated to range from 100-300 m in thickness. Norton Basin's data archive includes non-proprietary, high-resolution seismic profiles and information from exploration wells collected and drilled by industry and maintained by the U.S. Minerals Management Service. Although these Continental Offshore Stratigraphic Test (COST) wells and exploratory wells did not core the late Cenozoic section, cuttings provide some indication of the lithology and age of the Quaternary sediment. COST Well #1 (~63.8°N, 166°W, 59 m water depth) penetrated 2.8 km of upper Eocene to middle Miocene

sediment, which was overlain unconformably by ~ 1 km of upper Miocene and Quaternary silt and silty sand. Non-marine Upper Cretaceous sediment was recovered beneath a regional unconformity (the ~43 Ma Eocene “red” event). A similar sequence was obtained from Norton COST Well #2, drilled ~56 km to the east of COST Well #1 in 149 m of water (Turner, 1983a, 1983b). Age control is provided by diatoms, pollen, and calcareous nannofossils. Benthic foraminifera in both wells record the deepest paleodepths (middle to outer neritic) during the late Oligocene (Turner, 1983a, 1983b). Cores collected near the center of Norton Basin will thus provide a record of Eocene, Miocene, and Plio-Pleistocene sediment accumulation south of the modern Bering Strait.

Faulting and uplift on the flanks of Hope Basin have delivered Paleogene and possibly Cretaceous sediment to depths of ~600 m below the basin surface where these units rise over and thin against the Kotzebue Arch. Thus, a north-to-south transect of cores with 800 m penetration could sample an expanded Miocene and younger section in the center of the Hope Basin and condensed Oligocene, Eocene, and possibly Cretaceous units on the basin margin adjacent to the northern Bering Strait (Figs. 2 and 3).

Platforms

The combination of USGS and industry-collected MCS data and published stratigraphic information extracted from exploratory offshore drill holes in Navarin, St. George, Bristol, and Norton basins (Bering Sea COST wells), and coastal wells in Hope Basin, provides sufficient information to select drilling sites at which scientific objectives can be achieved. Primary and alternative sites can be selected at crossing MSC lines.

Scientific drilling in deeper waters (500-4000 m) of the Bering Sea Basin to the south and the Chukchi Cap to the north can be sited along digitally recorded SCS or MSC reflection profiles. Some industry data is available for the slopes and northern abyssal floor of the Bering Sea Basin, but records for off-shelf locations elsewhere are principally archived by the USGS. Identification of drilling sites at both shelf and off-shelf sites would benefit from special seismic processing to enhance the resolution of the stratigraphic and structural fabric of the upper 300-400 m of basinal sequences.

Workshop deliberations identified the need for subsurface core samples and in-situ data from the Bering and Chukchi seas to address three principal scientific themes, (1) late Cenozoic and older paleoclimatic-oceanographic evolution, (2) Mesozoic and Cenozoic tectonic evolution, and (3) late Quaternary geo-archeology. These general topical matters and linked sub-thematic categories are listed in Table 1 (above). Described opposite these entries are comments about the adequacy of existing data to identify drilling sites where desired sediment cores and downhole measurements can be gathered, and the type of drilling platforms that can provide them. These platforms include a JR-class riserless drilling vessel and a multitude of Mission Specific Platforms (MSP).

Table 1: Targets and Platforms

| Primary Science Focus | Status of Site Selection Data | Sampling/Drilling Platform Type |
|---------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------|-----------------------------------------------------------|
| Paleoclimate / Paleoceanography of the Bering and Chukchi Shelves | | |
| Late Neogene and younger 50 – 100 m water depth | USGS and industry seismic lines Enhanced high resolution processing needed | Mission Specific Platform (MSP) or Joides Resolution (JR) |
| Late Cretaceous and Paleogene 50 – 150 m water depth | USGS and industry seismic lines Enhanced high resolution processing needed | MSP or JR |
| Regional Tectonics: Mesozoic and Cenozoic Evolution of the Bering and Chukchi Seas | | |
| Bering Sea Basin floor 3500-4000 m depth and Bering Sea Basin continental slopes/Umnak Plateau | USGS and industry seismic lines Enhanced high resolution processing needed | JR (may not need riser) |
| Bering/Chukchi Shelves 50 – 150 m water depth | USGS and industry seismic lines Enhanced high resolution processing needed | MSP or JR (hard rock drilling) |
| Chukchi Cap 500 - 1500 m water depth | Have necessary data (USGS) | MSP or JR (ice breaker escort) |
| Geo-Archeology | Need high resolution data: Swathmapping, AUV and ROV observations | MSP |

Complementary Projects and Proposals

Integrated Ocean Drilling Project Proposal 477Full4

IODP proposal 477Full4 is complementary to proposed drilling of sedimentary basins in the Bering and Chukchi seas. Proposal 477Full4 includes distal Bering Sea coring sites in order to obtain a continuous record of marine sedimentation and oceanographic conditions. A primary goal of this proposal is to link marginal basin processes to open Pacific marine and climate records over the last several million years.

Highlights of IODP proposal 477Full4 include:

- ◆ The extent of North Pacific Intermediate Water (NPIW) formation, part of which occurs in the Bering Sea, particularly during glacial intervals. The NPIW is a large and climatically important water mass; formation extent of the NPIW has a profound effect on global circulation, including the global conveyor belt system proposed by Broecker (1987b).
- ◆ The Bering-Arctic-Atlantic gateway connection. Current differences between deep and bottom water mass characters (e.g., chemical properties such as nutrient contents) of the Pacific and the Atlantic Oceans are in part due to the one-way flow of Bering Sea water through the Bering Strait into the Arctic Ocean. This flow affects the conveyor belt system (e.g. NADW) and, in turn, global circulation. Past global circulation, for instance during the glacial intervals, was very different. Changes in circulation were caused, in part, by the lack of Bering Sea flow into the Arctic Ocean due to falling sea level and emergence of the Bering Land Bridge.
- ◆ Surface circulation, sea-ice distribution, and productivity changes. Surface circulation in the Bering Sea is directly linked to the behavior of two major water masses: the Alaskan Stream water mass, which currently enters the Bering Sea through the Aleutian passes; and Bering Sea water exiting to the Arctic Ocean via the Chukchi Sea. Modulation of these water mass exchanges significantly affects sea-ice distribution and biological productivity. Relevant proxies include diatoms and radiolarians, siliceous plankton ubiquitous in the Bering Sea (Katsuki and Takahashi, 2005; Tanaka and Takahashi, 2005). Some species of diatoms, especially ice algae, can be used to reconstruct sea-ice conditions. Due to the wide variety of radiolarians living at surface (e.g. 0-50m) and intermediate (e.g. 300-800m) water depths, radiolarians can be used to reconstruct past subsurface water mass distributions. Planktonic and benthic foraminifera, primarily carbonaceous microplankton, are crucial for correlation and chronology. Past studies have shown that they are preserved in the Bering Sea and extremely useful for biostratigraphy, although their preservation states vary significantly depending on water depths (Okada et al., 2005; Okazaki et al., 2005).

Acquisition of continuous marine records from distal Bering Sea basins will facilitate dating of discontinuous records from proximal Bering Sea shelf basins, provide a biostratigraphic link between the Bering Strait and North Pacific, and permit comprehensive reconstruction of Bering Sea circulation, sea-ice cover, and gateway dynamics. Hence IODP proposal 477Full4 complements and augments the biostratigraphic, paleoclimatic, and paleoceanographic goals of a Bering Sea shelf and/or Bering Strait coring project. An IODP drilling expedition to address the science of proposal 477Full4 is presently scheduled for the summer of 2008.

Paleoceanography of the Arctic Ocean

Sea level records recovered from scientific drilling in Bering Sea basins will place important boundary conditions on the oceanographic evolution of the Arctic Ocean. When the Bering Strait is emergent, one of the three primary inputs of water to the Amerasian Basin (Bering Strait, Fram Strait, and riverine) will be cut off, altering the chemistry and circulation of the Arctic Ocean.

To fully understand the impact of these changes, it will be necessary to recover complementary records of Arctic Ocean evolution through scientific coring. In August 2004, the IODP conducted the first Arctic Coring Expedition (ACEX; IODP Leg 302) and acquired more than 400m of sediment core from the Lomonosov ridge (Moran et al., 2006). Paleoclimatic analyses of the relatively continuous Paleogene and Neogene sections of the sedimentary record include the following highlights:

- ◆ Presence of fresh surface waters in the middle Eocene (~ 49 Myr) Arctic Ocean are indicated by abundant remains of the freshwater fern *Azolla*. SSTs were estimated by applying the TEX₈₆ index, an organic paleothermometer that is independent of salinity. Relatively low SSTs associated with in situ *Azolla* growth indicate lack of transport from adjacent seas, primarily the North Atlantic. Termination of the *Azolla* phase is accompanied by a local SST increase of ~3°C, recording renewed transport of heat and salt from the North Atlantic into the Arctic (Brinkhuis et al., 2006).
- ◆ The presence of IRD in the Arctic Ocean during the middle Eocene (~ 45 Myr ago) provides evidence of Arctic cooling and proximal glaciers some 35 Myr earlier than previously thought. Therefore, Paleogene cooling was likely bipolar, with contemporaneous evolution of ice on both poles. Synchronous ice development at the poles suggests that global cooling was driven primarily by greenhouse gases rather than tectonic changes (Moran et al., 2006).
- ◆ Neogene pulses of IRD record episodes of Arctic cooling coincident with the expansion of East Antarctic ice (~14 Myr ago) and Greenland ice (~3.2 Myr ago). These data suggest that increased albedo from Arctic sea ice growth may have contributed substantially to Pliocene cooling and glacial ice expansion in the Northern Hemisphere (Moran et al., 2006).

Following the success of the ACEX drilling on the Lomonosov Ridge, at least two proponent groups have formed to advocate further scientific drilling in the Arctic Ocean, on the Chukchi Plateau and on the Mendeleev Ridge. Cores recovered from these bathymetric elevations will complement the existing Lomonosov Ridge record, enhance the significance of records recovered from Bering Sea basins, and clarify relationships between freshening of Arctic Ocean surface water, opening of the Bering Strait, sea ice growth, and Neogene episodes of global cooling.

Chronology and Correlation

Dating of intercalated terrestrial and marine deposits presents a challenge in that sedimentation is not continuous and unconformities due to marine transgressions and subaerial erosion will be encountered. In order to surmount problems caused by depositional hiatuses and reworking, members of the chronology breakout group recommend integration of established dating methods with overlapping temporal resolutions and application of relatively novel techniques for dating exposed surfaces such as unconformities and paleosols (Tables 2-4). Specific methods are discussed below, with greater detail provided for novel or experimental techniques.

Table 2: Dating Methods

| Method | Dating Range | Material | Application |
|------------------------------------|-----------------|------------------------------------------|----------------------|
| Biostratigraphy | 0 – 80+ Myr | Diatoms, pollen, spores, dinoflagellates | Marine & Terrestrial |
| ¹⁴ C | 100 yr – 40 kyr | Macrofossils, pollen | Marine & Terrestrial |
| U-series | 1 yr – 400 kyr | Calcareous tests/shells | Marine & Terrestrial |
| Paleomagnetic Intensity | 1 kyr – 800 kyr | Sediment | Marine & Terrestrial |
| ¹⁰ Be (atmospheric) | 10 kyr – 5 Myr | Marine or lacustrine sediment, loess | Marine & Terrestrial |
| ⁸⁶ Sr/ ⁸⁷ Sr | 1 yr – 100 Myr | Calcareous tests/shells | Marine & Terrestrial |
| Paleomagnetic Reversals | 10 kyr – 80 Myr | Sediment, lava | Marine & Terrestrial |
| ³⁹ Ar/ ⁴⁰ Ar | > 10 kyr | Coarse-grained tephra | Marine & Terrestrial |
| ¹⁶ O/ ¹⁸ O | 0 – 5 Myr | Calcareous tests/shells | Marine |
| Orbital Tuning | 0 – 5 Myr | Continuous proxy climate records | Marine |

Table 3: Correlation

| Method | Dating Range | Material | Application |
|-----------------------------------------------|--------------|--------------------------------------------------------------------------------------|---------------------------------------------------------------|
| Sedimentology | 0 – 2.7 Myr | Grain size, color, magnetic susceptibility, opal content, isotopic composition, etc. | Terrestrial & Marine Correlation with other marine records |
| Tephrochronology | 0 – 50 Myr | Tephtras | Terrestrial & Marine |
| Terrestrial vs. Marine Origins | 0 – 2.7 Myr | C/N, ⁹ Be/ ¹⁰ Be of sediment, fossil content, etc. | Terrestrial & Marine |
| ¹⁶ O/ ¹⁸ O Stratigraphy | 0 – 5 Myr | Foraminifera | Terrestrial Discontinuous records complicate procedures |
| Sequence Stratigraphy | 0 – 80+ Myr | Paleosols, unconformities, transgressive packages | Terrestrial & Marine |

Biostratigraphy

Diatoms and Palynomorphs

Cores of Norton and Navarin basins (Fig. 1) recovered abundant and well preserved diatoms, palynomorphs, and foraminifera. Younger units were dated primarily by diatoms (Turner, 1983a, 1983b; Turner et al., 1985), which are abundant and diverse in fine-grained sediment throughout the Bering Sea. Relatively high-resolution diatom biochronologies are currently available for the Quaternary and Neogene, and zones have recently been established for Oligocene and early Miocene assemblages of the North Pacific (Gladenkov, 2006). Direct correlation with paleomagnetic stratigraphy is available for the past 18 million years based on results from nearby North Pacific cores (Yanagisawa and Akiba, 1998).

Stratigraphically older sections of Norton and Navarin basin cores have been successfully dated by palynomorphs (Turner, 1983a, 1983b; Turner et al., 1985), which are common in shallow marine sediment as well as terrestrial coal and lacustrine deposits. In the case of diverse and well-preserved assemblages, stage-level determinations are routine for the Cretaceous and Paleogene. Palynomorphs will thus be particularly important to compilation of a broad chronostratigraphic framework for nonmarine and shallow marine sequences of pre-Miocene age.

Radiometric Dating

Radiocarbon

Accelerator Mass Spectrometer (AMS) measurements of radiocarbon in animal macro- or microfossils can be used to date late Pleistocene and Holocene sections of the cores, provide reliable age constraints for the Pleistocene/Holocene transgression, and permit correlation with coeval sections in eastern and western Beringia. Small, articulated marine bivalves are currently considered optimal for radiocarbon dating of sediment from Arctic shelf environments, as bulk carbon, pollen and macrofossil plant remains typically include reworked organic matter. Regardless of the material measured, interpretation and correlation of radiocarbon dates is likely to be hampered by the presence of reworked organic material in transgressive units and deltaic sediment and complicated by differences in marine and terrestrial correction factors. It is thus essential to employ U-series dating to test and calibrate radiocarbon ages.

U-Series

Disequilibrium between daughter and parent isotopes in the ^{238}U - ^{235}U - ^{232}Th series has been successfully employed to date both sediment and organisms. Isotopic pairs utilized to obtain ages include: $^{210}\text{Pb}/^{226}\text{Ra}$ activity ratio (dating range: ~1 - 120 yrs; Baskaran et al., 2005); $^{226}\text{Ra}/\text{Ba}$ ratio (range: ~100 - 9,000 yrs; Berkman and Ku, 1998); $^{234}\text{U}/^{238}\text{U}$ excess activity ratio (range: 10 kyr – 1 myr); and $^{230}\text{Th}/^{234}\text{U}$ activity ratio (range: ~1 kyr - 400 kyr; e.g., Baskaran et al., 1989). Thus, Bering Sea core horizons younger than ~400 kyr with constituent fossil mollusk shells and/or foraminifera can be dated by one or more of the U-Th series pairs.

Based on $^{230}\text{Th}/^{234}\text{U}$ of 400 mollusk shells, Kaufman (1971) initially concluded that the ages obtained by the $^{230}\text{Th}/^{238}\text{U}$ method were unreliable. The problem with the methodology was attributed to postmortem migration of U into the shells; fossil shells have U concentrations of 0.5-1.0 ppm, whereas U concentrations in shells of living mollusks range between 0.05 and 0.10 ppm. In addition, ~75% of fossil marine shells had

$^{234}\text{U}/^{238}\text{U}$ activity ratios higher than those of seawater (Kaufman, 1971). Subsequent study with high-precision mass spectrometric techniques indicates that the interior shell (inner ~30% of the specimen) exhibits closed system behavior in the vast majority of mollusks and can be employed successfully to date them (Kaufman et al., 1996). There is also great potential for dating Bering Sea shell material via $^{226}\text{Ra}/\text{Ba}$ activity ratios, because low levels of ^{226}Ra (0.5 gram sample of ~20 fg/g of ^{226}Ra or ~0.04 dpm/g) can be precisely determined by modern mass spectrometry. Therefore, U-Th series methods can be employed to provide high precision dates for Holocene and late Pleistocene cores, calibrate marine radiocarbon dates, and bridge the gap between radiocarbon dating and other chronologies.

Chemostratigraphy

C/N Ratios

Recognition of terrestrial or marine origins is essential for correlation and proper calibration of bulk radiocarbon dates. Whereas presence of reworked material or absence of plant and animal fossils may preclude differentiation of marine and terrestrial deposits on the basis of biostratigraphy, marine and terrestrial sediment usually have markedly different stable carbon and nitrogen isotope compositions ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ respectively). Marine sediment invariably has higher $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values compared with terrestrial lake sediment. Measurement of the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values of Total Organic Matter (TOM) from a sediment core can thus be used to determine whether sediment is primarily composed of marine or terrestrial organic matter.

Oxygen Isotopes

Oxygen isotope measurements ($\delta^{18}\text{O}$) of foraminifera shells are one of the most common tracers of climate change. Because H_2^{16}O evaporates more readily than H_2^{18}O , the $\delta^{18}\text{O}$ value of water vapor, cloud droplets, precipitation, and continental ice are low compared to that of seawater. When continental ice volume is low, then the whole ocean $\delta^{18}\text{O}$ value is relatively high, and vice versa. In addition, regions where evaporation dominates have relatively high surface ocean salinity and $\delta^{18}\text{O}$ values compared to regions dominated by precipitation. The offset between the $\delta^{18}\text{O}$ composition of foraminiferal calcite (CaCO_3) and the $\delta^{18}\text{O}$ of seawater in which they calcify is controlled by temperature. Thus, foraminiferal $\delta^{18}\text{O}$ values reflect the temperature and $\delta^{18}\text{O}$ of seawater, which is influenced by changes in ice volume and local salinity. On most timescales, and in most environments, the effects of changes in local salinity and temperature are small relative to the effect of changes in ice volume on the $\delta^{18}\text{O}$ record of benthic foraminifera. Because ice volume fluctuations influence the $\delta^{18}\text{O}$ of the global ocean, benthic $\delta^{18}\text{O}$ records from around the globe typically share a significant amount of variance and can thus be used as a tool to correlate records across distant locations, thereby providing relative age control. Several 'reference' $\delta^{18}\text{O}$ curves with absolute age control (control points provided by orbital tuning, radiocarbon, U-Th radioisotopic ages, and paleomagnetic reversals) have been developed (Lisiecki and Raymo, 2005). Thus, $\delta^{18}\text{O}$ stratigraphy does provide some quasi-absolute age control depending on the time interval, with errors on the order of at least a few thousand years.

Strontium Isotopes

The seawater $^{87}\text{Sr}/^{86}\text{Sr}$ evolution curve can also be used as a stratigraphic dating tool. Foraminifera from eight sediment cores collected at eight DSDP holes have been used to reconstruct high precision $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic evolution for the past 100 Myr (Hess et al., 1986). More recently, this curve has been extended to ~ 500 Myr (McArthur et al., 2001). Precisions of ± 0.5 Myr can be obtained for periods of rapid Sr isotope evolution, but error bars may be as large as ± 2 Myr for intervals of slow isotopic evolution (Dickin, 2005). Foraminifera and other biogenic material can thus be analyzed for initial $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios and dated by correlation to the established curve.

Beryllium Isotopes

^{10}Be is produced in the atmosphere by nuclear interactions with oxygen (Goess and Phillips, 2001). The product of spallation reactions, atmospheric ^{10}Be mixes with dust particles and is delivered to the land or sea surface by precipitation. Eventually, the nuclides are deposited in ocean sediment; they can be extracted as hydroxides and converted to oxides for AMS measurements (Kim and Englert, 2004; Kim and Sutherland, 2004). Required sediment collection amounts are ~ 10 -100 g (Tuniz et al., 1998).

^{10}Be concentrations in marine deposits are related to sedimentation rates. Concentrations have been shown to correlate inversely with geomagnetic intensity (Frank et al., 1997) and indirectly with marine oxygen isotope curves (McHargue and Donahue, 2005). Records from cores of the Norwegian Sea and Arctic Ocean demonstrate that high ^{10}Be concentrations correspond to interglacial stages, whereas low ^{10}Be concentrations are indicative of glacial stages. This is due to higher sedimentation rates during glacial periods and lower sedimentation/accumulation rates during interglacial periods (Aldahan et al., 1997). Thus ^{10}Be concentrations are an independent proxy of changes in climate and sedimentation rates that can be used in conjunction with oxygen isotopes to date ocean cores (Eisenhauer, 1994).

Continuous ^{10}Be profiles from Bering Sea cores could be compared to records of paleomagnetic intensity and oxygen isotope stratigraphy in order to refine chronologies and augment paleoclimate reconstructions. In addition, ^{10}Be records are relevant to the study of land bridges because $^{10}\text{Be}/^9\text{Be}$ ratios can be used as an indicator of terrestrial sediment influx. $^{10}\text{Be}/^9\text{Be}$ ratios thus provide a means of distinguishing terrestrial and marine deposits and serve as an important indicator of sediment transportation from the terrestrial region to a submerged Bering Strait.

Magnetostratigraphy

Changes in the polarity of the Earth's magnetic field as recorded by sedimentary deposits can be used to develop a chronostratigraphic framework for cores spanning millions of years. Reversals of the Earth's magnetic field were first reported almost fifty years ago, and the pattern of normal and reversed polarities for the past 80 million years, known as the Magnetic Polarity Time Scale, is now well-established (Gradstein et al., 2005). This time scale can be used to date sedimentary sequences from the past one million years with a resolution of a few thousand years. In addition, changes in paleomagnetic inclination and declination, known as secular variation, can be used to date records that span the last 10,000 years (Verosub, 2000).

Over the past twenty years, methods have been developed that make it possible to obtain reliable records of the relative paleointensity variations of the geomagnetic field

(King et al., 1983; Tauxe, 1993; Roberts et al., 1994; Verosub et al., 1996; Valet, 2003). These records show that the field variations occur on time scales from a few thousand to a few tens of thousands of years and that these variations are globally coherent (Tauxe and Valet, 1989). These studies have led to the development of a global paleointensity record which now spans the last 800,000 years (Williams et al., 1998; Guyodo and Valet, 1999). For the past 10,000 years, the paleointensity record supplements dating based on paleosecular variation and radiocarbon; for the 50,000-100,000 years prior to that, the record complements dating based on AMS radiocarbon and U-series studies. For the previous 700,000 years, the paleointensity records bridges the critical gap between U-series dating and the magnetic polarity stratigraphy.

Another important property is magnetic susceptibility, which is routinely measured using simple instrumentation. Additional magnetic parameters can be determined by specialized paleomagnetic and rock magnetic equipment. At the simplest level, the magnetic parameters provide a means of correlating between suites of cores from the same site and between suites of sites in a given depositional system. However, magnetic properties usually record Milankovitch and sub-Milankovitch cyclicity (Vidic et al., 2000). These attributes are particularly useful for studies of sediment from the Bering Strait, because oxygen isotope ratios can become unreliable at high latitudes.

Tephrochronology

Approximately 150 distinct and datable tephra units have been identified in surficial sediment, lake deposits, and marine cores from sites in and around Alaska, Yukon, and Kamchatka, but very little is known about the marine distribution of these ash layers. Any coarse-grained ash deposits present in Bering Sea cores can be dated directly by the $^{40}\text{Ar}/^{39}\text{Ar}$ method. Furthermore, local and regional correlation of tephra units can be a powerful and cost-effective way to provide age control for sediment of late Neogene to Holocene age. Tephra can also be used to demonstrate definitive correlations between widely separated marine coring sites and terrestrial geologic sections (Beget, 2005; Beget and Muhs, 2004).

During a series of previous projects funded by the National Science Foundation, NASA, the Alaska Volcano Observatory, and the National Park Service, tephra units were sampled from the Bering Land Bridge National Park and nearby regions of Arctic Alaska. These tephra have been described in terms of their major, minor, trace, and rare earth elemental composition using state-of-the art geochemical procedures. Many tephra layers of Pleistocene and Holocene age are already known to be present in this area, with volumetrically important tephra coming from local volcanoes in the Espenberg Maars (Beget et al., 1996) and the Aleutian arc (Beget et al., 1992). Recent work has identified other volcanoes around the Bering Strait and in northwestern Alaska that have undergone explosive eruptions and may have dispersed tephra across the Bering Strait region (Beget et al., 2005).

Tephra from cores of the Bering Sea can be described in terms of major, minor, trace, and rare earth elemental composition. To identify the volcanic source, these geochemical “fingerprints” can be compared with the existing tephra dataset of more than 3000 samples of Alaskan tephra maintained at the Alaska Center for Tephrochronology (ACT). Dating and geochemical characterization of constituent tephra units could thus provide reliable correlations for cores from Bering Sea basins, permit independent

evaluation of ^{14}C dates and calibration models, and establish precise correlations between terrestrial and marine deposits throughout Beringia and the Bering Sea.

Sequence Stratigraphy

Observations of early Eocene coals and paleosols developed in fluvial, paludal and lacustrine environments from the North Aleutian Shelf COST No. 1 Well (T.S. White, core observations) and the Norton Sound COST No. 2 Well (Turner, 1983b) suggest that Eocene paleosols may be widespread throughout the greater Bering Sea basin. Coal deposits of early Miocene and older age also occur north of the Bering Strait in Hope Basin (Tolson, 1987). In addition, micromorphological evidence indicates that paleosols are present in a chronostratigraphically broad range of sedimentary units of the Red Dog area, western Brooks Range (Dumoulin and White, 2005), where well-developed soil fabrics are found in claystones from the Upper Devonian-Lower Mississippian(?) Kanayut Conglomerate, the Pennsylvanian-Permian Siksikpuk Formation, Jurassic-Lower Cretaceous Kingak Shale(?), and the Lower Cretaceous Ipewik Formation. Recognition of an early Eocene geosol (widespread paleosol) throughout Alaska, including the Seward and Alaska Peninsulas (Dickinson and Ager, 1987), provides an important stratigraphic marker bed in strata that is otherwise difficult to date (White, 2005). These Paleozoic, Cretaceous and Eocene paleosols developed during past conditions of extreme warmth and exist within continental strata, but they are often intimately associated geographically and stratigraphically with shallow marine units, providing good opportunities for high-resolution correlation.

Recognition of subtle, amalgamated paleosols in alluvial strata is critical to understanding variations in base level and applying sequence stratigraphy to non-marine rocks. In this context, the development of alluvial plain paleosols, and high-resolution stratal correlations between alluvial and shallow-marine deposits, are topics that can provide considerable insight into the sequence stratigraphic development of paleosol-bearing alluvial sequences. In turn, these advances provide the framework in which paleoenvironmental records can be properly understood. Detailed geochemical profiles augmented by chronostratigraphic information provide one way of establishing high-resolution basin-scale correlations by recognizing similar patterns in different localities. A chemostratigraphic approach is based on the notion that sequence boundaries and marine flooding surfaces may be observable within geochemical data sets. For example, chemostratigraphic profiles may be constructed using Rock Eval pyrolysis-derived records of organic matter provenance, which can be used to unravel stratigraphic stacking patterns and to understand the development of accommodation space in a basin (White, 1999; 2004). Using this approach, Young (2002) was able to construct parasequence-scale correlations between Cretaceous paleosol-bearing strata and coeval marine strata deposited in the Western Interior Seaway of North America. Distinctive paleosols present on the margins of the Bering Strait and in the Norton Basin COST wells will facilitate high resolution, inter- and extra-basinal correlations of terrestrial sequences and may eventually permit sequence stratigraphic correlations with marine units.

Exposed Surfaces

Establishing the history of exposure and submergence of the Bering Strait is crucial to clarifying the effect of this gateway on global climate and understanding the biogeography of modern plants, animals, and humans. Burial of subaerially exposed

surfaces such as paleosols, loess deposits, volcanic ash, and unconformities can be dated directly by thermoluminescence, optically stimulated luminescence, and/or cosmogenic isotopes formed in situ (Table 4). Although the applicability of these techniques to submerged terrestrial deposits is still under investigation, recent studies of underwater land bridges in the western Pacific suggest that cosmogenic isotopes can be used to reconstruct the history of emergence during the LGC (Kim and Imamura, 2004).

Table 4: Special Opportunities

| Method | Dating Range | Material | Application |
|------------------------------------------------------------|--------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------|
| Thermoluminescence Optically Stimulated Luminescence | 0 – 200+ kyr | Tephra, sand, loess, other exposed sediment | Terrestrial sediment, unconformities, submarine dunes, and artifacts |
| Exposure Dating | 0 – 100+ kyr | ^{14}C , ^{10}Be , ^{26}Al , ^{36}Cl , ^{21}Ne of rocks or sediment from submerged or buried surfaces | Reconstructing exposure and burial history of loess, paleosols, or unconformities Experimental in cores |

Thermoluminescence and Optically Stimulated Luminescence

A luminescence age is a measure of the time since rock or sediment was last exposed to sunlight (or heated). The thermoluminescence (TL) dating technique can be used to date samples with ages from 1-500 ka using light emitted by a crystalline or glassy material when it is heated. Emitted light is the result of electronic defects caused by previous exposure to ionizing radiation, such as α , β , γ , or X-rays. The source of the radiation may be uranium, thorium, other elements in their decay chains, ^{40}K , and/or cosmic radiation (Wintle and Huntley, 1982). The TL age is obtained by dividing the intensity of accumulated paleodose by the annual dose rate. Field measurements of gamma spectrometry (K, U, Th and cosmic ray) are needed to determine the annual dose rate. Alternatively, the dose rate can be estimated from the composition of the sediment, but the accuracy of such estimates presents one of the several limitations to TL.

TL dates of the polymineralic fine fractions (4-11 μm) of deep-sea cores from the North Pacific and Antarctic Ocean are comparable to dates provided by biostratigraphic and isotopic chronologies (Wintle and Huntley, 1979; Wintle and Huntley, 1980). Berger et al. (1984) report satisfactory agreement of radiocarbon and TL dates of a marine core collected off the gulf coast of Florida, but this is not generally the case. Reliable ages have been obtained for loess deposits younger than 120 ka (last glacial-interglacial), although dates up to 800 ka have been reported (Singhvi and Mejdahl, 1985; Berger et al., 1992; Waters et al., 1997; Proszynska, 1983; Wintle et al., 1984; Rendell et al., 1983). TL dating of the fine-grained glass phase of volcanic ash would be ideal (Berger, 1991; Kaufman et al., 2001).

Optically Stimulated Luminescence (OSL) dating is similar to TL dating in that exposure to sunlight sets, or resets, the clock. However, an advantage of OSL dating is that it is associated only with electronic traps that are easily bleached by photons; quartz and feldspar grains are bleached after a few minutes of sunlight exposure versus hours for the corresponding TL response. Most laboratories now employ OSL in preference to TL techniques. OSL dating uses light of a particular wavelength or range of wavelengths, usually blue, green, or infrared, to eject light-sensitive electrons trapped in the crystal lattice. Both OSL and TL use quartz or feldspar from sediment samples. The preferred grain fractions are 4-11 μm for silt and 100-300 μm for coarser grains. Approximately 10-30 g of sediment are needed for OSL and 50 g for TL.

OSL dating of light-exposed sediment is becoming increasingly popular as a method for establishing a chronology for Quaternary deposits. Comparison with independent dating methods indicates that OSL ages are reliable for sediment older than 100 ka. Ratios of OSL dates to radiocarbon ages computed for 8 samples range from 0.81 ± 0.08 to 1.04 ± 0.08 , for an average of 0.94 ± 0.03 (Murry and Olley, 2002). OSL dating requires samples that were exposed to sunlight for at least one hour, accumulated in a relatively homogenous stratigraphic unit, and have not undergone significant water-content variation or diagenetic changes during burial. Great care must be taken during sample collection and handling to prevent exposure to sunlight.

With respect to Bering Sea cores, TL dates of marine sediment and volcanic ash can provide supplemental age information for selected horizons. Archeological artifacts, such as tool or pottery fragments, can also be dated by TL (e.g. Fedje and Josenhans, 2000). Furthermore, TL and OSL can be employed to date submergence and burial of terrestrial surfaces that underlie transgressive marine deposits. Because dating of submerged terrestrial deposits remains experimental, OSL and TL ages of terrestrial units (e.g. loess, paleosols, or tephra) must be compared to chronologies based on paleomagnetism, biostratigraphy, and isotopes. TL/OSL ages could also be compared to dates determined by decay of cosmogenic nuclides, another method suitable for dating burial of unconformities and submergence of land bridges.

Cosmogenic Isotopes in the Crust

Cosmogenic nuclides are produced both in the atmosphere and the crust of the earth, and several of these nuclides can be used effectively for dating the burial of exposed horizons. ^{10}Be , ^{14}C , ^{26}Al , and ^{21}Ne are produced in situ at or near the rock or mineral surface by cosmic rays. These nuclides are the result of quartz spallation reactions that occur within the outer 2 m of the rock. At greater depth, these nuclides are generated by muon interactions (Brown et al., 1994; Kim and Englert, 2004); in water depths greater than 20 m, muon-induced production is dominant. ^{36}Cl is produced by similar reactions in basaltic rocks (Stone et al., 1998). All five nuclides can be used to determine duration of exposure and time of burial (Stone et al., 1998; Lal, 1991).

Due to variations in cosmic ray intensities, production rates of cosmogenic nuclides are a function of geomagnetic latitude and altitude as well as mineral content (Lal, 1991). The half-lives of ^{14}C , ^{10}Be , ^{26}Al , ^{36}Cl and are 5,700 yr, 1.5 Myr, 0.7 Myr, and 0.3 Myr, respectively; ^{21}Ne is stable (Gosse and Phillips, 2001). It may be possible to obtain ^{10}Be , ^{14}C , and ^{26}Al from the same sample by using wet-chemical techniques, because these nuclides are produced in situ in quartz (Lal and Jull, 1994). Measurement of multiple isotopes with different half-lives allows us to unravel the history of exposure

for samples with complex geological histories (Kim and Imamura, 2004). Appropriate cosmogenic nuclides have a half-life less than or equal to one fifth of the time elapsed since burial (Goess and Phillips, 2001). Production rates of ^{10}Be , ^{14}C , ^{26}Al , and ^{21}Ne in 1g of quartz at sea level at high geomagnetic latitude are approximately 6, 20, 36, and 24 atoms/g/yr (Goess and Phillips, 2001; Graf et al., 1993; Reedy et al., 1994). The necessary sample size can be determined from the estimated exposure time, production rate, and geometry of the site, but generally 5-10 g of quartz are required. Accelerator mass spectrometry (AMS) detection limit of $^{14}\text{C}/^{12}\text{C}$, $^{10}\text{Be}/^9\text{Be}$ and $^{26}\text{Al}/^{27}\text{Al}$ are generally better than $\sim 10^{-14}$ (Kim and Englert, 2004; Tuniz et al., 1998).

A recent study of migration between Japanese islands confirms that pre-exposure by neutron spallation can be detected by measuring cosmogenic nuclide concentrations in underwater rocks. Dating of land bridge emergence using underwater production of cosmogenic nuclides is therefore feasible (Kim and Imamura, 2004). A current project using bedrock samples from the present sea level down to a depth of 35 m in the Tsugaru Strait (Aomori area) is under investigation to unravel the exposure history of land bridges during the last ice age using multiple cosmogenic nuclides, including ^{10}Be , ^{26}Al , ^{14}C , and ^{21}Ne .

Similar studies can be employed to date emergence of the Bering Land Bridge. When a land bridge is exposed, neutron-induced production begins. When water covers the site after deglaciation, neutron-induced production ceases, but muon-induced production continues at a very low rate. Because there are (in principle) two unknowns, exposure duration and time of burial, two or more radionuclides with well-known production rates, i.e. ^{10}Be , ^{26}Al , and ^{14}C , can be used to constrain the exposure and burial history of the sample. Ages generated by this novel technique can be verified or rejected based on comparison with biostratigraphic, radiometric, and/or TL dates of submergence.

Terrestrial Paleocology

Grass and sedge were diverse and abundant in Beringian steppe and tundra biomes, but graminoid genera and species cannot be distinguished on the basis of pollen analysis alone. Identification of graminoid macrofossils, phytoliths, and cuticle fragments thus has the ability to substantially augment traditional vegetation and climate reconstructions based primarily on palynomorphs. Vegetation-based estimates of temperature and precipitation can then be combined with independent estimates derived from insect faunas and evolving stable isotope proxies in order to enhance and constrain climate models and to test Guthrie's (2001) theory of a mesic refugium/filter on the Bering Land Bridge.

Plant Fossils

Pollen

Pollen and spore assemblages combine input from local and regional vegetation cover and from transport mediums such as rivers and winds. In areas where numerous modern reference samples have been statistically correlated with climate variables, identification of modern analogs for ancient palynomorph assemblages results in a quantitative estimate of past temperature and precipitation (Overpeck et al., 1985; Webb and Bryson, 1972). Surface samples from lacustrine cores provide an excellent modern pollen database for Alaska, but records that extend to the mid or early Holocene are lacking. Consequently, palynological studies of Bering Strait and Bering Sea shelf cores

will focus initially on reconstruction of Holocene paleoclimates using semi-quantitative methods. Semi-quantitative palynological climate indexes facilitate identification of relative changes in paleotemperature and precipitation based on the changing ratios of pollen from selected plant groups.

Due to the lack of climate-sensitive arboreal genera, pollen spectra from steppe and tundra biomes may appear relatively uninformative until semi-quantitative indices are used to distinguish climate-driven changes in vegetation cover. Such semi-quantitative indices have previously been used to identify humid and arid intervals in records from lakes in semi-desert and desert regions of southern Asia and north Africa, where relative changes in humidity are correlative with changes in the extent and severity of the Asian monsoon (van Campo and Gasse, 1993; Gasse and van Campo, 1994). Reconstruction of changes in moisture availability based on the proportions of grasses (Poaceae), sage (*Artemisia*) and goosefoot (Chenopodiaceae) from the steppes of northern Mongolia (Fowell et al., 2003) is particularly relevant, as the Mongolian steppe may be the closest modern analogue for the vegetation of the Bering Land Bridge. Although steppe vegetation prevailed in Mongolia throughout the middle and late Holocene, grass-dominated, meadow-steppe vegetation correlates with lake highstands, whereas increases in desert-steppe taxa such as sage and goosefoot occur during lacustrine lowstands (Fowell et al., 2003; Peck et al., 2002). Similarly, forb, graminoid, and shrub-dominated tundra can be distinguished by the relative abundance of grass (Poaceae), willow (*Salix*), alder (*Alnus*), and sedge (Cyperaceae) (Bigelow et al., 2003).

Selection of an appropriate semi-quantitative index for the assemblages from Bering Sea cores cannot be made until samples from coring sites have been examined, because it is essential that the index taxa be well-represented throughout the cores (Gasse and van Campo, 1994). Ultimately, semi-quantitative palynological indices will facilitate recognition of changes in steppe and/or tundra vegetation and test theories of regional climatic gradients through production of high-resolution paleoclimate reconstructions sensitive to spatial and temporal changes in humidity.

Macrofossils

Macrofossils not only reveal the vegetation present on the landscape, but also provide insights into local climate conditions. Wood, seeds, needles, and other durable remains generally travel only short distances from the source plant (Birks, 2001), thus they are a robust proxy of the local vegetation. However, because they are rare (as compared to pollen), they are also quite sensitive to taphonomic processes. Hence the absence of a taxon in the macrofossil assemblage does not necessarily indicate its absence from the local vegetation. For this reason, plant macrofossils should be studied in collaboration with a pollen, which mainly reflects the regional vegetation (Birks and Birks, 2000).

Unlike palynomorphs, many plant macrofossils are identifiable to the species level, allowing a more detailed reconstruction of the local vegetation. For example, LGM pollen records from Alaska are dominated by herbs and forbs. The three most common pollen taxa are *Artemisia*, Cyperaceae (sedges), and Poaceae (grasses). Each of these taxa includes numerous and ecologically diverse species. Consequently, reconstructing the vegetation and climate of tundra biomes based on pollen spectra is problematic (see Anderson et al., 2004 for a brief summary). LGM macrofossils collected from cores in the Bering and Chukchi Seas (Elias et al., 1996) and from a well-preserved buried soil on

the Seward Peninsula (Goetcheus and Birks, 2001) reveal a vegetation mosaic. The marine cores contain abundant aquatic taxa, while the soil samples are dominated by the calcophilic sedge *Kobresia myosuroides* (Goetcheus and Birks, 2001), a species indicative of a dry environment with continuous additions of calcareous loess.

The significance of *Artemisia* pollen in fossil assemblages is debatable. Some researchers (see discussion in Ritchie, 1984) suggest that *Artemisia* pollen is derived mainly from species that grow in the Arctic today, such as *A. arctica*, while others suggest it could represent arid-adapted steppic taxa, such as *A. frigida* (Guthrie, 1990). These two interpretations have vastly different implications for vegetation and climate. The former suggests a vegetation somewhat similar to the modern fell field tundra; the latter suggests a warmer and dryer vegetation with similarities to the relict steppe vegetation present today on hot, dry slopes of interior Alaska. Recent plant macrofossil analyses from the Yukon Territory indicate that at least some of the *Artemisia* pollen probably came from the steppic taxon *A. frigida* (Zazula et al., 2006).

Plant macrofossils have thus proven to be an invaluable proxy for Beringia and the Bering Strait region. In the search for evidence of mesic refugia, it is essential to combine plant macrofossil and pollen analyses. Pollen analysis may indicate that boreal taxa were present in the region. However, if the taxa were reproducing vegetatively, then the pollen record is not sufficient. Non-reproductive remains (i.e., wood or leaves) are usually identifiable to the species level (i.e., black spruce vs. white spruce, or tree birch vs. shrub birch). These sorts of specific identifications will enhance pollen-based reconstructions and provide a more rigorous assessment of the Bering Land Bridge as a glacial refugium.

Cuticle

Graminoid leaves and stems are commonly the most abundant plant remains in glacial age paleosols and paleoturf, which may be encountered during drilling on the land bridge. Identifiable grass florets and fruits from MIS 2 in eastern Beringia include *Poa* sp., *Elymus* sp., *Deschampsia* sp. and *Festuca* sp. Cyperaceae (sedges) are also represented by well-preserved fruiting bodies of *Carex* sp. (Zazula et al., 2006). Although grass and sedge seeds, fruits and florets can be identified to genus and, in some instances, to species, there is a considerable amount of leaf and stem material that cannot be identified based on macroscopic characteristics. Fortunately, the leaves of different species of grasses and sedges have markedly different micro-morphologies that can be used to identify specimens to sub-tribe, genus and species (Morley and Richards, 1993; Wooller, 2000; Wooller et al., 2000; Wooller, 2002; Ficken et al., 2002; Beuning et al., 2003).

Micro-morphological graminoid features include the shape and size of stomata, the shape and size of long cells, the shape of phytoliths (biogenic silica produced in the leaves of plants), the arrangement of cells within the costal (vein) and inter-costal regions, and the width of the stomata. The micro-morphology of modern and fossil cuticles can be examined using the SEM or, less often, a light microscope (Wooller, 2000). A list of observed features can be entered into a database, such as Watson and Dallwitz (1988, 1994). Preliminary examination of Pleistocene graminoid cuticles from the permafrost tunnel in Fox, AK, shows that they retain micro-morphological features. An image database specifically for grasses and sedges of eastern Beringia is currently being compiled at the University of Alaska Fairbanks.

Grass cuticle micro-morphological analysis has contributed significantly to our understanding of past vegetation dynamics (Morley and Richards, 1993), but to date it has primarily been applied in the tropics and sub-tropics, where there is high graminoid species diversity (Morley and Richards, 1993; Wooller, 2000; Wooller et al., 2000; Wooller, 2002; Ficken et al., 2002; Beuning et al., 2003). Beringian floras are also characterized by abundant and diverse species of sedge and grasses. Micro-morphological analysis of graminoid remains is thus critical to the development of robust paleoecological reconstructions for the Bering Land Bridge.

Dispersed Phytoliths

Phytoliths are microscopic bodies of opal, amorphous hydrogenated silica, which is taken in solution by plants from soils, deposited in plant tissues and released into soils and terrestrial sediment upon decay of the plant. Many, but not all plants produce phytoliths, and silicification is prevalent in the Poaceae (grasses), Cyperaceae (sedges), Pinaceae (pine family), and Asteraceae (asters) (Piperno, 1988). Many subfamilies and genera of Poaceae can be identified from phytoliths, making them an effective method for reconstructing local vegetation in regions known to have grass-dominated pollen assemblages (Blinnikov et al., 2002), such as Beringia. Phytoliths are common in loess deposits and paleosols in which fossil pollen is typically rare, highly degraded, and unsuitable for quantitative analyses. Phytolith analyses have been successfully applied to reconstruct mid and high-latitude vegetation in Europe (Blinnikov 1994, Carnelli et al., 2001), western North America, (Kurmann, 1985; Blinnikov et al., 2002), western Beringia, and Mongolia (Kiseleva, 1989). Furthermore, the analysis of phytoliths from modern plants and soils facilitates identification of modern vegetation analogues through multivariate statistical methods (Fredlund and Tieszen, 1994; Blinnikov, 2005). Identification of modern analogues for assemblages of pollen, macrofossils, cuticle, and/or phytoliths would greatly enhance vegetation-based reconstructions of climatic conditions on the Bering Land Bridge.

$\delta^{13}\text{C}$ of Plants

The stable carbon isotope content of terrestrial plant remains is an indicator of past water use efficiency. $\delta^{13}\text{C}$ of plants is influenced by a number of environmental conditions including salinity, humidity, the stable isotope composition of atmospheric CO_2 , and soil moisture (O'Leary, 1988; Lin and Sternberg, 1992; Ehleringer, 1991). Although the C_4 photosynthetic pathway is favored over the C_3 pathway in relatively warm climates (Ehleringer, 1978; Tieszen et al., 1979; Ehleringer and Monson, 1993; Ehleringer and Cerling, 1997), dry-adapted C_4 plants are exceedingly rare in modern eastern Beringia (Welsh 1974; Sage et al., 1999). Under drier conditions, C_3 plants become more water-use-efficient (e.g. Ehleringer and Monson, 1993). To reduce water loss through transpiration, these plants discriminate less against the heavier stable isotope of carbon in CO_2 , and plant biomass becomes enriched ^{13}C (O'Leary, 1988). Fossil plant biomass can retain the $\delta^{13}\text{C}$ signature (e.g. Wooller et al., 2004a; Smallwood et al., 2003), in some instances over millions of years (e.g. Schweizer et al., 2006).

Admittedly, an additional environmental condition that may have influenced the water-use-efficiency and $\delta^{13}\text{C}$ values of past plants is the concentration of atmospheric CO_2 , which has been shown to influence the physiology of plants (e.g. Polley et al., 1993). For example, atmospheric $\delta^{13}\text{C}$ values were significantly lower during MIS 2 (Raynaud et

al., 1993; Smith et al., 1999). However, this technique can be used to determine whether plants growing during the LGM at sites in eastern Beringia had notably higher water-use-efficiency compared with comparable modern species growing on the Bering Land Bridge.

A systematic survey of the range of $\delta^{13}\text{C}$ variation demonstrated by modern grasses and sedges from eastern Beringia shows that sedges and grasses from dry habitats have significantly less negative $\delta^{13}\text{C}$ values compared with those from wet habitats, which is consistent with theory (O'Leary 1988, Ehleringer 1991). The five specimens of C_4 grasses that have been located in modern eastern Beringia have totally distinct $\delta^{13}\text{C}$ values. While we do not anticipate encountering any C_4 grass remains in our fossil samples, the presence of C_4 biomass in, for example, MIS 2 age samples would be completely obvious (as well as remarkable), because the $\delta^{13}\text{C}$ of C_4 plants is distinct from that of C_3 plants (Deines, 1980; Ehleringer, 1991). Some decompositional processes can slightly alter the stable isotopic composition of plant matter (e.g. Macko et al., 1993; Fogel and Tuross, 1999; Wooller et al., 2003), but this would generally be insufficient to shift the signature from one indicating high water-use-efficiency (e.g. $\delta^{13}\text{C} = -22\text{‰}$) to one of low water-use-efficiency (e.g. $\delta^{13}\text{C} = -32\text{‰}$).

The $\delta^{13}\text{C}$ of organic material can be analyzed precisely using stable isotope ratio mass-spectrometry, where the $\delta^{13}\text{C}$ of a sample is measured relative to an international standard (Pee Dee Belemnite - PDB) and expressed in standard delta (δ) notation. An internal laboratory standard [e.g. Acetanalide ($\text{C}_8\text{H}_9\text{NO}$)] is analyzed as a check on the analytical precision. Typical precision for $\delta^{13}\text{C}$ is ± 0.1 standard deviation. Preliminary $\delta^{13}\text{C}$ measurements of fossil graminoid samples from the permafrost tunnel in Fox, AK, demonstrate that sufficient fossil material is available to conduct $\delta^{13}\text{C}$ analyses. Thus stable isotope data, used as a physiological proxy, can be compared with paleoecological information derived from pollen, cuticle, phytolith and macrofossil analyses to reconstruct the environment of the Bering Land Bridge.

Insect Remains

Beetles are the largest group of organisms on Earth, and their chitinous remains are well-preserved in water-logged sediment throughout the world (Elias, 1994). The current species have been in existence for more than one million years, and their modern distribution and ecological requirements are relatively well studied. These factors, combined with great mobility, make beetles sensitive and reliable indicators of Pleistocene terrestrial environments. Assemblages of fossil insects (mainly beetles) are both abundant and well-preserved in frozen, organic-rich sediment of Beringia. Because the majority of these fossils may be specifically identified, they provide detailed, precise information on past environments, including mean summer and winter temperatures, vegetation regime, and humidity.

Fossil beetles already play an important role in the reconstruction of Beringian paleoenvironments. To date, more than 25 fossil localities have yielded Late Pleistocene beetle assemblages, comprising more than 300 species (Elias, 2000). This research has documented rapid climate change toward the end of the last glaciation, especially in arctic regions of Eastern Beringia and the Bering Land Bridge (Elias et al., 1997; Elias, 2001). These studies have also demonstrated the existence of mesic tundra on the exposed land bridge, as opposed to steppe-tundra (Elias et al., 1996). It is thought that

the mesic environments of the land bridge may have acted as a barrier to migration of steppe-adapted species of plants and animals during the Late Pleistocene (Guthrie, 2001). Identification of fossil beetles from Bering Sea cores will shed light on the extent and continuity of the humidity gradient and provide a further test of Guthrie's "mesic buckle" hypothesis.

Paleosols

Paleosol records of episodic intense Arctic warmth during the past 100 million years may be particularly useful and relevant given current observations of accelerated Arctic warming associated with the ongoing warming of Earth's atmosphere. Oxygen isotope data obtained from siderite spherules in the Cretaceous Nanushuk Group, North Slope, AK, have been applied to reconstructions of Cretaceous "greenhouse" atmospheric hydrology (Ufnar et al., 2002, 2004). Thus paleosols provide a unique opportunity to reconstruct atmospheric hydrology and circulation, and thereby variations in freshwater and sediment flux to the marine realm. Paleosol carbonates (e.g. Ludvigson et al., 1999; White et al., 2000; Tabor and Montanez, 2002) and clay minerals (e.g. Takeuchi and Larson, 2005) can contain a record of paleoprecipitation $\delta^{18}\text{O}$ chemistry, providing a powerful tool to reconstruct past atmospheric hydrologic cycles. Major oxide and elemental compositions of carbonate nodules and soil matrix are also useful for paleoclimate reconstructions (e.g., Stiles et al., 2001, 2003; Retallack, 2005). However, given the emphasis of eustatic sea-level control on sedimentation, alluvial sequence development remains subject to considerable debate (Ethridge et al., 1998). Therefore, the task of reading the paleoclimate record from alluvial paleosols often involves first understanding other factors involved in paleosol formation, including their sequence stratigraphic evolution (e.g., White et al., 2005).

Stable Isotopes and Terrestrial Temperatures

At high latitudes $\delta^{18}\text{O}$ of precipitation is highly correlated with mean annual temperature (Dansgaard, 1964; Rozanski and Araguás-Araguás, 1993), and this correlation is widely used to reconstruct paleotemperatures from $\delta^{18}\text{O}$ variations in ice cores. Lakewater $\delta^{18}\text{O}$ measured in 58 lakes (lake area/catchment $\sim 1:20$) of the eastern Canadian Arctic is highly correlated to mean annual air temperature (MAT) (Sauer et al., 2001). Lakewater $\delta^{18}\text{O}$ has previously been reconstructed from autochthonous calcite in lakes from mid and high latitudes (e.g. Anderson, et al., 2001), and from aquatic cellulose (Sauer et al., 2001). However, lakewaters across much of the Arctic are acidic, and cellulose of unequivocal aquatic origin is rarely continuously preserved.

An alternative means of reconstructing MAT from lakewater $\delta^{18}\text{O}$ uses remains of the chironomid (Diptera: Chironomidae) larvae ubiquitous in high-latitude lakes. The larval stages of lacustrine species are obligate aquatic dwellers, and their chitinous head capsules, shed by the larvae during molting, remain well preserved under a wide range of environmental conditions. Chironomids acquire oxygen for biosynthesis largely from the water in which they live, and to a lesser extent from their diets (Schimmelmann, 1987). The $\delta^{18}\text{O}$ of chironomid head capsules can be used to reconstruct lakewater $\delta^{18}\text{O}$, and by inference $\delta^{18}\text{O}$ of precipitation. These isotopic measurements can be coupled with a reconstruction of past temperatures based on the taxonomic composition of the chironomids present and their respective ecological tolerances (e.g. Wooller et al., 2004b) in order to estimate MAT.

A modern calibration data set (Wooller et al., 2004b) spans >20 °C mean annual air temperature and 11‰ in the $\delta^{18}\text{O}$ of precipitation. Chironomid $\delta^{18}\text{O}$ is highly correlated with the expected $\delta^{18}\text{O}$ of precipitation ($r^2=0.96$) and with current MAT ($r^2=0.98$). The slope of the regression against current mean annual temperature (0.65) is similar to the observed relationship between $\delta^{18}\text{O}$ of precipitation and temperature (0.69; Dansgaard, 1967). The average error in predicted MAT from chironomid $\delta^{18}\text{O}$ is 1 °C. These data demonstrate that chironomid $\delta^{18}\text{O}$ provides a reliable recorder of $\delta^{18}\text{O}$ of precipitation in the watersheds of stream-fed lakes of modest dimensions, and that chironomid $\delta^{18}\text{O}$ can be used to estimate MAT with an average uncertainty of ± 1.0 °C. Our results demonstrate that $\delta^{18}\text{O}$ in chironomid head capsules are equilibrated with the $\delta^{18}\text{O}$ of the lakewater in which they lived. For lakes of appropriate dimensions relative to their catchments, mean lakewater $\delta^{18}\text{O}$ closely approximates mean annual $\delta^{18}\text{O}$ of precipitation, thereby allowing down-core changes in chironomid $\delta^{18}\text{O}$ to serve as a proxy for the evolution of MAT in lacustrine sediment.

Sedimentary basins on the Beringian shelf contain sediment of possible lacustrine origin. Of the two basins most proximal to the Bering Strait, Hope Basin contains Miocene terrestrial siltstone and sandstone units (Tolson, 1987) (see Figs. 2 and 3), while both Norton Basin (Turner et al., 1983 a,b) and Hope Basin (Tolson, 1987) contain coal deposited in terrestrial wetlands. Identification and sampling of preserved lacustrine sediment in the Bering Sea would provide a unique opportunity to estimate mean annual air temperature on the Bering Land Bridge with an uncertainty of approximately ± 1.0 °C.

Climate Models

Although preliminary attempts have been made to combine the currently sparse and somewhat contradictory Beringian shelf proxy database with earth system climate modeling to elucidate regional climate and vegetation characteristics (e.g. Kaplan 2001; Kaplan et al., 2003; Hetherington et al. submitted), serious contradictions and gaps remain. If we are to shed light on the viability of the Beringian subaerial continental shelf as a corridor used by migrating peoples during the LGC, a combination of climate model output and proxy data will be needed to understand the environmental and climatological characteristics of the region, particularly during periods of rapid climate change when slow, gradual adaptation to a changing environment was not a viable alternative for early peoples.

Vegetation biomass calculations, such as those generated by the UVic earth system climate model (Meissner et al., 2003; Matthews et al., 2003; Hetherington et al., submitted), allow determination of the productivity of regions from which and into which humans migrated. Models can also generate paleoclimate and paleo-vegetation maps for critical intervals during the LGC. Output from model simulations can then be compared with archeological data to determine whether patterns (e.g., spatial and temporal correlations) exist. Additional vegetation and ice extent proxy data, combined with a better understanding of sea-level and sea-ice history in Beringia, will enable a more extensive evaluation of the accuracy of climate model simulations and test the value of using models as an interpolating tool to provide paleoenvironmental information when proxy records are sparse.

Paleoceanography and Paleoclimate

In order to understand the impact of the Bering Strait on global climate change, it is essential to refine existing dates of submergence based on migration of mollusks and bowhead whales (Marincovich and Gladenkov, 2001; Dyke and Savelle, 2001). In addition to unconformities and transgressive units, changes in sediment transport, SSTs, salinity, water mass transport, and productivity in the Bering Sea also record the opening and closing of the strait. Reconstructions of Bering Sea paleoceanography and climate based on multiple sedimentary and biological proxies will clarify the effects of an open or closed gateway on global ocean circulation, NADW formation, sea ice cover, and albedo, contribute data for new climate simulations, and provide a rigorous test of the numerous existing paleoclimate models and scenarios.

Sedimentary Properties

Inorganic Chemistry and Elemental Composition

X-ray fluorescence (XRF) core scanners allows rapid and non-destructive determinations of many elements from Al to U in concentrations from 100% to ppm levels at sub-mm resolution, making sedimentary cores comparable with tree-rings and ice cores in terms of resolution (Jansen et al., 1998). These high-tech instruments are now widely used for high-resolution research in marine environments. XRF core scanners also have the potential to provide unique high-resolution records from terrestrial sediment, including laminated or varved lacustrine archives.

XRF high-resolution scanners facilitate diagnosis of environmental and climatic variability, including abrupt climatic changes recorded in terrestrial, lacustrine or marine sediment. Through sub-millimeter examination of geochemical series, this instrument adds a new dimension to the paleoclimatic and paleoenvironmental studies of marine and terrestrial sediment cores. In varved sediment, annual resolution is possible. At present, XRF scanners have been used primarily for fast, low-resolution logging of long IODP cores and documentation of long geochemical time-series (Palike et al., 2001; Jahn et al., 2003; Westerhold et al., 2005). The new generation of XRF core scanners will be able to provide unprecedented high-resolution (up to 0.2 mm) records of elemental composition, digital x-ray, micro-radiographic, and photographic images.

XRF scanning of Bering Sea cores at sub-millimeter resolution would produce a time-series of climate-sensitive geochemical proxies from marine sediment of the Bering Strait and, where present, lacustrine sediment of the Bering Land Bridge.

Possible geochemical proxies and paleoclimate indicators include the following:

- ◆ Paleoproductivity proxies Ca, Ca/Ti, and Si/Ti (Jahn et al., 2003; Westerhold et al., 2005; Grutzner et al., 2005)
- ◆ Proxies of terrestrial vs. biogenic input and watershed erosion, including Fe/Ca, Ca/Ti and/or Si/Ti (Palike et al., 2001; Jahn et al., 2003; Grutzner et al., 2005)
- ◆ Ti, Rb, Cr and Ni as proxies of terrestrial supply (Chebykin et al., 2002; Goldberg et al., 2005; Grutzner et al., 2005)
- ◆ Rb/Sr as an indicator of weathering rates, humid or arid conditions, and precipitation variability (Kalugin et al., 2005)

- ◆ Potential proxies of paleoproductivity and upwelling such as Ba and Br (Warning et al., 1999; Kaiser et al., 1999)
- ◆ Mo, Cd, Re and U as indicators of oxic-anoxic conditions in closed basins (Ivanochko and Pedersen, 2004)
- ◆ X-ray density records for information regarding lithological and physical properties of sediment and the nature, number, and thickness of fine laminations

Although these are some of the most promising paleoclimate proxies obtained by XRF scanning, analytical work need not be limited to the indicators listed above. High-resolution records of elemental composition, digital x-ray, micro-radiographic and photographic images, U-channels, and thin-sections can be collected from strategic intervals identified by preliminary, low-resolution XRF logging. XRF scanning of all cores for both low-resolution logging and high-resolution proxy records thus has the capacity to extract long XRF geochemical time-series for correlation, spectral analysis, and astronomical tuning of Bering Sea sedimentary records.

Clay Mineralogy

The relative distribution of clay minerals (such as kaolinite and chlorite) in cores can be used to evaluate the sources, transport processes and depositional mechanisms of the sediment. High kaolinite/chlorite ratios in marine sediment adjacent to the northwest coast of Alaska have been attributed to input of kaolinite from the foothills north and west of the Brooks Range, delivered to the Bering Sea by the Yukon-Kuskokwim river system (Naidu et al., 1982). The clay mineral stratigraphy of cores collected from the Hope Basin, north of the Bering Strait, is therefore likely to contain a record of temporal changes in the supply of Yukon River clay into the Chukchi Sea, corresponding to the closing and opening of the Bering Strait gateway.

Biogenic Silica

The use of opal proxy records in paleoclimate research has been criticized due to spatial variations of production and preservation (Cortese et al., 2004). However, opal accumulates in sediment when diatom production is high, hence the abundance of biogenic silica in the sediment is determined primarily by production and secondarily by preservation/dissolution processes. In regions where diatoms dominate the biomass, opal is thus a proxy for paleoproductivity. Records of biogenic silica concentrations are also useful for correlation, identification of glacial and interglacial stages, and identification of marine versus terrestrial environments.

Multiple methods for determination of biogenic silica concentrations in marine and lacustrine sediment are currently in use. The most common method involves wet-alkaline extraction (Mortlock and Froelich, 1989), followed by colorimetric determination using a molybdate-blue complex for an average error of 2.5 - 5.0%. Similar leaching techniques were used by Colman et al. (1994) and coupled with silica determination by inductively-coupled-plasma (ICP) atomic-emission spectrometry.

In core samples, nutrient ratios (e.g. Si/N) can be used to establish diatoms as the principal producers relative to calcareous plankton. Records of opal mass accumulation rates (MAR), opal/organic carbon, and opal/carbonate reflect changes in silica supply that may be attributed to one or more of the following: fluctuation of upwelling intensity driven by changes in along shore wind strength; changes in ocean stratification and

general circulation patterns; rising or falling sea level; variability of fluvial discharge; or changes in air and SST. Changes in the relative concentrations of biogenic silica may thus be used in conjunction with other proxies to determine the timing, mechanisms, and consequence of major tectonic, climatic, and biologic events. Biogenic silica concentrations from the Bering Sea have the potential to record both regional geologic and global climatic events. Plio-Pleistocene cooling, Northern Hemisphere glaciation, insolation-driven climate changes, opening/closing of the Bering Strait, changes in ocean circulation patterns, and fluctuations in the amount of fluvial discharge from the Yukon River are likely features of long-term records which may be detectable in cores from the Bering Strait.

Foraminifera

Benthic and Planktonic Taxa

Benthic and planktonic foraminifera are highly diverse, and many species have wide geographical distributions. Species distributions of benthic foraminifera are mainly controlled by the flux of organic matter to the sediment and oxygenation conditions of bottom water and sediment pore water (van der Zwaan et al., 1999), which vary in the ocean as a function of water mass distribution, water depth and biological productivity. Quantitative assemblage analyses can be used to reconstruct paleoproductivity and/or estimate paleo-water depth, because in most cases, water depth correlates with these variables. Planktonic foraminifera species distributions are strongly related to SST, although nutrient concentrations, biological productivity, density gradients and seawater salinity strongly impact species assemblages in some regions. In addition to using assemblage information to reconstruct palaeoenvironmental conditions, the geochemical (isotopic and metal ratio) composition of their calcite tests is used extensively to reconstruct past oceanic conditions.

Foraminiferal Mg/Ca

Mg and Ca are conservative elements in the ocean, with residence times of thirteen million and one million years, respectively. As such, secular changes in Mg/Ca are only likely to change significantly over very long timescales. The incorporation of magnesium (Mg) relative to calcium (Ca) into foraminiferal calcite shells varies exponentially with calcification temperature (Anand et al., 2003; Dekens et al., 2002; Nurnberg et al., 1996). Thus the Mg/Ca composition of surface dwelling planktonic foraminifera can be used to reconstruct SST. Sub-surface dwelling foraminifera can be used to reconstruct temperature below the surface if their depth ecologies are well understood; robust calibrations for an array of species are being established (Elderfield et al., 2002). Calibration of Mg/Ca of multiple species of benthic foraminifera has been conducted over the temperature range of 0.8°C to 18°C (Lear et al., 2002; Martin et al., 2002), but the Mg/Ca to temperature relationship is significantly non-linear, making it more difficult to apply the technique to reconstruct temperature changes below ~5°C.

The analysis of Mg/Ca ratios in calcite requires careful clean lab techniques to prepare shells. Prior to analysis, shells are crushed, weighed, subjected to multiple sonication steps to remove fines, to reductive cleaning to remove oxy-hydroxide coatings, and to oxidative cleaning using the “Boyle protocol” (Boyle and Keigwin, 1986) to remove organics. Measurements of Mg/Ca are usually made using an inductively coupled plasma optical emission spectrometer (ICP-OES or ICP-AES). For example, the

protocol at UCSC (Wara et al., 2003) produces precision for Mg/Ca in liquid and foraminiferal consistency standards around 0.051 mmol/mol (1σ , $n=250$) and 0.232 mmol/mol (1σ , $n=45$), respectively. Typically, Mn/Ca is monitored in order to check for the presence of authigenic MnCO_3 overgrowths (Boyle, 1983). Sr/Ca has a very different composition in recrystallized calcite and can be monitored to check for post-depositional recrystallization (e.g., Andreasen and Delaney, 2000), in concert with microscopic evaluation of foraminifera for recrystallization. Based on published calibrations, temperature estimates based on Mg/Ca of foraminifera have a precision of $\sim\pm 1^\circ\text{C}$.

Foraminiferal $\delta^{18}\text{O}$

Unlike Mg/Ca of foraminifera, the $\delta^{18}\text{O}$ of foraminifera is related to a combination of factors: the $\delta^{18}\text{O}$ of the seawater in which they calcify and the temperature of calcification. The $\delta^{18}\text{O}$ of seawater is influenced by whole-ocean shifts due to variations in the amount of ice stored on land (which makes $\delta^{18}\text{O}$ an effective stratigraphic tool to correlate records from sites from around the globe) and local changes in precipitation and evaporation. Because the salinity of seawater is also influenced by precipitation and evaporation, the $\delta^{18}\text{O}$ of foraminifera can be used to reconstruct salinity if the ice volume and temperature effects can be accounted for. Typically, if independent estimates of ice volume and temperature can be made, they are subtracted from the $\delta^{18}\text{O}$ foraminiferal record and the residual is thought to reflect local salinity variations. The degree to which this residual can be calculated varies widely, but a common approach is to first subtract independent paleotemperature estimates (for example, those made using Mg/Ca). Next, to eliminate ice volume influences, it is useful to look at *differences* between sites that will be directly related to gradients in $\delta^{18}\text{O}$ of seawater and therefore salinity. In ideal cases, if absolute ice volume and temperature changes can be estimated, and the $\delta^{18}\text{O}$ of seawater to salinity relationship can be constrained, the $\delta^{18}\text{O}$ of foraminifera can be used to make estimates of salinity.

To perform the analyses, a split of each crushed, homogenized foraminifera sample used for elemental ratios is ultrasonically cleaned and dried, and isotopic measurements are made using a light stable gas ratio mass spectrometer outfitted with an automated carbonate reaction periphery. External precision based on long-term reproducibility of standards is 0.035‰ for $\delta^{13}\text{C}$ and 0.05‰ for $\delta^{18}\text{O}$. Because of compounded errors related to calibration, age model, and the uncertainty of the paleo-relationship between $\delta^{18}\text{O}_w$ and sea surface salinity, errors on absolute paleo-salinity estimates can be quite large. Hence it is more common to reconstruct relative, rather than absolute surface salinity from $\delta^{18}\text{O}$ records.

Radiolarians

Radiolarians are siliceous marine microzooplankton that dwell primarily in pelagic and hemipelagic waters and exhibit high diversity. Hence they are useful environmental tracers, especially for changes in water mass (e.g., Okazaki et al., 2003). The pioneering work of Morley and Hays (1983) demonstrates that the production of radiolarians living in waters shallower than 200 m is restricted owing to sea-ice conditions. Thus the abundance of fossil radiolarians decreases as temperature and salinity decrease. Using a quantitative approach to the radiolarian fossil record, it is possible to reconstruct both sea surface conditions and vertical water mass structures in

the Bering Sea. For example, comparison of surface dwellers (e.g., *Stylochlamyidium venustum*) and intermediate water dwellers (e.g., *Cycladophora davisiana*) enables reconstruction of sea-ice distribution and extent of North Pacific Intermediate Water (NPIW) formation.

Based on the relative abundance patterns of *C. davisiana* in seven piston cores obtained from the Bering Sea, source regions of North Pacific Intermediate Water during the last 100 kyr were reconstructed as follows: (1) both the Okhotsk Sea and the Bering Sea during MIS 5 to 3; (2) the Bering Sea around the LGM; and (3) the Okhotsk Sea after the LGM (Tanaka and Takahashi, 2005). In summary, high-resolution analyses of relative abundances and accumulation rates of selected radiolarian species in Bering Sea cores permits reconstruction of sea surface conditions including sea-ice cover, temperature, salinity, vertical water mass structure, and the extent of NPIW formation.

Diatoms

Assemblage Analyses

Distribution of fossil diatom assemblage provides useful information for paleoceanographic reconstruction, especially in the high latitude regions. Relative to other primary producers, diatoms grow comparatively well in high nutrient conditions, and such conditions generally occur at high latitudes. Thus, Bering Sea diatoms can be used as proxies of basic features of the marine environment, including temperature, primary productivity, sea-ice cover, and surface circulation. Paleoenvironmental reconstruction is performed using diatom accumulation rates and relative abundances of individual taxa. Techniques call for preparation of smear slides directly from the core sediment, followed by identification of the first 300 randomly encountered diatom valves to species level. Processing to remove the clay fraction, organic matter, or calcite is not necessary in deep basins of the Bering Sea, because diatoms generally overwhelm the sediment (Sancetta and Robinson, 1983). However, processing may be necessary to remove terrigenous material from shelf samples. Counts are transformed into percent abundances. Paleo-temperature and sea-ice cover can be reconstructed using the Td index method of Kanaya and Koizumi (1966) and the transfer function technique of Imbrie and Kipp (1971). Distributions of sea-ice and marginal ice cover zones can also be mapped using ice algae and ice margin assemblages.

In the case of enclosed marginal basins such as the Bering Sea, specific diatom taxa can provide useful paleoenvironmental information. During glacial periods, the Bering continental shelf was emergent, and the Bering Strait was closed (e.g., Takahashi, 1999). The abundance of shelf-dwelling benthic diatoms in glacial sediment of the Bering Sea is the result of sea-level drop and erosion of shelf material (Sancetta et al., 1985). Modern surface water circulation and configuration of glacial passes suggest that the south Bering Sea was significantly influenced by the Alaskan Stream during glacial stages. Fluctuations in the relative abundance of *Neodenticula seminae*, a tracer of the Alaskan Stream water mass (Sancetta, 1982) confirms that inflow of the North Pacific water into the Bering Sea changed remarkably during the late Quaternary (Katsuki and Takahashi, 2005).

Diatoms as a Proxy for Sea Ice

Diatom assemblages can be used as a proxy for sea-ice extent and its annual duration. The majority of sea-ice reconstructions for polar regions have drawn

conclusions based upon percent abundances of diatoms with sea-ice affinities (Sancetta, 1983; Sancetta and Robinson, 1983; Gersonde and Zielinski, 2000; Gorbarenko *et al.*, 2004). In Antarctica, Gersonde and Zielinski (2000) determined that sea ice was present when more than 3% of the assemblage consisted of sea-ice diatoms, but they didn't go so far as to estimate the annual duration of sea-ice cover.

In the Bering Sea, two species unequivocally indicate the presence of sea ice: *Fragilariopsis oceanica* and *Fragilariopsis cylindrus* (Horner and Alexander, 1972). *Fragilariopsis* species are frozen into sea ice and bloom when the ice begins to melt in the spring. Diatoms do not bloom when sea ice is present, so the annual duration of sea ice should not have an effect on the percent *Fragilariopsis* in a sample (Gersonde and Zielinski, 2000). However, because sediment samples taken from a core generally represent an average of decades to centuries of deposition, high percentages of *Fragilariopsis* suggest that sea ice reached the sample site relatively often. Sancetta (1983) determined that low percentages of *Fragilariopsis* are indicative of 1-2 months of sea ice, while high percentages denote up to 6 months of sea ice. However, these annual durations are qualitative estimates unsupported by empirical correlation of percent *Fragilariopsis* to sea-ice duration.

Over 80 surface sediment samples have already been analyzed for diatoms on the Bering Shelf (Sancetta, 1982) where sea ice persists today between 0 and 5 months per year. Additional surface samples from the Chukchi Sea (Sancetta, 1982) expand this data set to include points where sea ice persists for up to 8 months per year. However the number of samples for each month is usually very small (i.e. for 1-2 months of sea ice there are only 4 samples). The opportunity exists for further statistical correlation of modern diatom assemblages with the annual duration of sea ice in the Bering Strait region and improvement of assemblage-based proxy estimates of past sea-ice duration.

A quantitative method to determine sea-ice duration around Antarctica using the modern analog technique has been proposed by Crosta and Pinchon (1998). This statistical technique numerically compares fossil and modern data to determine whether the modern assemblage is a good analog for the fossil assemblage. Their model provides the researcher with a standard error for each estimate of sea-ice duration, and new modern samples can easily be added to improve the output. Although this method has been able to predict the number of months per year that sea ice was present around Antarctica with an error of approximately $\pm 1-2$ months, it has been met with strong criticism (Gersonde and Zielinski, 2000)

Diatom-bound $\delta^{15}N$ as a Tracer of Surface Ocean Nutrient Status

Phytoplankton preferentially assimilate ^{14}N -nitrate (Pennock *et al.*, 1996; Waser *et al.*, 1998), leaving surface water nitrate enriched in ^{15}N (Altabet and Francois, 1994; Wu *et al.*, 1997; Sigman *et al.*, 1999b). Because nitrate is the ultimate N source for phytoplankton in nutrient-rich surface waters, elevation in the $^{15}N/^{14}N$ of surface nitrate is paralleled by the $^{15}N/^{14}N$ of organic nitrogen produced in the surface ocean and exported as sinking organic matter (Altabet and Francois, 1994; Altabet and Francois, 2001; Lourey *et al.*, 2003). Thus, the degree of nitrate utilization occurring in the surface ocean is regionally correlated with the $\delta^{15}N$ of N exported from the euphotic zone and stored in the sediment (Altabet and Francois, 1994; Farrell *et al.*, 1995; Francois *et al.*, 1997). $\delta^{15}N = \{[(^{15}N/^{14}N_{\text{sample}})/(^{15}N/^{14}N_{\text{reference}})] - 1\} * 1000$, where the reference is atmospheric N_2 .

However, use of bulk sedimentary isotopes to reconstruct changes in the isotopic composition of the sinking flux in open ocean settings is complicated by diagenetic processes occurring within the sediment, which tend to raise the $\delta^{15}\text{N}$ of the residual organic matter. Studies of modern productive, continental margin sediment frequently find no evidence for this effect (Altabet et al., 1999; Thunell et al., 2004); however, open ocean studies have observed clear enrichments of as much as 5‰ (Altabet and Francois, 1994; Altabet, 1996; Sachs et al., 1999), and downcore changes are likely in such settings.

To avoid problems of diagenetic alteration, a growing body of paleoceanographic work is focusing on the organic matter internal to microfossils, and most work to date involves the siliceous frustules of diatoms (Shemesh et al., 1993; Sigman et al., 1999a; Crosta and Shemesh, 2002; Crosta et al., 2002; Robinson et al., 2004; Robinson et al., 2005). Studies indicate that this organic matter is native to the diatoms and protected from early bacterial diagenesis (King, 1977; Swift and Wheeler, 1992; Kröger et al., 2000; Ingalls et al., 2003; Poulsen et al., 2003; Ingalls et al., 2004).

Recent studies employ a new method for measuring diatom-bound $\delta^{15}\text{N}$ ($\delta^{15}\text{N}_{\text{db}}$) in both Antarctic and the Subarctic Pacific sediment and confirm that bulk sedimentary $\delta^{15}\text{N}$ is not always a reliable indicator of past changes in the $\delta^{15}\text{N}$ of the sinking flux (Robinson et al., 2004; Robinson et al., 2005; Brunelle et al., in review). For instance, in a record from the Bering Sea extending back to the last interglacial, $\delta^{15}\text{N}_{\text{db}}$ progressively increases as the climate cools, showing a 3.5‰ increase from early stage 5 to latest stage 2. Bulk sedimentary $\delta^{15}\text{N}$ measured in the same core does not rise until latest stage 3, and the overall increase is only 1.5‰.

These recent measurements of $\delta^{15}\text{N}_{\text{db}}$ in a core from the Bering Sea basin have been used to reconstruct a history of nutrient utilization at this site (Brunelle et al., in review). Combined with measurements of opal content and biogenic barium, indicators of paleoproductivity, these data suggest that surface nutrient utilization was higher but biologic productivity lower during much of the last glacial period, indicative of a more strongly stratified water column in the Bering Sea. Thus, in conjunction with paleoproductivity proxies, $\delta^{15}\text{N}_{\text{db}}$ has the potential to yield information about nutrient status as well as physical oceanographic characteristics. Downcore measurements of $\delta^{15}\text{N}_{\text{db}}$ at sites on either side of the Bering Strait will help constrain changes in both the prevailing biogeochemical characteristics and water column structure, which will be of particular importance when considering how the opening and closing of the strait affects local and regional oceanography.

Marine Organic Compounds

There is a large array of paleoceanographic proxies that utilize specific organic compounds extracted and separated from the organic fraction of the sediment. Marine derived organic compounds, such as alkenones, can be used to reconstruct surface ocean conditions. A common technique involves the measurement of the alkenone unsaturation index (U^k_{37}), which has a strong correlation with ocean temperatures in the modern ocean and has been extensively calibrated. The U^k_{37} index utilizes long-chain (C37) ketones synthesized by certain species of phytoplankton (coccolithophorid algae). Because it is found in the organic fraction of the sediment, it is an indicator of past SSTs that is completely independent from the Mg/Ca temperature proxy, which is measured on calcite

shells. The technique involves the separation and quantification of C37:2 relative to C37:3 alkenones using gas chromatography, and calculation of the index from these quantities [$U^{k'37} = C37:2 / (C37:2 + C37:3)$]. Typical internal precision, based on replicates of lab liquid consistency standards, is ± 0.005 , equivalent to $\pm 0.14^\circ\text{C}$. External precision, based on replicates of sediment standards is ± 0.008 (± 0.24). SSTs can be calculated from $U^{k'37}$ (Herbert, 2000; Muller et al., 1998), which typically gives reasonable absolute temperatures when applied to recent sediment.

The carbon isotopic ($\delta^{13}\text{C}$) composition of alkenones can be used to obtain information about the carbon dioxide concentrations of surface water, because the difference between the $\delta^{13}\text{C}$ of alkenones and those of the coeval surface-dwelling planktonic foraminifera represents the approximate carbon isotopic fractionation ($\epsilon_{p37:2}$) that occurs during photosynthetic carbon fixation. ϵ_p is primarily controlled by the $[\text{CO}_{2\text{aq}}]$, cell geometry of the organism (Popp et al., 1998), and cellular growth rate (Bidigare et al., 1997, 1999; Laws et al., 1995). The hydrogen isotopic (D/H) composition of alkenones can be used to reconstruct the D/H of surface seawater (Englebrecht and Sachs, 2005), which reflects the regional balance of precipitation-evaporation. Measurements of the isotopic composition of organic compounds such as alkenones can be made with quite good precision, but precision of the climate/ocean parameter estimates varies widely depending on the environment and on the quality of calibrations, which require regional groundtruth studies.

Summary

Coring intercalated terrestrial and marine sediment preserved in Bering Sea basins will, for the first time, permit direct dating of the opening and closing of the Bering Strait and clarify its role in the onset and termination of northern hemisphere glaciations. Whereas the presence of terrestrial sediment, including coal and paleosols, has been well documented in the Cretaceous-Eocene sections of Bering Sea basinal sequences, the origin of Plio-Pleistocene units remains uncertain. Workshop participants agree that additional processing of existing seismic data is needed in order to extract further information regarding the nature and thickness of sedimentary units and select optimal coring sites.

Identification of terrestrial and marine deposits in cores will be based on micropaleontology, sedimentology, C/N ratios, and beryllium isotopes. Units will be dated by multiple methods with overlapping temporal ranges. Experimental methods, including TL, OSL, and cosmogenic isotopes can be employed to provide additional estimates of the dates of land bridge emergence and burial. Correlations will be based on sedimentology, chemostratigraphy, and marker beds such as ash deposits and paleosols. Radiometric dating of tephra units will facilitate correlation of terrestrial and marine records throughout Beringia and explore connections between explosive volcanism and rapid climate change.

Reconstruction of in Bering Sea productivity, water mass circulation, depth, SST, and sea-ice cover based on sedimentary, isotopic, and biological proxies will clarify the impact of changes in global ocean circulation caused by opening and closing of the Bering Strait gateway. This dataset has the potential to resolve decades of debate regarding the nature and significance of the gateway with respect to abrupt and gradual climate changes. Analyses of insects, pollen, grass cuticle, phytoliths, and stable isotopes

from terrestrial deposits will provide the first paleoclimatic and paleoecological reconstructions of the submerged Bering Land Bridge. With these data, we can finally address longstanding questions regarding human habitability, biogeography, and the relationship between land bridge emergence, competition, and faunal extinctions.

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