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24 June 1994



Dr. G. Leonard Johnson
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Dear Dr. Johnson,

This letter is in reference to ONR Grant Number N00014-93-1-1224, "Waste Disposal Practices of the Former Soviet Union in the Arctic Environment." Due to your request for the change in end date from 30 June 1995 to 15 April 1994, JOI is submitting the following final report for activities in the period covered, 1 January to 15 April 1994.

With scientific staff familiar with Arctic research, JOI proposed to support the final synthesis and summarize the results from the ONR research program on radionuclides in the Arctic Program which resulted from the waste disposal practices of the former Soviet Union. This support was to have included development, scientific editing, formatting for printing, publishing, and distributing the final document from this analysis.

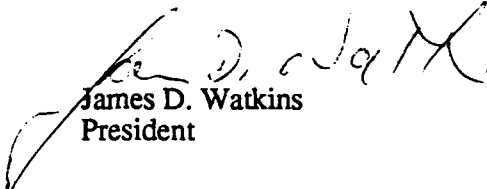
At your request, JOI changed the scope of work to cover editing and formatting of the paper *Arctic Structural Evolution: Relationship to Paleoceanography* (Johnson et al., in press) and delivering a camera ready version for publication (attached) in the forthcoming special edition Journal of Geophysical Research.

Funds expended during this time primarily covered salaries, and minor shipping costs. Costs incurred after 15 April are due to preparation of the final report. All remaining monies will be returned.

JOI appreciates your support of this activity and looks forward to continue working with you in the future.

Sincerely,

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James D. Watkins
President

cc: M. Fitzgerald
L. Claflin
C. Hayes, Administrative Grants Officer
Director, Naval Research Laboratory
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Arctic Structural Evolution: Relationship to Paleoceanography

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This paper summarizes major events in the tectonic evolution of the Arctic from a paleoceanographic perspective focused on the formation of oceanic basins in the Mesozoic and Cenozoic. Despite its present cold climate, the Arctic land masses once lay much farther to the south and were gradually carried northward by plate tectonic motions. For example, in the Late Carboniferous northern Greenland, which was part of Pangea, was situated at only 30°N with the Panthalassa Sea to the north. By Late Jurassic-Early Cretaceous, a series of allochthonous blocks had collided with both the North American and Siberian plates. The Pacific Ocean was separated from the Arctic Basin by rotation of the North-Slope Chukotka block counterclockwise away from the Canadian Arctic Islands by Mid Cretaceous. It is speculated, based on the magnetic patterns, that the Alpha-Mendeleev Ridge complex may either have been a separate precursor block or may represent oceanic crust modified by a hot spot. Sea floor spreading in Late Cretaceous or Early Paleocene rifted the present Makarov Basin in a wedge-shaped manner, with the Siberian end wider than the Canadian. The Eurasia Basin has a well-ordered set of magnetic anomalies, and thus this basin can be confidently dated to have been created just after the Cretaceous-Tertiary boundary. Creation of the Eurasia Basin eventually opened the pathway for exchange of waters between the Arctic and Atlantic oceans. The cold-oxygen rich waters from the Arctic ventilate the world's oceans and provide an important mechanism for global heat transfer and for the cycling of nutrients and carbon.

INTRODUCTION

Only in the last several decades has the morphology of the major sea floor structural features of the Arctic been defined, and detailed bathymetric data is still largely lacking. The Arctic Ocean is unique among the oceans of the world in that 49% of its area is underlain by continental shelf, primarily the wide European and Siberian continental shelves. These shelves act as ice factories, producing the Arctic sea ice and the cold residual brines that are formed by the freezing process. These waters sink as an oxygen rich dense water mass contributing to the renewal of water masses of the global ocean and to the cycling of nutrients and carbon [Broecker, 1987]. Thus the polar and subpolar seas have a global impact on the entire marine environment [Nansen Arctic Drilling Program Science Committee, 1992]. An additional Arctic characteristic of potential importance to global change is gas hydrates. These have the potential to release large quantities of methane, a greenhouse gas, if they become unstable [Kvenvolden and Grantz, 1990]. The complex sea floor topography of the Arctic Ocean is pivotal in its strong influence over the world ocean, and evolution of this sea floor must correspondingly be related to paleoclimate changes. Accordingly, this paper will focus on the paleogeography and time of formation of the Arctic Ocean

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and its two contained basins: the Amerasia and Eurasia (Figure 1). For a morphological description of the Arctic see Johnson [1990 and references contained within], and for a plate tectonic summary see Lawver et al. [1990 and references contained within].

The Cenozoic history of the Eurasian Basin is well understood because it involves the Eurasia and North America Plates (Figure 1) and is therefore constrained by data from more southerly regions. Additionally, it contains a readily decipherable sea floor magnetic pattern (Plate 1). The oldest positive magnetic lineation that can be identified with certainty in the Eurasia Basin is anomaly 24, similar to the Norwegian Sea. Other lineations at the base of the Lomonosov Ridge suggest that spreading may have occurred as early as 54-64 million years ago (Ma) [Jackson et al., 1993; Jackson and Johnson, 1986 and references contained therein]. The source of Amerasia Basin however is problematic, and there are as many hypotheses on its origin as there are investigators. An excellent summary is contained in Lawver and Scotese [1990]. In this paper we will present our ideas, based on aeromagnetic data, and relate the tectonic history to the paleogeography.

AMERASIA BASIN EVOLUTION

The following discussion is devoted to the Amerasia Basin; however it is recognized that the major paleoceanographic effect in the northern hemisphere was related to the opening of the Eurasia Basin. Three basic models have been proposed for the origin of the Amerasia Basin and the tectonic structures contained within: 1. creation of the basin by sea floor spreading, with possible modification by "hot spot" activity; 2. entrapment of continental crust with subsequent crustal thinning; and 3. a former region of subduction or compression. See Lawver and Scotese [1990] for a synopsis of the three models. For specific details and an expanded bibliography see Churkin and Trexler [1980, 1981]; Green et al. [1984]; Jackson et al. [1990]; Pogrebitsky et al. [1993a, b]; Sweeney et al. [1978]; Taylor et al. [1981]; and Vogt et al. [1984].

The key to the problem is the origin and nature of the Alpha-Mendeleev Ridge, which is the largest single submarine feature in the Arctic Ocean. In areal extent it exceeds the Alps, and, in addition to the massive exposed structure, large portions are buried beneath the Canada Abyssal Plain. The Alpha Ridge is covered for the most part by a sedimentary sequence up to 1 km in thick and has yielded Cretaceous marine sediments [Clark et al., 1986; Nansen Arctic Drilling Program Science Committee, 1992, and references contained within the latter]. The basement material on which the sedimentary cover was deposited has a sound velocity of 5.3 km/s, typical of oceanic layer 2 and also of indurated sedimentary rocks. A continental origin based on aeromagnetic data from Pogrebitsky et al. [1993a, b] is worth serious consideration and is supported by the magnetic anomaly patterns (Plate 1). It should be noted that King et al. [1966] had reached the same conclusion using

fewer data. Dredged material during the Canadian Expedition for Study of the Alpha Ridge (CESAR), from exposed basement of the ridge yielded a weathered alkaline volcanic [Van Wagoner and Robinson, 1985] consistent with a volcanic origin. The sound velocity in the layer below ranged from 6.45 to 6.8 km/s and at a depth of 20 km a velocity of 7.3 km/s was measured [Forsyth et al., 1986]. This velocity structure is similar to oceanic plateaus [Carlson et al., 1980]. The measured depth of the crust mantle boundary is 38 km at the CESAR site. This thickness could be interpreted as either continental or thickened oceanic crust due to hot spot activity such as beneath the Iceland-Faeroe Plateau. Figure 2 from Gramberg et al. [1993] shows a seismic refraction line coincident with the axis of the Makarov Basin. Moho lies at a depth of 15-20 km, which is intermediate between normal oceanic depths of about 8-10 km in the Eurasian Basin, and the Alpha Ridge with depths in excess of 30 km [Jackson and Johnson, 1986].

The magnetic anomaly pattern of the Alpha Ridge is extremely variable with peak to trough anomalies of up to 1500 nT and wave lengths of 20-75 km. While some anomalies are traceable for some distance and have a lineation pattern which is predominately NE-SW in the Canada Basin [Jackson et al., 1993], they do not exhibit a regular pattern consistent with sea floor spreading. This is obvious by comparing the pattern in the Eurasia Basin with that of the Alpha Ridge province (Plate 1). Plate 1 extends the area covered by the Alpha Ridge pattern to encompass the Canadian side of the Makarov Basin and a large section of the Canada Abyssal Plain, suggesting that this feature exists at depth there and has been covered by sediments. Riddihough et al. [1973] first noticed that the intense short-wave length magnetic anomaly pattern associated with the Alpha Ridge appears to extend across the shelf of northwest Ellesmere Island to include the Pearya terrane. Trettin [1987] defines the Pearya terrane as an amalgam of four largely shallow marine sequences which he suggests may have originated from the Caledonides of Svalbard. The rocks in this geologic provenance range from Proterozoic to Upper Silurian [Sweeney et al., 1990]; Macnab et al. [1992a] recognized this as an "exotic terrane." It should also be noted that this pattern is similar to the Siberian craton [Zonenshain et al., 1990; Pogrebinsky et al., 1993a, b] (Plate 1). In general the magnetic pattern is similar to the Iceland-Faeroe hot spot province except that sea floor spreading magnetic anomalies are totally obscured [Johnson and Tanner, 1971]. Other analogous terranes in terms of depth and size include the Campbell Plateau, Lord Howe Rise and Kerguelen Plateau (M. Langseth and K. Crook, personal communication, 1993). This suggests that a continental origin for Alpha Ridge must be considered. A possible scenario is that it is an exotic terrane that entered the Arctic prior to the closing of the Arctic by the rotation of the Alaska-Chukotka block.

The magnetic pattern in the southern Canada Basin is quite different from farther north and it exhibits a subdued

pattern consistent with sea floor spreading (Plate 1) [Taylor et al., 1981]. It has been suggested that these anomalies date to M-12, or 127 Ma of the Early Cretaceous, to M-25 or 153 Ma, Oxfordian (Upper Jurassic) [Jackson and Johnson, 1986 and references contained within], consistent with dates based on other geologic and geophysical data [Sweeney, 1985]. This rifting event would have been responsible for rotation of the North Slope-Chukotka block away from the Canadian Islands to form the southern Canada Basin. It is apparent in Plate 1 that the rifting did not completely pierce the Alpha Ridge, however, it may well have caused magmatic intrusions and thinned the presumed continental crust causing subsidence of the Alpha Ridge. The limited seismic reflection data over the complex shows many extensional features such as step faults and grabens [Jackson et al., 1990].

Figure 3 shows the hypothesized fit of the blocks at the end of the Mesozoic. The region between the Kolyma and Alpha-Mendeleev blocks is presumed to be stretched continental crust morphologically represented by the wide continental shelf of the East Siberian Sea (Figure 1) and on Plate 1 by the Nova Sibir-Chukchi Foldbelt (NSCF). The magnetic field in the NSCF is subdued, with wide linear northeast striking anomalies of 200-500 nT (Plate 1). These may represent sea floor spreading flow lines and be related to northeasterly rifting of the Chukchi Plateau region as postulated by Grantz et al. [1979]. The shelf region consists of a number of east-west striking basins which are very poorly documented but which are assumed to represent a Cretaceous tensional event [Okulitch et al., 1989]. It is assumed, in this event, that the continental crust was stretched and thinned and broke into a series of fault blocks in the upper, brittle section. The thinning did not, however, pass a threshold point (20%) and the continental crust thus did not completely rupture.

CHRONOLOGY OF THE ARCTIC BASIN

In the earliest Mesozoic the present day Arctic was either a low lying shallow marginal sea or dry land at low paleolatitudes (Figure 4). The Panthalassa Sea lay to the north [Green et al., 1984], however, its extent was probably quite restricted allowing free exchange of terrestrial and marine fauna and flora between the Canadian Territories and Siberia [Kos'ko, 1993]. Initial rifting occurred during the Carboniferous to Late Jurassic in the Sverdrup Basin [Balkwill and Fox, 1982], and along the continental margin from Banks Island to the continental slope west of Point Barrow dating from the Early Jurassic (Table 1) [Grantz et al., 1990]. The continental margin of the East Siberian Sea was strongly deformed in Late Kimmerian time [Sekretov, 1993] perhaps as a result of compression from the initial Canada Basin spreading. The initial Early Cretaceous has been associated with an episode of crustal dilation, nearly normal to the present continental margin, that may have generated the NE striking system of faults and dikes within the Sverdrup Basin [Sweeney et al., 1990].

Rifting of the paleo-Canada Basin created an oceanic basin shown which comprises the southern Canada Basin of today (Figure 3). By Middle Cretaceous time, this rifting had rotated the North Slope-Chukotka block counterclockwise and moved it along transform faults nearly 70 degrees. In late Lower Cretaceous time, large extensional basins formed in the continental shelf of Siberia [Kos'ko et al., 1993]. Northward drift carried northern Greenland to 60°N by Albian time. The Nova Sibir-Chukchi Foldbelt also formed in the Early-Mid Cretaceous along the Amerasia margin. In late Maastrichtian time the Sverdrup rim began to collapse, which too may reflect tensional conditions in the Canada Basin.

Sea floor spreading in the Late Cretaceous or Early Paleogene rifted the present Makarov Basin in a wedge shaped manner, with the Siberian end wider than the Canadian. On northernmost Ellesmere Island mafic flows and intrusions have isotope ages of 93-88 Ma, and there may be a chronological and structural relationship with the opening of the Makarov Basin. The Lomonosov Ridge is commonly accepted to be a sliver of the Barents/Kara Shelf split off by initiation of sea floor spreading in the Eurasia Basin by the present mid-ocean ridge at about the Cretaceous-Tertiary boundary.

Grantz et al. [1992] and Grantz and shipboard party [1993] suggest that the Chukchi Borderland was separated from the continental margin by east-west extension of the East Siberian Sea in the Tertiary. As noted earlier Grantz et al. [1979] suggested a more northerly motion. They further indicate that the basin to the west of the ridge is underlain by continental crust that has been thinned in an east-west direction sufficiently intensively to have created the Chukchi Abyssal Plain by block rotation and listric faulting. This tectonic event completed the formation of the present day Amerasia Basin. This model, as do all others, requires large strike slip faults to accommodate the creation of new crust created by the opening of the Canada Basin and later the Makarov Basin. The location of these faults is still shrouded beneath the sea ice; however Kos'ko et al. [1993] note that large strike slip displacements up to 600 km may be present north of Wrangel Island. Sea floor spreading continues today at the slow half rate of 0.2 to 1 cm/yr in the Eurasia Basin.

PALEOCEANOGRAPHY

The opening of the Eurasia Basin and the Greenland/Norwegian Seas was a major event having profound effects on the world's oceans as it allowed the fresh ice-laden polar waters a pathway to the south. The low salinity upper layers, conditioned by river inputs, enter the Greenland/Norwegian Seas and the North Atlantic and affect the entire upper ocean by strengthening stratification. The cooled, brine-enriched deeper waters sink to contribute to the renewal of the deep and bottom water masses of the global ocean. Variations in the nature and flux of these deep waters have a profound impact on global temperature distribution and on ocean and atmospheric

chemistry [Nansen Arctic Drilling Program Science Committee, 1992]. The Fram Strait is the major gateway for exchange of waters between the Arctic and the Atlantic. Sea floor spreading began in the Greenland Sea at anomaly 13 (approximately 35 Ma) but the adjacent Yermak and Morris Jesup plateaus inhibited water mass interchange until much later, possibly until the Miocene and/or Pliocene time [Kristoffersen and Husebye, 1985]. Also within the Eurasia Basin, the Lomonosov Ridge is a present day barrier to all water masses deeper than 1600 m. In the past it must have lain at shallower depths, however, it is uncertain at what time it started to subside.

In the Amerasia Basin a small oceanic basin (present southern Canada Basin) was created by partial rifting of the Canada Basin about 153 Ma. The Makarov Basin was formed by a later separate rifting event in the Late Cretaceous-Early Tertiary. Shallow marine conditions existed, however, over larger areas prior to the initial rifting (Figures 3, 4). During the late Albian through early Maastrichtian (Late lower Cretaceous-late Upper Cretaceous) there was a shallow water connection between the Arctic and the Gulf of Mexico through the western interior seaway, likewise, another connection existed to the region of Baffin Bay [Marincovich et al., 1990]. The northern migration of the land masses during the Mesozoic gradually moved them into high latitudes, establishing the present day climate. The obstruction by land masses to free meridional circulation of oceanic water masses since Early Cretaceous led to the isolation of the marine Arctic from the world's oceans.

SUMMARY

Several investigators have suggested that the Alpha-Mendeleev Ridge originated by rifting from the Lomonosov Ridge while both were attached to the Barents-Kara Shelf [Zonenshain et al., 1990; and Green et al., 1984]. Green et al. [1984] postulated that the Alpha Ridge was a thinned, intruded continental fragment that was rifted away from the Barents Platform. Based on the magnetic fabric, we suggest rather that the Alpha Ridge is more nearly similar to the Siberian sector. It may well be a terrane which preceded the Kolyma block and docked up against the Canadian Ellesmere Island. This may be related to the Late Devonian-Early Carboniferous regional folding and faulting that was most intense near the continental margin of NW Canada [Sweeney et al., 1990]. Based on magnetics the Alpha Ridge province has a much greater areal extent than is evident morphologically. Also, the magnetic pattern does not resemble that of the Barents Shelf. However, based on the geologic affinities of Pearya and Svalbard, a European origin is possible. We suggest that it is possible that the Alpha-Mendeleev block is a continental terrane which was emplaced prior to the opening of the Canada Basin and subsequent rifting of the Chukchi Plateau. A major problem is the subsidence of this block to oceanic depths. It is suggested that

it is not normal "continent," but rather denser material with extensive intrusions [Pogrebitsky, 1976] perhaps as the result of hot spot activities as postulated by Lawver [1993].

It is hoped that analysis of the recently collected Carboniferous-Permian limestones from the Northwind Escarpment [Grantz and shipboard party, 1993] will shed further light on their affinities. They may be related to the shallow-water carbonate deposits of the Omolon Massif which is part of the South Anyui suture [Zonenshain et al., 1990] (Plate 1) or similar deposits in the NW Territories. From Early Cretaceous until the Miocene/Pliocene the Arctic has been isolated from deep water mass exchange with the world's oceans by tectonic events which have additionally moved it northward to its present high latitude and present day key role in global change processes.

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FIGURES

Plate 1. Magnetic Field and Tectonic structures of the Arctic Region (Macnab et al. 1992a, b; Macnab, 1993). Magnetic data over mainland Russia were collected by the Ministry of Energy of the former USSR and digitized by the U. S. Naval Oceanographic Office. Portions of the data over the Arctic Ocean were assembled at Sevmorgeologia and digitized at the Atlantic Geoscience Centre; most of the remaining offshore data were collected by the U. S. Naval Research Laboratory. Data over the North American mainland were assembled in part during the DNAG Project. Tectonic structures are in part based on the work of Y. Pogrebitsky and L. Zonenshain (Pogrebitsky et al., 1993). III Siberian Craton, IV Eurasia Basin, V Northeast Asiatic Orogenic Belt, VII Amerasia Basin; 5 Nova Sibir-Chukchi Fold Belt, 6 Verkoyansk-Kolymia Fold Belt, 8 Canada Basin, 9 Lomonosov Ridge; 8 Taimyr-Nova Zemlya Suture, 9 Laptev Rift Zone, 11 De Long Rise, 12 Chukchi Cap, 13 Wrangel Zone, 16 Alpha Ridge, 17 Makarov Basin, 18 Mendeleev Ridge, 20 Pearya Terrane.

Figure 1. Physiographic Provinces of the Arctic modified from Johnson [1990]. Heavy bar denotes location of refraction line shown in Figure 2.

Figure 2. Seismic refraction profile along the strike of Makarov Basin based on Gramberg et al. [1993]. Location is shown in Figure 1.

Figure 3. Schematic illustration of the Arctic prior to sea floor spreading in the Eurasia Basin. It shows limited sea floor creation in the Makarov and southern Canada Basin by sea floor spreading. C is the Chukchi Plateau region which is assumed to be continental and rifted towards the NE from the adjacent shelf (arrow). Map is not intended to show rigorous geographic locations but relative locations.

Figure 4. Triassic (A) and Early Albian (B) and paleogeographic reconstructions of the Arctic based on Green et al. [1984]. Maps are not intended to show rigorous geographic locations but rather relative location of the major structural units.

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