A NEW CRUSTAL MODEL OF THE LINCOLN SEA POLAR MARGIN

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ABSTRACT

Velocity models for the first seismic profile across the Lincoln Sea continent-ocean transition show a complex crustal structure including a uniform 3- to 5-km-thick cover that overlies 6 km of 4.3-4.7 km/s material in a basin beneath the continental shelf and a thinner ($\approx$ 2 km) unit with a velocity of 5.0-5.4 km/s beneath the adjacent Arctic Ocean. The midcrustal structure includes an upper unit with an oceanic layer 2-type velocity of 5.7-6.1 km/s and a lower unit with a velocity > 6.5 km/s. A high-velocity (> 7.4 km/s) lower crust of the northern Lincoln Sea differs from the lower crust of the Lomonosov Ridge near the pole and suggests different crustal origins for these two regions. The Moho lies at a depth of 23 km beneath the Lincoln Sea continent-ocean transition and is underlain by an upper mantle with an estimated velocity of 8.3 km/s. The velocity structure indicates that the continent-ocean crustal transition lies 15-20 km seaward of the shelf-slope bathymetric break. Bathymetrically, the shelf break is located 150 km north of Ellesmere Island and is stepped beginning at depths of 300 m and 600 m.

We interpret the crust of the Lincoln Sea continent-ocean margin as a transition from thinned continental crust to the south, perhaps containing material of the Pearya Terrane exposed on Ellesmere Island, and a complex, atypical oceanic crust to the north with similarities to oceanic plateaus or volcanic margins. We suggest the crust to the north represents the southern flank of an enigmatic Lincoln Sea Plateau. The Plateau may be either an intruded and underplated segment of the Lomonosov Ridge or an intrusive complex with similarities to the Alpha Ridge.

INTRODUCTION

The Lincoln Sea covers the junction of major tectonic elements that form the transition from the Arctic Ocean to the North American-Greenland craton. Crustal segments include the Mendeleev-Alpha Ridge, Makarov Basin, Lomonosov Ridge, and Eurasian (Amundsen) Basin offshore (Fig.1) and the Pearya Terrane, Clements-Markham Fold Belt, and Hazen Fold Belt on Ellesmere Island and Greenland (Fig.2). From Late Archean time to the present, the tectonic evolution of these elements was accompanied by sedimentation and magmatism of probable oceanic- and continental-rift affinities (Williamson et al., 1992). From Cretaceous to Paleogene time, oceanic magmatism also introduced basic material into cratonic successions. The margin has been inferred to be a transcurrent fault to the east of the Lincoln Sea and a rifted margin to the west (Trettin, 1991).

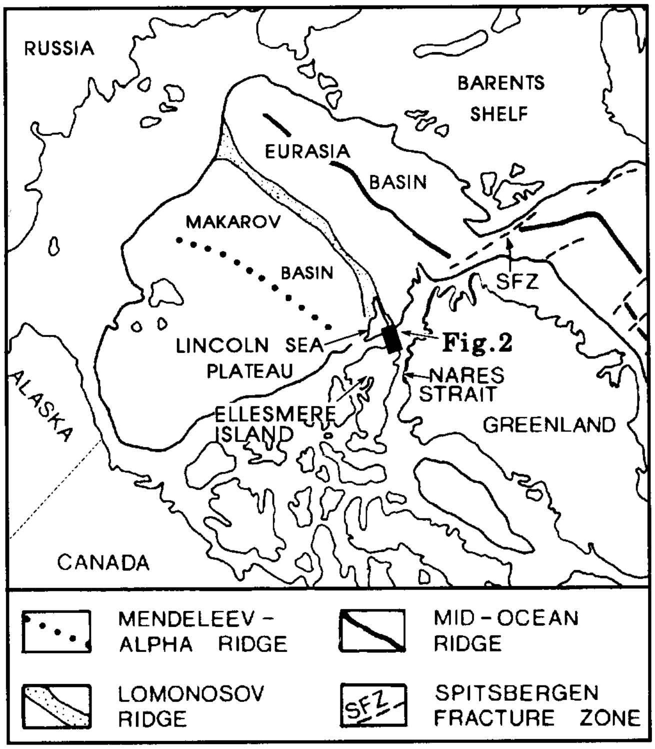

Fig.1. Regional setting of the Lincoln Sea study area near the junction of Greenland, Ellesmere Island, and the Lincoln Sea Plateau at the southern end of the Lomonosov Ridge.

Onshore, regional geological mapping has established clear tectonic domains and shallow structural relationships. Offshore, the nature of tectonic relationships underlying the Lincoln Sea is largely speculative due to limited geophysical data and a lack of deep structural constraints from seismic data. This study presents an interpretation of the first crustal seismic profile from the Lincoln Sea.

EXISTING GEOPHYSICAL DATA

Limited regional gravity and magnetic observations (Forsyth et al., 1990a; Bernero et al., 1985) and higher

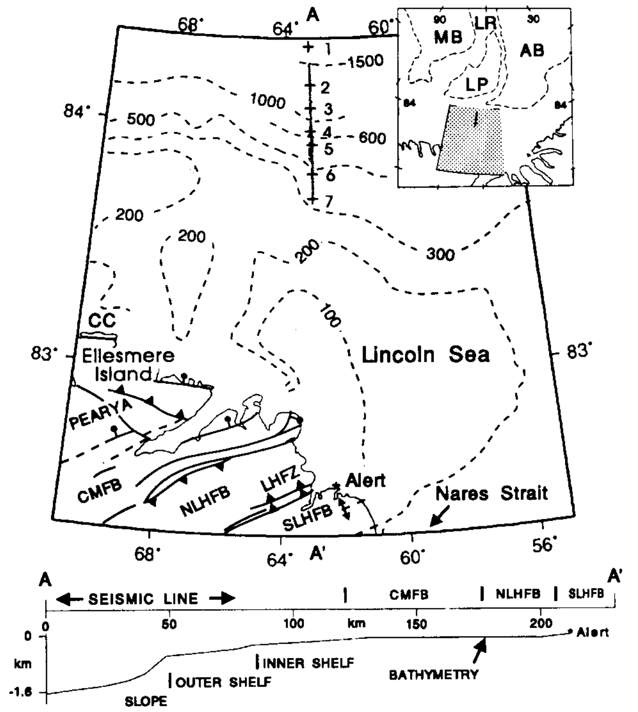

Fig.2. Location of the 1992 refraction survey across the Lincoln Sea margin. Crosses indicate shotpoints 1 to 7. The survey bathymetry outlines the shelf-slope break about 150 km north of Alert. Regional bathymetry (meters) from Canadian Hydrographic Service (CHS) charts 3499 and 8182 with permission, CHS map 7304, and this study. The abbreviations CC = Cape Columbia, FB = Foldbelt, CM = Clements-Markham, NLH = Northern Lake Hazen, SLH = Southern Lake Hazen, LHFZ = Lake Hazen Fault Zone. Inset, MB = Makarov Basin, AB = Amundsen Basin, LR = Lomonosov Ridge, LP = Lincoln Sea Plateau.

resolution aeromagnetic data (Nelson et al., 1992) are available for the study area. The clearly defined positive magnetic anomaly trends indicate that (1) the Lincoln Sea plateau is distinguished from the Lomonosov Ridge to the north by its shorter wavelength, positive anomalies and (2) the seismic profile presented here crosses east-west regional trends while complex regional structural trends converge immediately east of the seismic line (Nelson et al., 1992). To the south, Niblett et al. (1974) reported a conductivity anomaly coincident with the Lake Hazen Fold Belt and its extension beneath the Lincoln Sea.

GEOLOGICAL SETTING

Tectonism in the area may include events associated with the development of the Alpha Ridge, Makarov Basin, Lomonosov Ridge, and Amundsen Basin offshore and Pearya Terrane, Clements-Markham Fold Belt, and Hazen Fold Belt on Ellesmere Island and Greenland (Fig.2). If the Alpha Ridge, a Cretaceous volcanic edifice, originated from a major mantle plume (Forsyth et al., 1986), Alpha Ridge material may be represented in the study area at mid to lower crustal levels. The nature of the Makarov Basin is largely unknown. The Lomonosov Ridge is generally accepted to be an intruded and rifted continental fragment. At its southern end, adjacent to the seismic line, available bathymetry indicates the Lincoln Sea Plateau rises to about 500 m beneath sea level (Perry and Flemming, 1986).

Mid-Proterozoic gneiss of the Pearya Terrane mapped onshore may form part of the crust in the southern part of the study area. The transition between ocean and craton has been inferred to be a transcurrent fault zone to the east of the Lincoln Sea and a rifted margin to the west (Trettin, 1991). The nature of this transition and the extensions of tectonic elements beneath the sea are uncertain. The tectonic elements evolved from late Archean time to the present, through sedimentation and tectonic events as well as magmatism, as described above. Oceanic magmatism also has crossed the margin throughout the Cretaceous and Paleogene to introduce basic intrusions and extrusive strata into cratonic successions.

CRUSTAL REFRACTION SURVEY

The 1992 crustal refraction survey was conducted as part of a cooperative effort involving the Geological Survey of Canada and the Canadian Defense Research Establishment Pacific. The survey consisted of a 69.2-km profile with 1-km recorder spacing and seven shotpoints at approximately 10-km intervals recorded on the sea ice across the continental margin (Fig.2). Shotpoints are numbered 1 to 7 from north to south, and model distances are shown with zero at shot 1 (Figs.3,4,5). Details of the survey and data are described in Argyle et al. (1992). The closer site spacing of this seismic study relative to earlier high Arctic refraction surveys (Forsyth et al., 1986, 1990b; Forsyth and Mair, 1984) provides a better resolved crustal velocity structure.

Because of the limited bathymetry data near the survey and the large time delay through the ocean, detailed modeling of water-wave arrivals recorded along the seismic line was required to define major changes in water depth beneath the recorders across the margin. Velocity depth profiles from this and earlier surveys were compiled to create a three-layer water velocity model. The high, impulsive amplitudes and uniform velocity of the water wave arrivals, together with up to eight clear ocean bottom reverberations, improved the computed resolution of both receiver location and water depths across the slope (Forsyth et al., 1994). Final locations are estimated to be accurate within +/-50 m and depths to within +/-10 m.

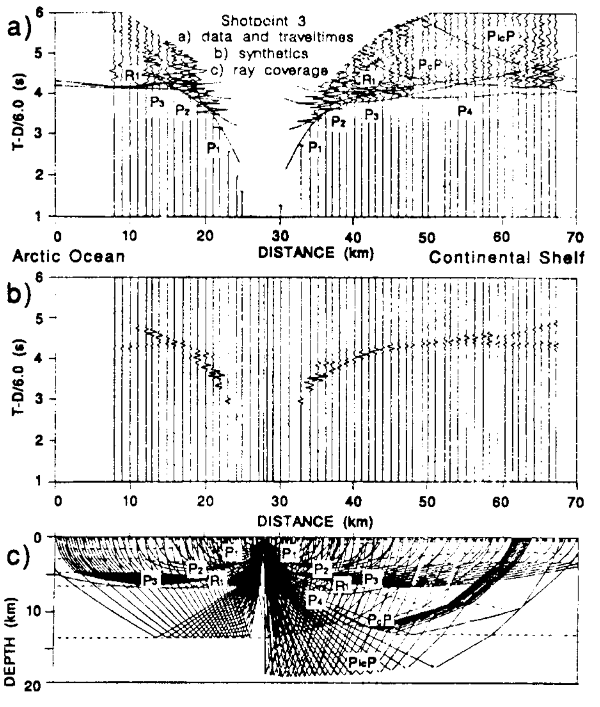

Fig.3. (a) Arrivals to lower crustal depths in true amplitude format recorded from shotpoint 3 with predicted traveltime curves, (b) modeled synthetics, and (c) ray-trace coverage. See text for description of seismic phases.

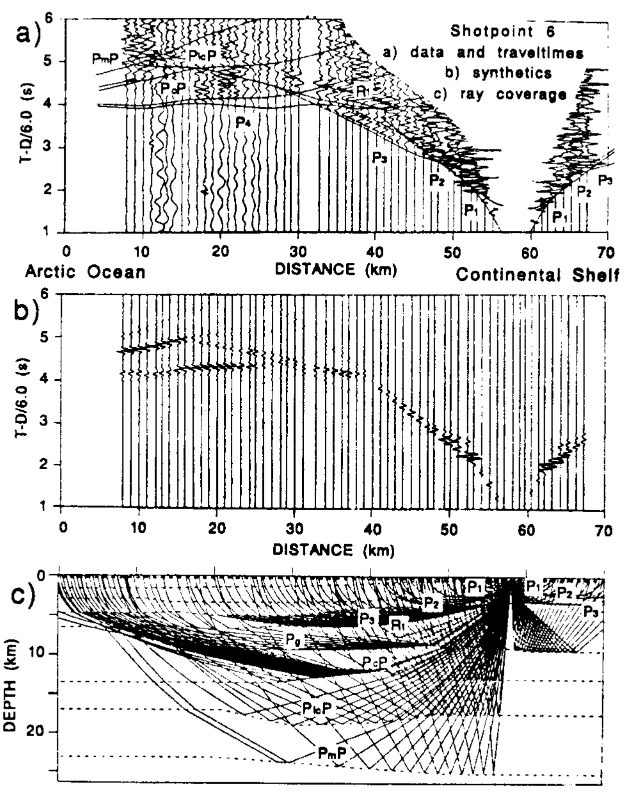

Fig.4. (a) Arrivals to Moho depths in true amplitude format recorded from shotpoint 6 with predicted traveltime curves, (b) modeled synthetics, and (c) ray-trace coverage. See text for description of seismic phases.

The data have provided the first well-determined bathymetric definition of the shelf-slope break in the study area (Fig.2). The profile suggests two steps, one beginning near 300 m depth and a second near 600 m, which is analogous to the margin near Nansen Sound (Sobczak and Halpenny, 1989). Along the margin adjacent to the seismic line, depth data are insufficient to document changes in the form and trend of the continental slope.

The seismic model is constrained by traveltimes and amplitudes of refracted and reflected arrivals from all seven shotpoints. Signal-to-noise ratio generally was very good (see below). Typical unfiltered, true relative amplitude (amplitudes scaled according to offset) seismic sections plotted with a reduction velocity of 6.0 km/s for shotpoints 3 and 6 are compared to modeled traveltime curves and synthetics in Figs.3 and 4. Refracted arrivals from the shallow sediments and the upper crust are indicated as phases P_1, P_2, and P_3. Similar P_1-P_2 crossover distances near 10 km offset support the interpretation of a uniform (≈3 km-thick) shallow sedimentary section. As the upper crust thickens from north to south along the profile, P_3 is observed as a first arrival at increasing distances (Fig.3). The reflection R_1 from the top of the midcrust increases in amplitude from southern shotpoints (4 to 7), in agreement with a larger velocity contrast at the base of the upper crust beneath the shelf than offshore (Figs.3,4). The refracted phase through the upper midcrust, P_4, is observed as a first arrival from all shotpoints, and P_cP is a wide-angle reflection from the top of the lower midcrust, identified most clearly from shots 3 and 6. The $P_{lc}P$ phase is a strong reflection from the top of the high-velocity lower crust (Fig.4), and P_mP, the wide-angle reflection from the crust-mantle transition, is a strong arrival evident from shotpoints 1 and 6 (Fig.4). More complete descriptions of the modeling technique, additional phases used to constrain the model, and the limitations of the Lincoln Sea wide-angle analysis are reported in Zelt and Smith (1992) and Forsyth et al. (1994). The continent-ocean transition model is shown in Fig.5.

SEISMIC CRUSTAL MODEL

Beneath the water layer, the data indicate that the seafloor material begins with a velocity of 1.8-1.9 km/s and a high-velocity gradient near 0.5 s^{-1} (Fig.5). The relatively uniform sedimentary cover reaches a velocity of 3.4-3.6 km/s at a depth of about 3 km beneath the shelf and 5 km beneath the Arctic Ocean. Underlying the sedimentary cover, the upper crust is divisible into a basinal wedge with a velocity of 4.3-5.0 km/s that tapers from a thickness of 6 km beneath the continental slope to about 1 km at the continent-ocean transition. Seaward of the transition, the basinal material abuts a 2- to 3-km-thick layer of velocity 5.0-5.4 km/s beneath the

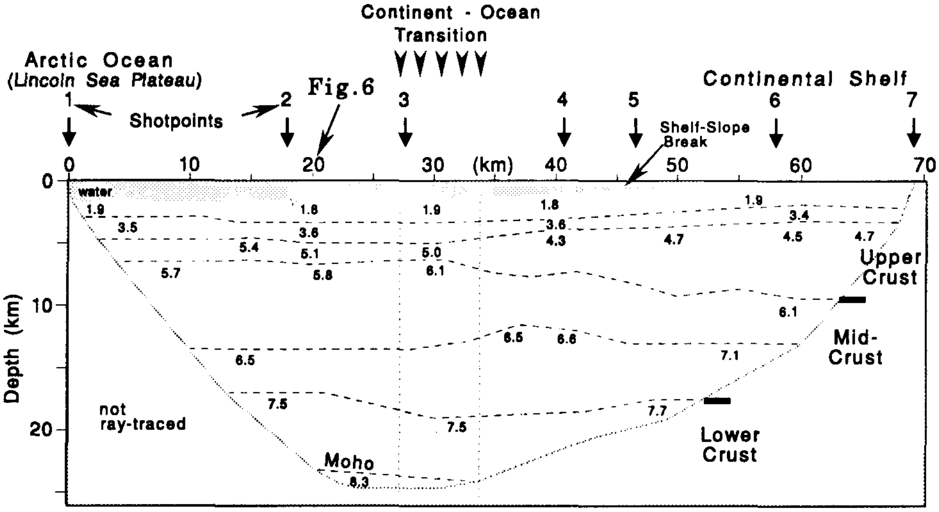

Fig.5. The velocity structure model across the Lincoln Sea margin. Model numbers indicate P-wave velocities in km/s.

Arctic Ocean. The midcrustal structure includes an upper unit with a velocity of 5.7 km/s increasing to over 6 km/s beneath the continental shelf. The shelf is underlain by a lower midcrustal unit with a velocity of 6.5-7.1 km/s. The upper unit thins and the lower unit thickens landward of the continent-ocean transition. The top of the midcrust shallows step-like from over 9 km beneath the continental slope to near 6 km beneath the continent-ocean transition and becomes subhorizontal beneath the Arctic Ocean (Fig.5). Ray-trace coverage provides good constraint on velocities and lateral geometry within the sampled region to lower crustal depths of over 15 km.

The lower crust includes 7.5-7.7 km/s material beginning at a depth of 17 km and deepens to about 19 km beneath the continent-ocean transition. The central low along the top of the lower crust is constrained by $P_{lc}P$ reflections (e.g., Fig.4). Given the better constrained upper- and midcrustal velocity structure, the P_mP traveltimes and amplitudes are best matched by a Moho depth of 23 km with a suggested dip toward the continent and an estimated upper mantle velocity of 8.3 km/s. It is noted that the maximum length of the profile of 69.2 km has not permitted recording of P_n as a first arrival, and Moho depth and upper mantle velocity must be regarded as preliminary estimates. Despite diminished ray coverage with depth, however, we suggest that it is unlikely that material with upper mantle-type velocities exceeding 8 km/s is present above 20 km within the area sampled.

INTERPRETATION

We suggest the upper crust includes a relatively uniform cover of probable Tertiary to Recent sedimentary rocks with a velocity less than 4 km/s. These sediments underlie both the shelf and adjoining Arctic Ocean. The sediments overlie marked lateral changes to a thickened oceanic crust at 15-20 km seaward of the shelf-slope bathymetric break (Fig.5). The wedge-shaped basin that pinches out beneath the base of the continental slope is underlain by material of velocity greater than 6 km/s at an undulating, or stepped, boundary that may represent a stratigraphic unconformity. Within this basin, secondary lateral changes in velocity within the range of 4.3 to 4.7 km/s that generally correspond to several of these steps have been inferred as evidence of possible normal faulting related to Late Cretaceous rifting (Forsyth et al., 1994).

The mid and lower crust also are characterized by complex lateral changes in apparent velocities and structure. The step-like nature of the suggested unconformity underlying the basin beneath the continental shelf contrasts with the more uniform sedimentary cover and suggests deformation prior to or perhaps during basin development.

The limited regional bathymetric data indicate the survey area lies adjacent to the southern end of the Lomonosov Ridge represented by the Lincoln Sea Plateau (Fig.1). However, the velocity structure north of the continent-ocean transition (Fig.6) shows that, although upper crustal velocities are similar, the high-velocity lower crust beneath the northern survey area differs from the velocity structure of the Lomonosov Ridge near the North Pole. Although the present study is of higher resolution than the survey near the North Pole, a comparison of lower crustal arrivals (cf. Forsyth and Mair, 1984, Figs.2,3) shows that the seismic phases from the mid to lower crust of the Lincoln Sea are more complex than the seismic sections along strike of the Lomonosov Ridge near the North Pole. Comparable high-velocity, lower crustal units are, however, present

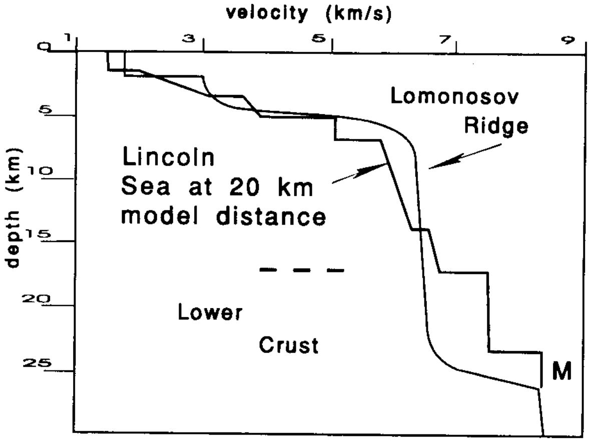

Fig.6. A comparison of the velocity structure from the Lincoln Sea margin and the Lomonosov Ridge near the North Pole after Forsyth and Mair (1984). The high-velocity lower crustal unit of the oceanic portion of the Lincoln Sea margin differs from the Lomonosov Ridge but resembles the lower crust of the Alpha Ridge. M=Moho.

beneath the eastern Alpha Ridge/western Makarov Basin (Forsyth et al., 1986) and are interpreted as crustal underplating beneath volcanic margins (White, 1992). We also note that the short-wavelength, positive magnetic signature distinguishes the Lincoln Sea Plateau from the Lomonosov Ridge to the north and is more characteristic of the magnetic signature of the intruded complexes such as the Morris Jessup Rise to the east or the Alpha Ridge to the west.

We therefore suggest (1) the crust of the Lincoln Sea continent-ocean margin is transitional between thinned continental crust to the south, perhaps containing material of Pearya terrane exposed on Ellesmere Island, and a complex, atypical oceanic crust to the north with similarities to oceanic plateaus or volcanic margins; (2) the high-velocity lower crust suggests affinities to the Alpha Ridge rather than the Lomonosov Ridge as previously thought; and (3) the crust beneath the northern survey area and adjacent Arctic Ocean represents the southern flank of the enigmatic Lincoln Sea Plateau to the north, which may be either an intruded and underplated segment of the Lomonosov Ridge or an intrusive complex with similarities to the Alpha Ridge.

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