Cenozoic Evolution of the Arctic Basin: from forests to tundra & sea ice

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The paleoclimatic and oceanographic history of the Arctic, including the history of sea ice, is contained in the sedimentary history of the deep basins as well as that of the continental shelves. Targeted sites are known on many continental margins where sedimentation rates are likely high enough to test old dogmas concerning the environmental history of the arctic. For example, much of the Cretaceous and Tertiary record is missing from existing Arctic Ocean cores, however patchy fossiliferous terrestrial and nearshore marine sedimentary records on the surrounding landmasses, including Greenland, indicate that the Arctic Ocean lacked much sea ice and adjacent landscapes lacked tundra until nearly 3.2 Ma. How did the Arctic evolve from the warm temperate climate of the Eocene at 75º N paleolatitude to tundra in the late Pliocene? What caused such change in overall pole-equatoral gradients? The late Cenozoic, especially post-mid Pliocene, is thought to have been a time of significant environmental change in the Arctic regions marked by the initiation of glacial/interglacial change some 2.6 Ma, yet no depositional sequence has been found to continuously record this phase of climate evolution with adequate fidelity for comparison with the low latitudes. How do we properly interpret sea ice IRD from glacial IRD starting as early as 8 Ma? High resolution seismic and coring/drilling studies are needed on the arctic shelves and perhaps the deep basins to capture this record from the marine environment. Such studies will also allow an evaluation of the changing role of the arctic water masses and sea ice in climate change and North Atlantic thermohaline circulation, especially the role of continuous contemporary connections to the fresher Pacific basin with or without seasonal pack ice. Past intervals without sea ice across the Arctic should provide the context for the scenario we will likely face by 2075. The new availability of mission-specific platforms within IODP may help provide the impetus for coring in previously inaccessible areas of the arctic.

High-resolution records of recent climate change highlighting variations during the Holocene and previous interglacials are important for understanding both the stability of our present climate and the vulnerability of the Earth system to thresholds of rapid climate change. Access to Arctic sedimentary and biological archives of this climate record should be a high priority.

(note: my text here is extracted verbatim in places and modified from materials I and others contributed to Grantz et al, 1991, Opportunities and Priorities in Arctic Geosciences, National Academy Press; and Schlosser et al, 2003, Arctic Research Support and Logistics, National Science Foundation. Many science issues remain the same and unresolved.)

Application of SCICEX geophysical data for tectonic studies in the Amerasian Basin

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Between 1995 and 1999, the U.S. Navy carried out five nuclear submarine cruises to the Arctic Ocean through the SCICEX (SCience ICe EXercise) program. Data routinely collected on all of the cruises includes narrow-beam echo-sounder bathymetry, gravity, ADCP, sail-mounted CTD, and ice-bottom profiles. During the last two cruises the SCAMP system was installed, which added the capability to collect swath-bathymetry, sidescan and CHIRP sub-bottom data. Most of the data is of very high quality with the navigation being the limiting factor.

The SCICEX cruises were designed to facilitate a number of research objectives in different disciplines. As a result, the geophysical data provides excellent reconnaissance coverage over almost all of the basin and detailed coverage over limited areas. Areas of detailed surveys in the Amerasian Basin include portions of the Lomonosov Ridge, the Chukchi Borderlands and the Alpha Ridge. This submarine data can be used to better define and also to begin to address scientific problems related to these major features of the Amerasian Basin.

The Lomonosov Ridge serves as an example of how the SCICEX data can be used. The Lomonosov Ridge forms the Eurasian continental margin of the Amerasian Basin. The different models for the origin and development of the basin predict a very different evolution and structure for the Amerasian flank of the Lomonosov Ridge. "Arctic-Islands transform" models assume that northern Alaska rifted off of Eurasia so the straight continental margin of Arctic Canada is a transform margin. This model predicts that the Lomonosov margin is a rifted margin. "Arctic-Alaska transform" models are also translational, but assumes that the Canadian Arctic Islands and East Siberian margins are rifted continental margins and that the Lomonosov Ridge and Alaska margin are transform margin. "Rotational" models involve counterclockwise rotation of Alaska away from Arctic Canada about a pole located near the mouth of the MacKenzie River. This model also predicts that the Lomonosov margin is translational, but it falls along a small circle about the opening pole rather than be linear as in the Arctic-Alaska transform model.

The SCICEX bathymetry and gravity data allows individual fault blocks associated with the Lomonosov Ridge to be traced across the Arctic Ocean. The Amerasian margin of the Lomonosov Ridge structure, much of which is buried beneath Makarov Basin sediments, falls very closely along a small circle about the Grantz et al pole for the rotational model for the development of the Amerasian Basin. This result both supports that model and emphasizes what additional data is needed to test and prove this hypothesis. The SCICEX data can be used in a similar manner in other portions of the Amerasian Basin to better define and address the outstanding tectonic problems as well as to quantify exactly what further data is needed to define the tectonic evolution of the basin in a plate tectonic framework.

Cretaceous to recent tectonics of the Arctic

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A number of scenarios have been proposed for the tectonic evolution of the Arctic. One of the first was a paper by Shatskiy (1935) who suggested that the Canada Basin had been a cratonic high that shed debris southward onto Arctic Canada and northern Alaska. This high was later oceanized by mantle convection that eroded the root and caused the area to subside. Karasik (1968) was the first to identify evidence of seafloor spreading for the Eurasian Basin. Grantz (1966) followed by Hamilton (1967) and Tailleur (1969) developed the idea of rotational opening of the Canada Basin as the result of seafloor spreading. A simple, windshield wiper-like rotational opening of Arctic Alaska/Chukotka away from the Canadian Arctic margin presents the problem of how to dispose of the partially continental Chukchi Borderland. Art Grantz [Grantz et al., 1998] has cored in situ material that dates to the Cambrian from Northwind Escarpment and gravity data suggest that at least part of the Northwind ridge is continental. Since other parts of the Chukchi Borderland may be continental as well, a simple, one-stage rotational opening of Canada Basin is not possible.

There is little information to support the time of opening of the Canada Basin since the normal constraints of easily identified magnetic anomalies are absent. Depth and heat flow versus age both suggest an Early Cretaceous age of opening but lineated magnetic anomalies in the Canada Basin are few and remain uncorrelateable. Geological information from the margins of the Canada Basin suggest opening may have begun about 140 to 135 Ma (Grantz and May, 1982; Harrison et al., 1999). The Cretaceous opening of the Canada Basin probably ceased sometime around 120 Ma or later, possibly because the Arctic Alaska/Chukotka block collided with a part of Siberia. An animation for the opening of the Canada Basin using rigid, tectonic plates produces some interesting problems particularly when the effect of the Cenozoic opening of the Eurasian Basin is considered for the area of Far Eastern Siberia. If opening of the Labrador Sea/Baffin Bay region began prior to opening of the Eurasian Basin then some form of Late Cretaceous to Early Cenozoic distributed extension may be overprinted on the simple rotational opening of the Canada Basin. Aerogeophysical data collected by the Naval Research Lab (Brozena et al., 1999) found bull's eye gravity anomalies with radiating magnetic anomalies southeast of the Mendeleev Ridge, some coincident with known seamounts such as the ones south of the Alpha Ridge at 150˚W and 160˚W. These highly magnetized "seamounts" may have been produced during the period after the Labrador Sea began to open, perhaps as early as 80 Ma and prior to the opening of the Eurasian Basin at about 56 Ma (Brozena et al., 2003).

If rigid plates are used to reconstruct the paleogeographical history of the Arctic, an "open" area south of the South Anyui suture in Far Eastern Siberia must existed after rotational seafloor spreading in the Canada Basin ended. This area presumably underwent closure and deformation with the Cenozoic opening of the Eurasian Basin. Evidence for such deformation in Far Eastern Siberia along what should have been the North American/Eurasian plate boundary needs to be explored. There are numerous other unanswered questions concerning the Cretaceous to recent tectonic evolution of the Arctic region, particularly with regards to timing.

References:

Brozena, J.M., Childers, V.A., Kovacs, L.C., and Lawver, L.A., 1999, New aerogeophysical evidence for the rotational opening of the Southern Canada Basin, *EOS*, Transactions, 1999 Fall Meeting American Geophysical Union, v. 80, n. 46, p. F995.

Brozena, J.M., Childers, V.A., Lawver, L.A., Forsberg, R., Faleide, J.I. and Eldholm, O., 2003. A New Aerogeophysical Study of the Eurasia Basin and Lomonosov Ridge: implications for Basin Development, Geology 31, 825-828 plus insert

Grantz, A., 1966. Strike-slip faults in Alaska. U.S. Geological survey Open-file Report 267, 82 p.

Grantz, A. and May, S.D., 1983. Rifting history and structural development of the continental margin north of Alaska, *in* Watkins, J.S., and Drake, C., eds., Studies in continental margin geology. American Association of Petroleum Geologists Memoir 34, 77-100.

Grantz, A., Clark, D.L., Phillips, R.L., Srivastava, S.P., and 14 others, 1998. Phanerozoic stratigraphy of Northwind Ridge, magnetic anomalies in the Canada Basin, and the geometry and timing of rifting in the Amerasia Basin, Arctic ocean. Geological Society of America Bulletin 110, 801-820.

Hamilton, W., 1967. Continental drift in the Arctic [abs.], *in* Symposium on continental drift, Montevideo, Uruquay, UNESCO, International Union of Geological Sciences, p. 192-193.

Harrison, J.C., Wall, J.H., Brent, T.A., Poulton, T.P., and Davies, E.H., 1999. Rift-related structures in Jurassic and Lower /cretaceous strata near the Canadian polar margin, Yukon Territory, Northwest Territories, and Nunavut: Geological Survey of Canada, Current Research 1999-E, 47-58.

Karasik, A.M., 1968. Magnetic anomalies of the Gakkel ridge an d origin of the central Arctic Ocean: Geophysical methods of prospecting in the Arctic 5, 8-19.

Shatskiy, N.S., 1935. On the tectonics of the Arctic (in Russian): The geology and mineral resources of the northern USSR Glavsenmorputi, Ist Geological Invitational Conference, Moscow, Translation, v. 1., 149-168.

Tailleur, I.L., 1969. Rifting speculation of the geology of Alaska's North slpe: Oil and Gas Journal 67, 128-130.

For a general review of tectonic models for the Canada Basin see:

Lawver, L.A. and Scotese, C.R., 1990. A review of tectonic models for the evolution of the Canada Basin, *in* Grantz, A., Johnson, L., and Sweeney, J.F., eds., The Arctic Ocean region: Boulder, Colorado, Geological Society of America, The Geology of North America, v. L, 593-618.

For a ultra-mobilistic view of the Ordovician to recent evolution of the Arctic see:

Lawver, L.A., Grantz, A., and Gahagan, L.M., 2002. Plate kinematic evolution of the present Arctic Region since the Ordovician, *in* Miller, E.L., Grantz, A., and Klemperer, S.L., eds., Tectonic Evolution of the Bering Shelf-Chukchi Sea- Arctic Margin and Adjacent landmasses: Boulder, Colorado, Geological Society of America Special Paper 360, p. 333-358, plus animation on CDrom and Plates in pocket.

Continental Structure/Tectonics and Formation of Amerasian Basin

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The Amerasian Basin of the Arctic presents an unsolved plate tectonic puzzle largely because there are so few constraints upon which to build models and reconstructions.
Proposed plate tectonic models for the Amerasian Basin include a wide variety of solutions to the puzzle, all of which make very different predictions for the tectonic, thermal and subsidence history of the various parts of the Amerasian Basin margins. A correct plate tectonic reconstruction of the Amerasian Basin is required in order to 1. understand the origin and evolution of the vast system of Arctic shelves and their sedimentary basins, 2. contribute to our understanding of how the bathymetry of the basin evolved, and 3. provide a geologic context for the modern tectonic framework of the region and the location of active faults and seismicity.

The greatest gap in our knowledge is NE Russia, whose onshore geology has the potential for contributing in a significant fashion to a more accurate plate tectonic model for formation of the Amerasian Basin. Similarly, the broad Siberian Shelf represents a region whose subsurface geology is poorly known, and seismic reflection data and wells are sparse if not existent. The timing of events prior to, during and after opening of the Amerasian Basin are not well-known (Alaska) or not known at all (Russia), but the age and nature of rock units, the timing and style of geologic structures, the extent and history of sedimentary basins and their correlation from Alaska to Russia could provide key information needed to test and create new models for the opening of the Amerasian Basin. Within the Amerasian Basin itself, a better understanding of the age and thickness of sediments, the age and nature of the Alpha Ridge (is it underlain by any thinned continental crust) and whether the Lomonosov Ridge represents a rifted margin or a strike-slip margin are among the outstanding unresolved questions whose answers are needed to constrain the tectonic history of the Basin.

An Overview of Depositional Environments in the Arctic Ocean

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The Arctic Ocean is a unique ocean basin because it is almost entirely enclosed by continental landmasses and is permanently ice covered. Links to other oceans are limited to the Bering Strait (Pacific), Nares Strait, Fram Strait and the Barents Sea (Atlantic). The Arctic Ocean Basin is traditionally discussed in terms of two regions: the Eastern Arctic Ocean and Western Arctic Ocean. These two regions are divided by the Lomonosov Ridge, which separates the Eurasian Basins (Amundsen and Nansen Basins) from the Amerasia Basins (Makarov and Canada Basins). This presentation summarizes results from expeditions that have taken place since the early 1990's for five physiographic regions: Nansen Basin, Gakkel Ridge, Amundsen Basin, Lomonosov Ridge, and Makarov Basin.

Lomonosov Ridge sediments represent a stratigraphy uninterrupted by mass flow deposits. The cores collected here are fine-grained sediments with intervals of sandy clay and clay clasts. Interpretation of the age of the Lomonosov Ridge sediment suggests a rate of deposition of 1 cm/ka and likely represents a minimum rate. When compared with Lomonosov Ridge sediments, the sedimentation rates of the Amundsen and Nansen Basins are higher, as a result of the dominance of turbidite deposition. In contrast to the other basins, the Makarov Basin sediments may have sedimentation rates that are only slightly higher than Lomonosov Ridge due to the lower frequency of turbidites deposited within this basin. These interpretations are supported by the overall sediment fill within each of the basins interpreted from seismic reflection data. Gakkel Ridge sediments are anomalous when compared with the other physiographic regions of the eastern and central Arctic Ocean. The sediments are dominated by two factors: their locally derived volcaniclastic source and the ubiquitous presence of mass wasting events.

Quaternary stratigraphy, paleoceanography, and glacial history of the Amerasian Basin

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Quaternary sediments in the Amerasian Basin are generally characterized by distinct cyclicity in lithology and microfaunal distribution that reflects contrasting glacial/interglacial sedimentary patterns. This indicates that glaciations at the Arctic margins and sea-level changes had a profound influence on hydrography, biology, and sedimentation in the basin interior. Thus, Amerasian sedimentary archives hold a key to understanding the evolution of the Arctic Ocean circulation, sea ice, and biota, as well as glacial history of the Arctic margins. However, the disparity of existing age models for basin sediments impedes the investigation of these archives. Traditional estimate of Late Cenozoic sediment age in the basin, based on paleomagnetic inclination measurements, indicated very low temporal resolution of <1 mm/kyr that offered limited use of these sedimentary records for paleoceanographic research. Recent data from the Eurasian Basin and Lomonosov Ridge allow re-evaluation of the age estimates for the Arctic Ocean sediments and suggest higher sedimentation rates suitable for much more detailed paleoceanographic reconstructions. There is a need to establish a definitive age control for Arctic Ocean sediments and extend it across the Amerasian Basin using a combination of chronostratigraphic techniques and proxy records such as stable-isotope, faunal, mineralogical, and clast provenance.

Investigation of sedimentary records from the basin needs to be complemented by surveying seafloor morphology by complex geophysical methods including multibeam bathymetry and sidescan and penetration sonar. This approach is critical for establishing the history of (1) ice grounding on continental margins and oceanic ridges and (2) mass-wasting processes related to glacial and seismic events and sea-level changes. Data recovered by SCICEX and Healy expeditions indicate extensive erosion of the Chukchi and Alaskan margins and the Chukchi Borderland by grounded ice to water depths of 700+ m, which implies the existence of huge, Antarctic-style ice shelves in the Pleistocene Arctic Ocean. Understanding the stratigraphy and provenance of these features is needed to reconstruct the extent and timing of ice shelves and their relationship with continental ice sheets at the Arctic margins.

Amerasian Basin questions: a view from Europe

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The European continent now borders the Arctic Ocean along the margin of the Eurasia Basin, where the Barents/Kara shelf and associated archipelagos form one of the Arctic's extensive passive continental shelves. Prior to opening of the Eurasia Basin and separation of the Lomonosov Ridge, continental Europe was adjacent to the Amerasia Basin. The opening of the Amerasia Basin is usually explained by the Cretaceous counterclockwise rotation of the Alaska-Chukotka block away from the Canadian Arctic margin. Implicit in this hypothesis is that the Amerasia Basin side of the Lomonosov Ridge is bounded by a continental-scale, curved dextral transform fault system that passes onto the Russian Arctic shelf, where it is usually linked with the South Anyui Suture. The rotational geometry and connection with closure of the South Anyui Ocean suggest a geodynamic mechanism controlled by Pacific events.

On the Barents/Kara shelf, however, there is little evidence of this Cretaceous tectonic regime. Three crustal fabrics generated by collisional orogenic events converge on the Barents/Kara Shelf: the western part of the shelf is dominated by the mid-Paleozoic Caledonian Orogeny, the eastern part by the Late Paleozoic to Early Mesozoic Uralian Orogeny and the southern part by the Late Proterozoic Timanian Orogeny. At least two of these orogens trend towards the region now occupied by the Arctic Ocean. In addition to collisional events, periodic extensional events have affected the European Arctic throughout Late Paleozoic and Mesozoic time, many of which were associated with rifting along the proto-North Atlantic system. These episodic rift events culminated in seafloor spreading when the Norwegian-Greenland Sea and Eurasia Basin began to open in Early Cenozoic time. The Late Mesozoic-Cenozoic tectonic evolution of the European Arctic appears to be dominated by this 'Atlantic' signature.

These relationships imply that only the thin continental sliver of the Lomonosov Ridge separates the 'Atlantic' tectonic regime of Europe from the 'Pacific' tectonic regime in the Amerasia Basin. Is such an abrupt boundary between two different tectonic regimes a credible interpretation, or should we be looking for a more diffuse transition, or even a more radical reinterpretation? Evidence for an 'Atlantic' signature may exist in the central Arctic Ocean (Makarov Basin and Alpha-Mendeleev Ridge), but would imply a different opening mechanism to the remainder of the Amerasia Basin, with the possibility of additional continental fragments that were originally part of Europe. Conversely, there may be 'Pacific' aspects to the tectonic evolution of the Barents/Kara shelf that have previously been overlooked? This talk will review what evidence we already have and what evidence we need to collect in order to resolve these issues.

Paleoceanography of the Arctic: Progress and Promise

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With global greenhouse warming, mean annual temperatures are expected to rise by as much as 3-5°C in the Arctic severely reducing the extent of seasonal and permanent sea-ice coverage. Given the influence of sea-ice formation on heat-exchange, albedo, and seawater density, these changes are expected to impact other climatic processes, particularly atmospheric and thermohaline ocean circulation. Though the exact nature of these changes remains unclear, it is evident from deep-sea sediment archives recovered from the north Atlantic that variations in the extent of Arctic sea ice over the recent past (~ 20 kya) have had significant impacts on global thermohaline circulation patterns. For example, in the North Atlantic at the height of the last glacial maximum, deep water formation rates were substantially reduced. Moreover, it appears these shifts in circulation patterns occurred quite abruptly, often over decades. It is also evident from studies of terrestrial and land-based marine sediments exposed in Canada and Alaska, that the Arctic was much warmer in the more distant past (i.e., the Eocene), and may have been largely ice-free. Mean annual temperatures in coastal regions were high enough (>12°C; Tripati et al., 2001) to sustain flora and fauna with temperate to sub-tropical affinities (i.e., palms, crocodiles; Harrington, 2004). As with present warming, empirical and theoretical evidence suggest that this extreme warmth was fostered by elevated greenhouse concentrations (Shellito et al., 2003).

Given the critical role of the Arctic in global climate, considerable motivation exists to resolve the natural climatic variability of this region, on short (~ 10-100 kyr) and long (1-100 myr) time scales. Though few sediment cores have been recovered from the Amerasian and neighboring basins, investigations of those few archives have yielded important insight into several aspects of Arctic paleoclimates and paleoceanography. This includes insight into ice drift and atmospheric circulation patterns (Darby & Bischof, 2004; Phillips & Grantz, 2002), the distribution of deep-water masses within basin (Polyak et al., 2004), as well as on the timing and extent of circum-Arctic continental glaciation (Thiede et al., 1998). From these and other studies, it is evident that the sediments in the Arctic have much to teach us about the climatic evolution of this region. To this end, efforts are currently underway to initiate deep coring operations with the Lomonosov Ridge as the first drilling target with the promise of recovering sediments extending back 50 myr.

Darby DA, Bischof JF. A Holocene record of changing Arctic Ocean ice drift analogous to the effects of the Arctic Oscillation. Paleoceanography 19, Pa1027, 2004.

Harrington GJ, Structure of the North American vegetation gradient during the late Paleocene/early Eocene warm climate. Evol. Ecol. Res., 6, 33-48, 2004

Phillips RL, Grantz A., Regional variations in provenance and abundance of ice-rafted clasts in Arctic Ocean sediments: implications for the configuration of late Quaternary oceanic and atmospheric circulation in the Arctic. Mar. Geol., 172: 91-115, 2002.

Polyak L, Curry WB, Darby DA, Bischof J, Cronin T., Contrasting Glacial/Interglacial Regimes in the Western Arctic Ocean as Exemplified by a Sedimentary Record From the Mendeleev Ridge. Palaeogeogr. Palaeoclim. Palaeoecol. 203: 73-93, 2004.

Shellito CJ, Sloan LC, Huber M, Climate model sensitivity to atmospheric CO2 levels in the Early-Middle Paleogene, Palaeogeogr. Palaeoclim. Palaeoecol. 193: 113-123, 2003.

Thiede J, Winkler A, Wolf-Welling T, Eldholm O, Myhre AM, Baumann KH, Henrich R, Stein R., Late Cenozoic history of the Polar North Atlantic: Results from ocean drilling. Quat. Sci. Rev., 17: 185-208, 1998.

Tripati A, Zachos JC, Marincovich L, Bice K, Late Paleocene Arctic coastal climate inferred from molluscan stable and radiogenic isotope ratios. Palaeogeog. Palaeoclimat. Palaeoecol. 70, 101-113, 2001.