IMPLICATIONS FOR CANADA BASIN DEVELOPMENT FROM THE CRUSTAL STRUCTURE OF THE SOUTHERN BEAUFORT SEA-MACKENZIE DELTA AREA

R.A. Stephenson, Institute of Earth Sciences, Vrije Universiteit, De Boelelaan 1085, 1081 HV Amsterdam, Netherlands
K.C. Coflin, Geological Survey of Canada, Atlantic Geoscience Center, PO Box 1006, Dartmouth, Nova Scotia B2Y 4A2, Canada
L.S. Lane and J.R. Dietrich, Geological Survey of Canada, Institute of Sedimentary and Petroleum Geology, 3303-33 Street, Northwest, Calgary, Alberta T2L 2A7, Canada

ABSTRACT

The interpretations of a number of crustal seismic-reflection and -refraction profiles are combined with regional potential field data to infer constraints on the planview of the continent-ocean transition in the southern Beaufort Sea. Variations in the gravity signature of the continental margin in the southern Beaufort Sea are attributed to the degree of continental crustal thinning and the thickness of the postrift sediment, complicated by the existence of a fracture zone north of the Mackenzie Delta. The change in the width of the continent-ocean transition zone suggests an interaction between pre-existing crustal features controlling the formation of the margin.

INTRODUCTION

Development of the continental margin in the southern Beaufort Sea-Mackenzie Delta area, and of the overlying Beaufort-Mackenzie (B-M) Basin, began in the Late Jurassic or Early Cretaceous, as a consequence of seafloor spreading in the western Arctic Ocean. Although the plate kinematics of the seafloor spreading in the Canada Basin are yet poorly understood, the strongest published arguments--those that are most consistent with the known onshore geology of the Canadian Arctic and Alaska--appear to favor a model in which Alaska rotated away from the Canadian polar margin with a pole of rotation in this area (e.g., Embry, 1990). The geology of this area, recently summarized by Dixon and Dietrich (1990), records a series of sedimentary-basin-forming episodes, punctuated by major tectonic events, beginning in the Proterozoic.

The Lower Jurassic to Lower Cretaceous strata were derived from a cratonic source to the southeast, and their depositional patterns suggest a syn-rift tectonic setting (Dixon, 1982, 1986; Poulton, 1989). Several tectonic elements relating to Jura-Cretaceous rifting have been identified along the Beaufort Sea margin. One such structure is the Eskimo Lakes fault zone (ELFZ, Fig.1), an array of northeast-striking en echelon listric normal faults (Norris and Yorath, 1981) that defines the southeast margin of the B-M Basin (cf. Cook et al., 1987). Intermittent rifting of at least Late Jurassic to Early Cretaceous age has been documented on the Treeless Creek fault (Dixon, 1986), one constituent fault of the ELFZ.

A major regional unconformity, of mid-Cretaceous age, has been interpreted as the end of rift-related deposition (Dixon et al., 1992), consistent with the earlier interpretation of a post-Albian rift-drift transition for the arctic margin in this region (Embry and Dixon, 1990). The Late Cretaceous sediments of the B-M Basin margin are not significantly affected by syn-depositional faulting and thus comprise the first postrift succession (Dietrich et al., 1989b). The Tertiary successions can be resolved into a series of deltaic depocenters that have migrated in a generally counterclockwise fashion throughout the Tertiary (Willumsen and Coté, 1982; Dixon and Dietrich, 1990). The postrift succession, of Late Cretaceous and Tertiary age, exceeds 15 km in thickness (e.g., Cook et al., 1987; Coflin, 1989; Dietrich et al., 1989a). Major structural features shown in Fig.1 affecting this succession include the Outer Hinge Line (OHL), a depositional hinge marking the edge of major northwestward thickening of Tertiary strata, and the Tarsiut-Amauligak fault zone (TAFZ), an east-west-trending zone of normal faults disrupting Eocene to Miocene strata and detached within the basin sedimentary succession (Dietrich et al., 1989b). An extensive database of exploration industry seismic-reflection data exists in the area and is augmented by considerable knowledge of the subsurface geology of the B-M Basin, both on- and offshore. The objective of this paper is to demonstrate how deep seismic and potential field data acquired in the late 1980's can be interpreted in the framework of this geological database to provide better constraints on the character and location of the ocean-continent transition in the southern Beaufort Sea and to discuss these results in terms of the origin of the Canada Basin.

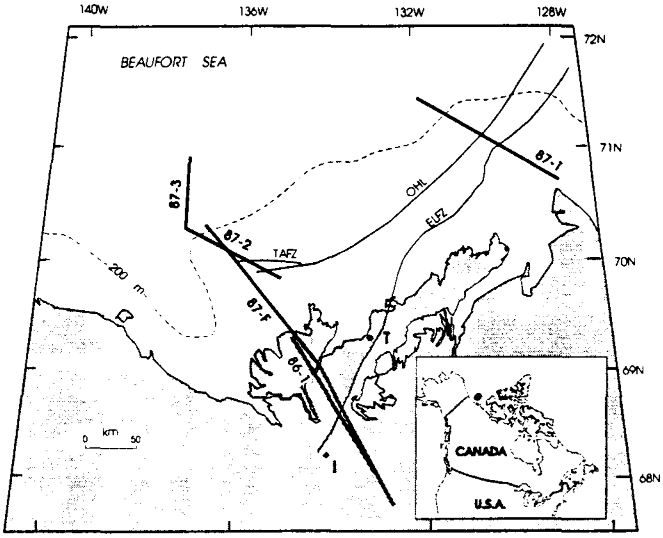

Fig.1. Location of the study area with the main tectonic elements (ELFZ, Eskimo Lakes Fault Zone; OHL, Outer Hinge Line; TAFZ, Tarsiut-Amauligak Fault Zone), positions of deep seismic-reflection (86-1 and 87-1,2,3) and -refraction (87-F) profiles (solid lines), and the 200-m bathymetric contour. I, Inuvik and T, Tuktoyaktuk (situated on the Tuktoyaktuk Peninsula).

GEOPHYSICAL DATA

The geophysical dataset used in the present study comprises four deep seismic-reflection profiles (86-1 and 87-1,2,3; Fig.1), one regional seismic-refraction profile

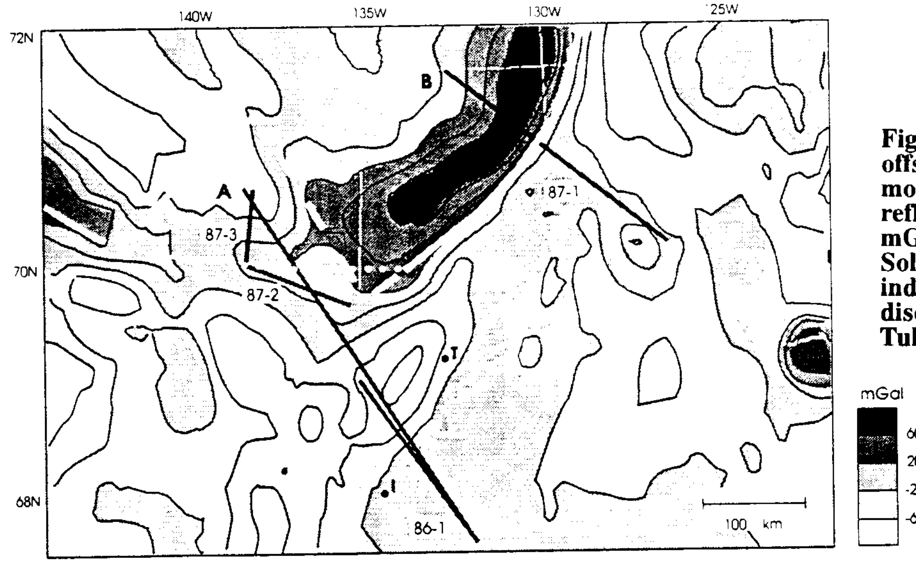

Fig.2. Gravity (Bouguer onshore, free air offshore) map with locations of gravity model profiles A and B and the seismic-reflection lines. Contour interval is 20 mGal. The coastline is shown in white. Solid, dashed, and dotted lines offshore indicate positions of the C-O boundary as discussed in the text. I, Inuvik; T, Tuktoyaktuk.

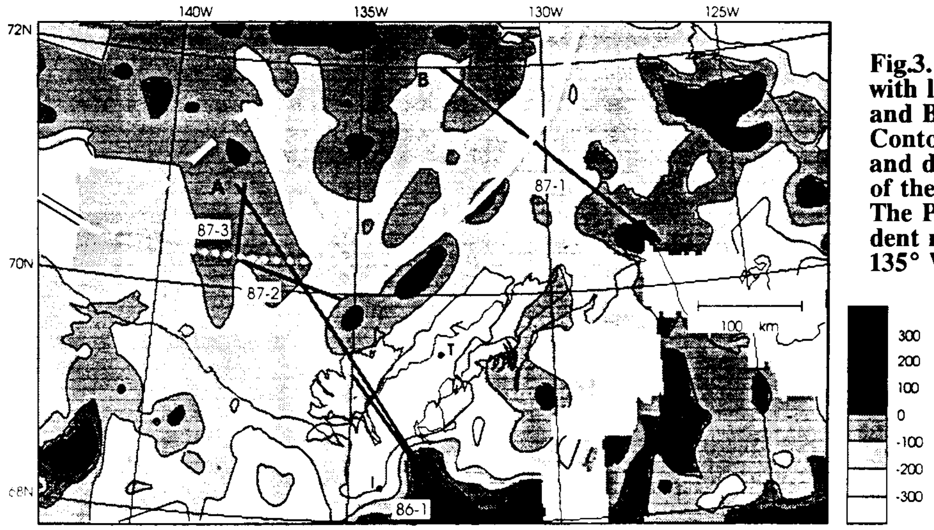

Fig.3. Aeromagnetic map of the study area with locations of gravity model profiles A and B and the seismic-reflection lines. Contour interval is 100 nT. Solid, dashed, and dotted lines offshore indicate positions of the C-O boundary as discussed in the text. The PSMA corresponds to the nearly coincident magnetic low between 130° W. and 135° W. longitudes. I, Inuvik; T, Tuktoyaktuk.

(87-F; Fig.1), and the gravity and aeromagnetic fields (Figs.2 and 3). Interpretations of deep reflection profiles 86-1, 87-2, and 87-3 (Fig.4) have constrained in part the crustal and upper-mantle velocity model determined along refraction-profile F (Fig.5). Gravity anomalies have been modeled in terms of crustal and upper-mantle density variations (Fig.6) along two profiles where the greatest seismic constraint exists (cf. Figs.1 and 2). The spatial patterns of the potential field data have been utilized to extrapolate the results from the profile locations.

Line diagrams of the four deep seismic-reflection profiles are shown in Fig.4. The reflection patterns are interpreted in Fig.4 in terms of Jurassic and younger B-M Basin succession (lightest shading) and basement (or crustal layer, darkest shading). These have been adapted from Cook et al. (1987) and Coflin (1989) for 87-1 and from Dietrich et al. (1989a) for 87-1, -2, and -3. These authors also provide details pertaining to the acquisition and processing of the seismic data. The main observations pertinent to the present discussion follow. The B-M succession is characterized on all profiles by a (generally) southeast-tapering package of subparallel relfections, similar in appearance to other seismic-reflection data collected on and near the Mackenzie Delta (Dixon et al., 1985). The base of the B-M Basin occurs at times of up to about 8.5 seconds, marked by a drastic decrease in reflection density. Beneath the northwesternmost part of 87-1, beyond the OHL, a number of extensional faults disrupt the crust, appearing to form a series of tilted half-graben (e.g., Coflin, 1989; Dietrich et al., 1989a). The ELFZ appears as a zone of northwest-dipping reflections, truncating the more horizontal events lying to the north, on lines 86-1 and 87-1. In both cases, the ELFZ is associated with deeper reflections, in Proterozoic strata, also dipping basinward, interpreted to be evidence of a fundamental Precambrian crustal "ramp" that controlled the development of the younger structures (Cook et al., 1987; Coflin and Cook, 1990). The only clear evidence of the Mohorovicic discontinuity in the deep reflection data lies at the southernmost end of 86-1, where a zone of moderate to weak reflections is recorded at 11 to 12 seconds.

Shown in Fig.5 is the crustal velocity model determined along refraction profile 87-F, using data recorded from five shotpoints along the line (Stephenson et al., 1994; for a complete description of the refraction survey and acquisition parameters, refer to Stephenson et al., 1989). The onshore part of the model cross-section approximately coincides with deep reflection line 86-1. Offshore, it intersects 87-2. Velocities within the sedimentary basin succession range from 1.9 km/s at the water-sediment interface to ~5.4 km/s above the layer interpreted to be crustal basement. Velocity gradients

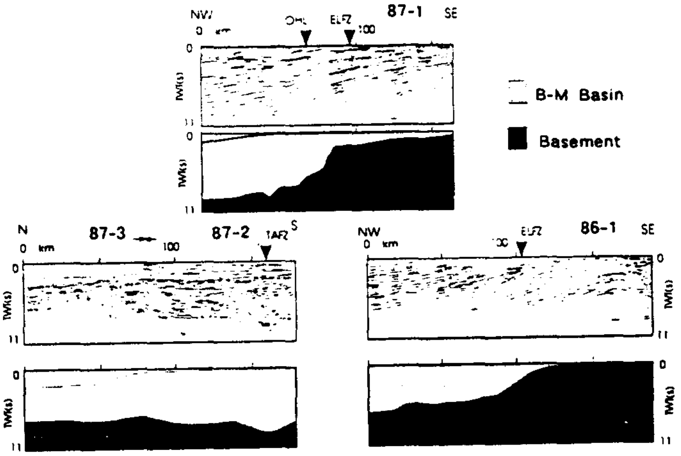

Fig.4. Line diagrams and crustal interpretations (adapted from Cook et al., 1987; Coflin, 1989; Dietrich et al., 1989a) of deep seismic-reflection profiles used to constrain gravity models along profiles A and B. Note the change of direction between lines 87-2 and 87-3; profile 87-2 is oriented approximately parallel and profile 87-3 approximately perpendicular to the strike of Tertiary folds and thrust faults related to Laramide deformation in the Brooks Range in Alaska (Dietrich et al., 1989a). TWT is two-way traveltime. Tectonic legend as in Fig.1.

are greatest in the upper 4 km of sediments. The depth of the basement offshore, to as far north as the shelf edge, is estimated to be about 12 km. The velocity model, converted to time, gives 7 seconds two-way travel time (TWT) where it intersects 87-2, comparing favorably with the depth of basement determined from the latter. The basement (crustal) layer near the southeast end of the line displays complex structure consistent with, but not resolving, the zone of compressional deformation seen on 86-1. At greater depth, extending northward beneath the ELFZ, there is a homogeneous layer with a velocity of 5.7 to 5.8 km/s. Beneath this layer, the model is characterized by an absence of crustal layering and average velocities of 6.3 to 6.6 km/s. The Moho at the southern end of the line generates an extremely strong wide-angle reflected phase and is modeled at a depth of about 36 km, equivalent to 11.4 seconds TWT, corresponding to approximately the top of the zone of weak Moho reflections seen on 86-1 (Cook et al., 1987). Offshore, the crustal layer thins to a total thickness of about 16 to 17 km. The shallowing of the Moho occurs north of the ELFZ, although the precise geometry of the Moho in this zone is not strongly constrained by the refraction data.

The regional gravity field of the study area (Fig.2) is dominated by a southwest-northeast-trending elliptical high parallel to the Tuktoyaktuk Peninsula. Similar anomalies are found elsewhere along the Canadian polar continental margin (e.g., Forsyth et al., 1990) and appear to be characteristic of many rifted continental margins (Hutchinson et al., 1982). The other major feature of the gravity field is the southwest-northeast-trending low situated over the northwestern part of the Mackenzie Delta, lying to the northwest of Inuvik (I) to Tuktoyaktuk (T).

Fig.6 presents the results of modeling the gravity anomalies along the two profiles (A and B) shown in Fig.2 (Stephenson et al., 1994). Profile B crosses the southern Beaufort Sea elliptical gravity high. Profile A crosses the major low on the northern Mackenzie Delta and skirts across the end of the elliptical high. The profile locations were chosen because of the coincident deep seismic data, which have provided the basic geometry of the models. For the most part, the final model densities of the crustal and the deeper sedimentary layers result from data inversions using initial values derived from refraction velocities and from seismic-reflection velocity analysis and borehole observations. Given the independent constraints, especially on bathymetry and the thickness of the B-M Basin and geometry of the ELFZ, the gravity data arguably provide good control on crustal-thickness variations along profiles A and B. The main results pertaining to the continental margin follow. On profile B, crustal thinning at the ELFZ is accompanied by coincident shallowing of the Moho. In contrast, along A, Moho shallowing is offset to the northwest from the ELFZ, consistent with the refraction velocity model. (The gravity low crossed by profile A is the result of upper crustal replacement by lower density sediments with no concomitant isostatic "replacement" of lower crust by mantle.) The crustal layer thins on profile B northwest of the ELFZ to about 8 km. The elliptical gravity high results from the abrupt subcrustal mantle edge in combination with the thick overlying sedimentary shelf succession. On A, the gravity anomalies are consistent with the refraction data, indicating a crustal layer of >16-km thickness. Beyond the northern limit of the refraction coverage, there is no indication of significant further Moho shallowing, which would be expected to produce a recognizable signature, in the gravity profile.

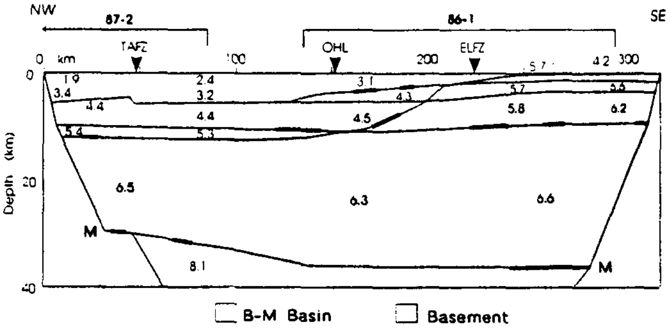

Fig.5. Crustal velocity model (units of km/s) along refraction profile 87-F (from Stephenson et al., 1994); seismic boundaries are thickened where they have produced wide-angle reflections. The Moho is labeled M. Velocities represent averages within regions of the model. The profile is (nearly) coincident with reflection lines 86-1 and 87-2, where indicated. Tectonic legend as in Fig.1.

The regional aeromagnetic field of the study area (Fig.3) has recently been described by Forsyth et al. (1990, 1994), who infer that the Polar Shelf Magnetic Anomaly (PSMA)--where it is in evidence elsewhere on the polar margin--marks the transition to oceanic crust. The southwest-trending linear magnetic low (separating elliptical highs) east of 135°W. longitude appears to be the trace of the PSMA in the southern Beaufort Sea. West of 135°W., trends change to a more northwest-southeast direction, truncating the PSMA north of the Mackenzie Delta, just west of profile A.

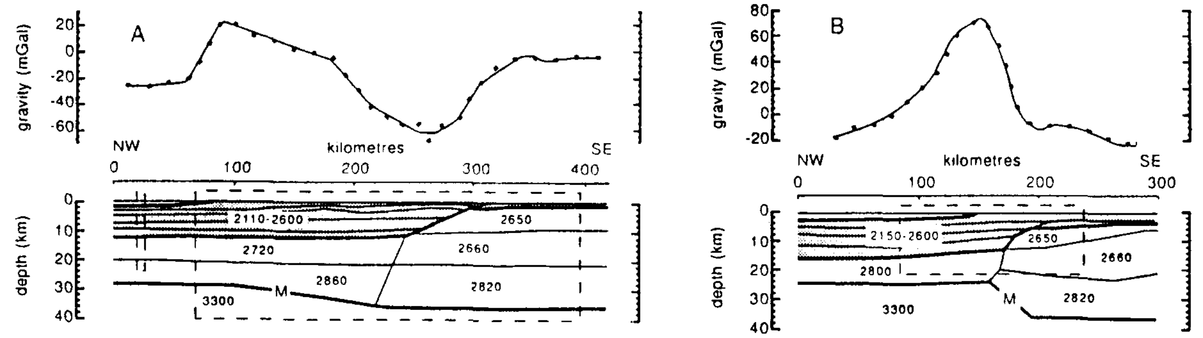

Fig.6A and B. Crustal and upper mantle-density models (units of kg/m^{-3}) along gravity profiles A and B showing observed (dotted curve) and computed (solid curve) anomalies (from Stephenson et al., 1994). The Beaufort-Mackenzie Basin sedimentary succession comprises the stippled layers; sedimentary layer densities increase with depth. The Moho labeled M. Bathymetry is from the gravity station data; other constraints are from nearly coincident seismic-reflection and -refraction data (approximately within areas enclosed by dashed lines). The profiles are aligned according to the position of the surface trace of the ELFZ.

CRUSTAL AFFINITY IN THE SOUTHERN BEAUFORT SEA

The modeled seismic-refraction and gravity data clearly indicate that the thickness of the crustal layer on the northern half of profile A is too great to be typical of oceanic crust, and it is interpreted to consist of thinned continental crust. The refraction model constrains further crustal thinning and the transition to crust of oceanic affinity (C-O transition) to lie north of about 70.1°N. latitude. The gravity model strongly suggests that there is no reason to believe that this transition occurs anywhere south of at least the northern end of profile A (72°N.). The much thinner crustal layer on the northern half of profile B is, conversely, interpreted to be oceanic crust. On profile B there is only a narrow zone of thinned continental crust, directly underlying the ELFZ. The C-O transition occurs over a distance of about 40 km--with the edge of oceanic crust marked by the cratonward gradient of the gravity high--and is coincident with the PSMA (Forsyth et al., 1990, 1994).

Seismic-refraction and other data off the Alaskan margin near the Canadian border show clear evidence of oceanic crustal basement (Mair and Lyons, 1981; Grantz and May, 1983; May and Grantz, 1990). Furthermore, the Alaskan continental margin, west of about 142°W. longitude, is characterized by positive gravity anomalies parallel to the margin similar to the southern Beaufort Sea high. Grantz et al. (1990) deduce an analogous position for the C-O boundary, aligned with the continental flank of the gravity high (solid line in Fig.2). Where the continental margin gravity high crosses profile A, however, it is attenuated compared to the Alaskan margin and to where it crosses B. The refraction and gravity modeling indicate that its southern flank on profile A does not coincide with the C-O boundary but with a broader zone of thinning of continental crust. It follows that the onset of oceanic crust trending southwestward from B direction must change direction relative to the gravity gradient somewhere east of profile A. The dotted line in Fig.2 illustrates the minimum divergence permissible, based on the northern limit of wide-angle Moho reflections observed on 87-F. The C-O boundary in such a case shifts in this area to approximately the peak of the gravity high from its continentward gradient elsewhere.

The minimum divergence positioning of the C-O boundary assumes that seismic contraints on Moho depth are firm, but that those from the gravity modeling on profile A are not necessarily so. However, it is not possible to reproduce the observed gravity values on the northern part of the profile with a model that incorporates oceanic crust unless it is assumed that the sedimentary basin succession significantly and abruptly thickens (and becomes less dense) north of the limit of seismic-refraction constraint (cf. Fig.6a). Reflection line 87-3 crosses A in this area but displays no evidence in the shallower part of the succession to imply any profound structural complexity at depth. It seems likely, therefore, that the C-O boundary lies north of the end of gravity profile A.

The southern limit of the position of the C-O boundary (the minimum divergence case), as deduced from the gravity and seismic data, cuts directly across the aeromagnetic trends west of the southwest-trending PSMA (Fig.3), where it is nearly coincident with the C-O boundary (east of 135°W. longitude). However, the aeromagnetic pattern suggests an alternative placement of the C-O boundary that is also consistent with the strong implication of the gravity modeling that it is not crossed by profile A. This is shown in Figs.2 and 3 as a dashed line and holds that the magnetic low east of the northwest-trending bifurcating anomaly is a continuation of the PSMA (being coincident with the C-O boundary). In this case the C-O boundary must cut southwesterly back to the southern flank of the Alaskan margin gravity high at about 142°W. to be consistent with the earlier arguments. There is no direct constraint on where this occurs in the present data sets.

The implied offset in the C-O boundary, perhaps as great as 150 to 200 km, can be interpreted as a fracture zone, with important implications for the kinematic evolution of the western Arctic Ocean basin (Lane, this volume). An alternative view is that the continent-ocean transition, where it trends northeast-southwest (i.e., crossed by profile B), is a transform margin and that the offset segment is rifted. The apparently very abrupt transition seen on profile B is consistent with this view, but it is not easily reconcilable with the almost complete lack of evidence for Mesozoic strike-slip movements within the ELFZ (Dietrich and Lane, 1991). The transform emplacement of Arctic Alaska in the Early Cretaceous, on a projection of the northeast-trending segment of the Beaufort margin, also appears to be precluded by known paleogeographic relationships and by potential field anomalies in the northern Yukon region (Dixon, 1986; Poulton, 1989; Lane, 1992).

The relationships of the inferred C-O transition in the southern Beaufort Sea with basement structure pre-existing Jura-Cretaceous rifting and with subsequent basin development in the area, including present-day seismicity, have been discussed by Dietrich and Lane (1992) and Stephenson et al. (1994). Elsewhere on the Canadian polar continental margin, the position of the continent-ocean boundary is known only from potential field data without benefit of additional seismic constraints. From these, it has been placed on the basis of the intermittent PSMA and the landward gradient of a series of large, elliptical, positive gravity anomalies (e.g., Forsyth et al., 1990, 1994), similar to the southern Beaufort gravity high. Extrapolating the results of the present study, the discontinuous nature of gravity anomalies (their segmentation into a series of elliptical highs) along the Canadian polar continental margin probably reflects zones of local complexity developed during rifting. Gaps in the gravity high occur where there are changes in the trend of the continental margin and correspond locally with other offsets seen in the aeromagnetic data and related to onshore geological trends (Forsyth et al., 1990; Lane, this volume).

SUMMARY AND CONCLUSIONS

An integrated interpretation of seismic-reflection, seismic-refraction, gravity, aeromagnetic, and geological observations in the southern Beaufort Sea-Mackenzie Delta area allows limits to be placed on the regional configuration of the ocean-continent transition on this part of the continental margin of the Canada Basin. The Beaufort-Mackenzie Sedimentary Basin overlies oceanic crust in the eastern part of the Canadian Beaufort Sea and overlies thinned continental crust in the western part of the study area, between the Mackenzie Delta and Alaska. The wedge of thinned continental crust constitutes a distinct crustal domain bounded by a transform fault on its northwest-trending oceanic face. This offers the possibility of a firm kinematic constraint on models of ocean-floor development within the Canada Basin.

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