A NEW PLATE KINEMATIC MODEL OF CANADA BASIN EVOLUTION

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ABSTRACT

Reinterpretation of the kinematic evolution of the Canada Basin is required by new data on Beaufort Sea continental margin structure. At least three kinematic stages were required to produce the Canada and Makarov basins. Stage One produced the western Makarov Basin and an area adjacent to Arctic Alaska. Stage Two produced most of the Canada Basin and the rifting of Chukchi Borderland northwestward, away from the Beaufort-Mackenzie region. Stage Three resulted from a ridge jump and fragmentation of the Arctic Ocean plate and produced a rectangular region in southern Canada Basin where spreading was oriented nearly east-west. Northern Canada Basin continued to spread northwestward, requiring an accommodation zone north of Chukchi Borderland.

The youngest eastern part of Alpha Ridge is post-accretionary, analogous to Hawaii; but the western part is syn-accretionary, analogous to Iceland.

INTRODUCTION

Numerous simple models have been proposed for the plate-tectonic evolution of the Canada Basin (reviewed in Lawver and Scotese, 1990). The most popular model invokes 66° of counterclockwise rotation of Arctic Alaska and Chukotka away from the Canadian Arctic Islands (Grantz et al., 1990a). That model is widely accepted on the basis of paleomagnetic data and the fit of geologic trends on such a rotation (Embry, 1992). The paleomagnetic data come from a single site--the Kuparuk River wells (Halgedahl and Jarrard, 1987). Unfortunately, the sample site lies too close to the Cretaceous paleopole to allow easy discrimination between different directions and styles of motion (Stone, 1989). Also, widespread remagnetization in Arctic Alaska has hampered studies at other sites that might confirm or refute a regional rotation (Hillhouse and Grommé, 1983). In spite of these drawbacks, the paleomagnetic argument has been cited as persuasive evidence in favor of rotation (Harbert et al., 1990). Also, Embry (1990) cited features that create sinuous trends after rotational restoration, in support of the model. Although his correlations generally permit such an interpretation, they do not preclude alternatives.

Conversely, existing data--including the following--conflict with the rotation hypothesis, casting doubt on its viability. The Alaska margin is 30 m.y. older than its supposed conjugate on the Canadian side, where thermal-modeling and sedimentation-rate studies now clearly indicate that a rift-drift transition occurred at the end of the Albian, and that this event was synchronous for the entire Canadian margin from Ellesmere Island to the Mackenzie Delta region (Sweeney, 1977; Embry and Dixon, 1990; Stephenson et al., this volume, a). Chukchi borderland and the Russian continental shelf overlap onto the Canadian Arctic Islands by as much as 600 km on restoration of 66° of rotation (Fig.1). The rotation model requires a hypothetical arcuate transform fault along which Chukotka was translated 2,600 km (Fig.1). The interpreted aeromagnetic anomalies in the southern Canada Basin do not fan sufficiently to validate the rotation hypothesis but instead can be (and have been) interpreted to consist of two distinct trends, supporting a multistage model (Vogt et al., 1982, Fig.9). Mantle velocity anisotropy indicates an opening direction nearly perpendicular to that required by the rotation hypothesis (Mair and Lyons, 1981).

The Frontier Geoscience Program of the Geological Survey of Canada funded geological, potential field, crustal-refraction, and deep crustal-reflection seismic studies designed to provide new data for the crustal structure and geological evolution of the Beaufort Sea continental margin. Stephenson et al. (1994; this volume, b) synthesized those regional data into a well-constrained crustal model. This paper summarizes the plate-kinematic implications of that synthesis. The evidence for, and implications of, this new model will be discussed more fully in a later paper (Lane, in prep.). This model is more complex than earlier models and uses the potential field data as supporting evidence rather than as primary kinematic data.

Future acquisition of high-quality, reliable potential field data for the Canada and Makarov basins is required before any model can be properly documented. Kinematic interpretations similar to those expressed here have been previously proposed, based on regional potential field data (e.g., Vogt et al., 1982). Whereas the earlier work cited several possible interpretations of the data, this model focuses on a single interpretation that does not violate data from the surrounding continental margins (Lane, in prep.).

NEW ARCTIC MODEL

In addition to the new Beaufort Sea data, this new model incorporates detailed aeromagnetic coverage of the Canadian polar margin adjacent to Prince Patrick Island, published bathymetry and potential field anomaly maps of the Arctic Ocean Basin, and published interpretations of the geology of the circum-Arctic margins. Two findings of the new Beaufort synthesis have direct implications for the tectonic evolution of the Arctic Ocean. First, an offset in the continental margin near 136°W. longitude (Stephenson et al., this volume, b)

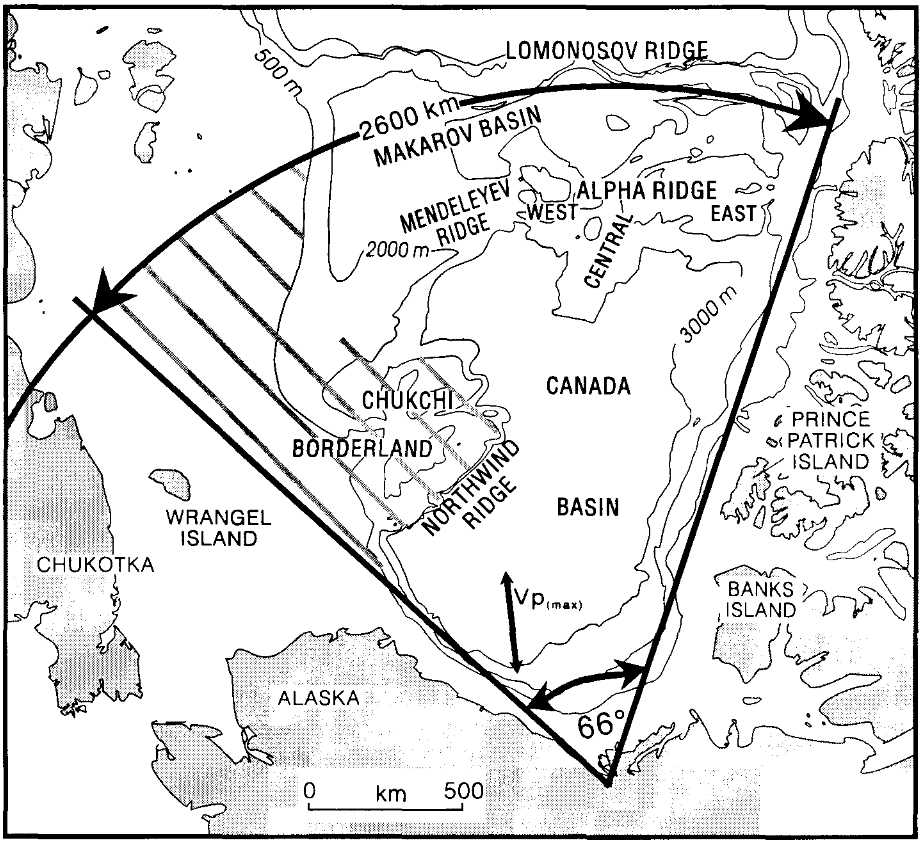

Fig.1. Bathymetric map of the Arctic region (modified from Grantz et al., 1990b) showing 66° of rotation on a hypothetical transform fault adjacent to Lomonosov Ridge (Grantz et al., 1990a). Hachured area is continental overlap resulting from restoration of their proposed rotation. Overlap area would increase using a less conservative estimate of the continent-ocean transition. Vpmax is the direction of maximum mantle P-wave velocity from Mair and Lyons (1981).

is defined by the simultaneous, abrupt termination of both the continental margin gravity high and a linear magnetic low previously identified as marking the continent-ocean transition farther northeast (Forsyth et al., 1990; Stephenson et al., 1994). The offset is interpreted as a fracture zone and therefore is a direct constraint on the kinematics of ocean opening in this part of the basin. Second, the damping of the continent margin gravity high west of 136°W. longitude reflects a local zone of complexity during the rifting event and can be extrapolated to other locations around the basin margin. The damping of the gravity high corresponds to changes in trend of the continental margin, and locally with other offsets based on the interpretation of the aeromagnetic low (Forsyth et al., 1990). Those areas were interpreted as other probable fracture zones (Stephenson et al., 1994; this volume, b).

Three stages of oceanic-crust formation are proposed. The first is the formation of the western Makarov Basin as well as oceanic crust along the Arctic Alaska continental margin. The second and best-defined stage is based on bathymetry, potential field data, and known crustal structure from widely scattered localities throughout the Canada Basin. Most of the present Canada Basin was formed during this stage. The final stage produced a rectangular zone in the center of the southern Canada Basin and contains a few north-south-trending magnetic anomalies. This stage resulted from a decoupling of the southern part of the basin from the northern part in the Late Cretaceous, possibly due to a ridge jump caused by the initiation of the Alpha Ridge plume (Lane, in prep.).

Stage 1

Four lines of evidence support an early stage of basin formation (Fig.2). First is the seismically well-defined evidence for Jura-Cretaceous extension followed by a Late Hauterivian (Early Cretaceous) age of the rift-drift transition along the Arctic Alaska continental margin (e.g., Grantz et al., 1990c). At least some oceanic crust probably formed there in the Early Cretaceous, perhaps effectively decoupling Arctic Alaska from later motions (see below). Second is the link between the tectonic evolution of Chukotka and that of the Arctic Ocean basin. Chukotka accreted to the Omolon massif and east Siberian continental collage in the Early Cretaceous, following closure of the south Anyuy ocean basin at the convergent South Anyuy suture (Zonenshain et al., 1990). The strikes of folds and thrust faults suggest that Chukotka was derived from northeast of its present location (Zonenshain et al., 1990). Also, the region suffered major tectonic shortening during that convergence. Kos'ko et al. (1993) estimate that at least 42-percent shortening occurred across Wrangel Island. Third, when the Arctic Ocean is closed to a pre-Stage 2 position, significant ocean basin remains. The Chukotka data suggest a Late Jurassic to

Early Cretaceous age because the formation of Arctic Ocean crust is assumed to be contemporaneous with the closure of the South Anyuy Ocean. Fourth, the Blow trough in northern Yukon is an extensional basin containing greater than 5 km of early Albian siltstones and turbidites (Lane, 1988), indicating that Arctic Alaska was indeed moving with respect to cratonic North America in early Albian time, although the Albian extension there implies only limited rotation of Arctic Alaska away from the craton. The foregoing provides only a partial constraint on Stage 1 motions. Fig.2 illustrates one speculative scenario consistent with convergence in Chukotka. Its inclusion here is to emphasize that the evolution of the Canada Basin includes a pre-Albian component and to provide a starting point for the better-defined later stages.

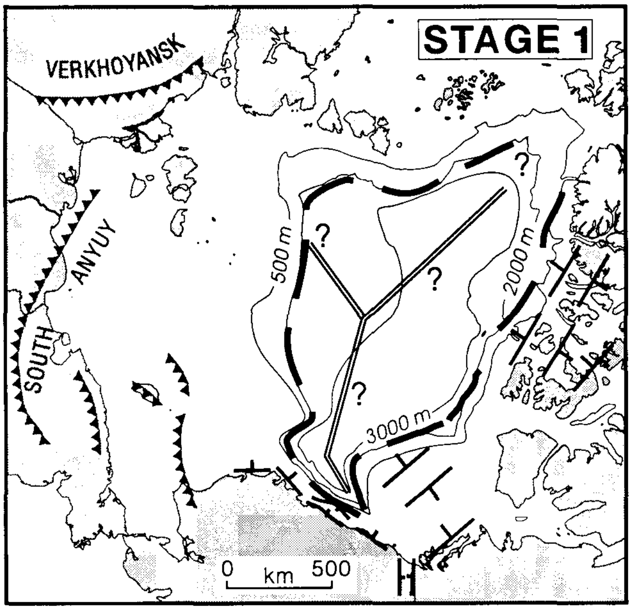

Fig.2. Speculative geometry at the end of Stage 1 spreading. Early Cretaceous convergence in Chukotka, and extension and igneous activity across the European shelf probably accommodated seafloor spreading. Heavy lines are continent-ocean boundary; double lines represent probable mid-ocean ridge.

Stage 2

This stage is supported by data from throughout the Canada Basin. The most definitive is the offset of the continent-ocean transition on the Beaufort Fracture Zone (Fig.3). Both the location and orientation of the offset are well-defined (Stephenson et al., this volume, b). Because fracture zones parallel the relative trajectory of conjugate plates, the conjugate of the eastern Beaufort Sea margin must have rifted to the northwest. The fracture zone appears to project northwestward along a diffuse linear gravity low to a point about 75 km beyond the 3,000 m isobath, at the western limit of reliable gravity data in the basin (Sobczak et al., 1990). Also, the valley and ridge geometry of Chukchi Borderland is nearly parallel with the eastern Beaufort Sea margin near the Mackenzie Delta, and also with the Canadian polar margin north of Prince Patrick Island (Fig.3).

Aeromagnetic anomalies in the Canada Basin are locally useful as corroborating evidence for Stage 2 kinematics (Fig.3). A few linear anomalies occur in the adjacent basin parallel to Northwind Ridge (Fig.3). Also, a succession of linear positive and negative anomalies occur in the basin, beginning approximately 300 km northwest of Prince Patrick Island (Fig.3). They have been previously examined (Vogt et al., 1982, Fig.13) and were interpreted as being "possibly of seafloor spreading origin." They are parallel to the adjacent Canadian polar margin, parallel to Northwind Ridge and its adjacent magnetic anomalies, and perpendicular to the Beaufort fracture zone and the synaccretionary western Alpha Ridge (Fig.1). These alignments among five widely dispersed physiographic and magnetic features in the Canada Basin argue against a fortuitous alignment, and strongly for a genetic correlation.

Stage 3

Evidence for Stage 3 is found in the southern Canada Basin, within an area defining a north-south elongate rectangle. The few linear magnetic anomalies that can be interpreted in southern Canada Basin have trends that vary about north-south, suggesting a broadly east-west-spreading direction there (Fig.4).

The west boundary of the Stage 3 area is locally constrained between magnetic anomalies trending north-south and those parallel to Northwind Ridge (Fig.4). The east boundary is approximately constrained by the termination of the Beaufort Fracture Zone gravity anomaly, and has been extrapolated northward parallel to the Stage 3 anomaly trend, as a first approximation. Due to inadequate data, the southern boundary is not constrained, except that the magnetic character of Arctic Alaska and the adjacent Chukchi Basin consists of elliptical anomalies unrelated to seafloor spreading.

The northern boundary of the Stage 3 area is a line between northern Prince Patrick Island and the northern edge of Chukchi Borderland. North of this line the magnetic stripes of Stage 2 origin are prominent features of the magnetic anomaly field (Fig.3). Detailed aeromagnetic anomaly data across the continental margin west of Prince Patrick Island show complex anomaly patterns and a prominent linear magnetic low, the polar shelf magnetic anomaly, which is deflected and offset along the same trend as the termination of the Stage 2 magnetic stripes (Forsyth et al., 1990). This line includes a fracture zone but is clearly more complex (Lane, in prep.). Accordingly it has been labeled as the Prince Patrick Lineament (Fig.4). The Stage 2 magnetic

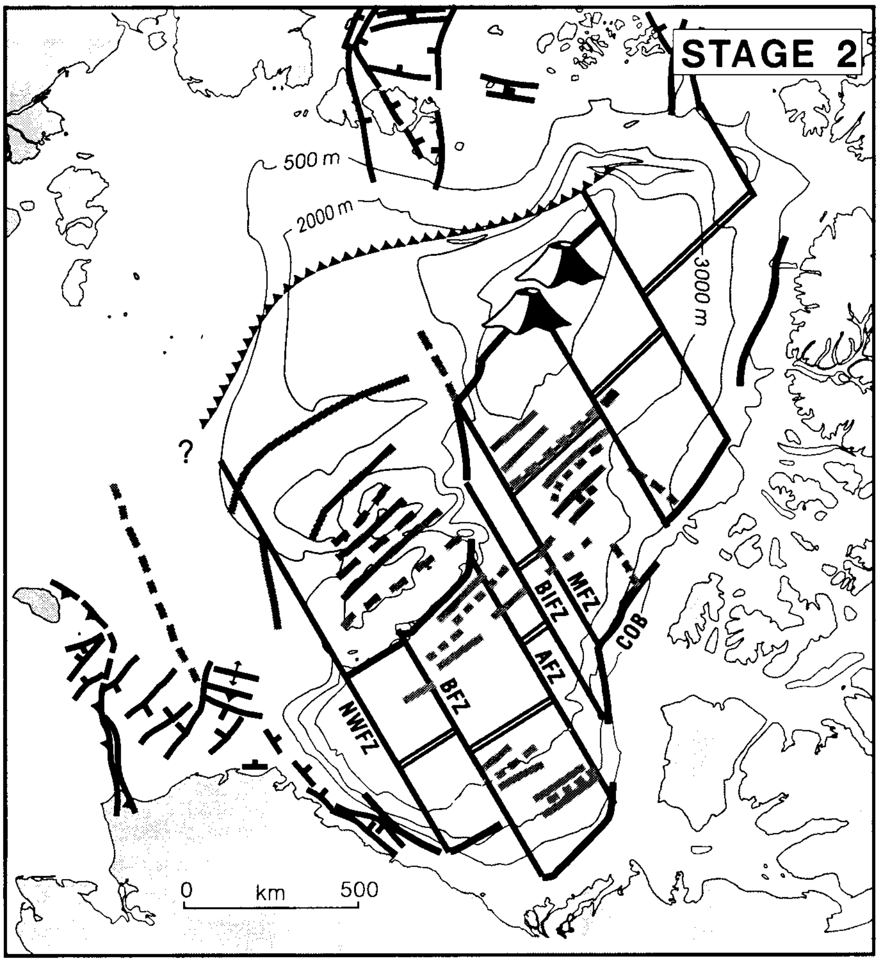

Fig.3. Canada Basin at the end of Stage 2 spreading. Chukchi borderland physiography and magnetic anomalies support northwestward extension. Continent-ocean boundary (COB) is modified from Forsyth et al. (1990), Grantz et al. (1990a), and Stephenson et al. (1994). Fracture zones: BFZ, Beaufort Fracture Zone; NWFZ, Northwind Fracture Zone; AFZ, Amundsen Fracture Zone; BIFZ, Banks Island Fracture Zone; MFZ, M'Clure Fracture Zone. Seafloor spreading may have been accommodated by convergence beneath the Russian Arctic shelf. If so, a small triangular plate (Arctic Plate) would be bounded on the SE by the spreading ridge, on the NW by the convergent zone, and on the SW by the NWFZ. Double lines are spreading axes; single lines are fracture zones (Stephenson et al., 1994). The COB has been repeated and displaced to the northwest to bracket the area of Stage 2 oceanic crust (shaded). The volcanoes on the linear submarine plateau (future Mendeleyev and Central Alpha ridges) represent the incipient Alpha Ridge plume. Solid and dashed grey lines are magnetic anomaly trends (positive and negative, respectively) interpreted here as being pertinent to Stage 2 (principally from Kovacs et al., 1990; P.G.O. Sevmorgeologia, unpublished).

anomalies trending northeast from the Prince Patrick Lineament indicate that the northward-trending Stage 3 anomalies are confined to the south of it.

Geometric requirements suggest that Stage 3 opening in the southern Canada Basin was connected through an extensional transform zone, shown schematically in Fig.4, to continued northwestward spreading farther north (Lane, in prep.).

DISCUSSION

Alpha Ridge (Fig.1) is underlain by an anomalously thick mafic crust (Asudeh et al., 1988), interpreted as a remnant of the same mantle plume that presently underlies Iceland (Forsyth et al., 1986). However, only the linear eastern segment of the ridge has been studied. The central and western parts of the ridge have a complex chevron shape inconsistent with a post-accretionary origin (Fig.1). Also, western Alpha Ridge is nearly perpendicular to the bathymetric trend of Chukchi Borderland (Fig.1) and to the Canadian polar margin (Fig.3). The simplest interpretation consistent with the ridge's complex shape is that western Alpha Ridge is syn-accretionary, like the modern Iceland plume. The syn-accretionary segment is bracketed on the east by central Alpha Ridge, and on the west by the northern part of Mendeleyev Ridge (Fig.1). The latter two segments are parallel to each other and nearly perpendicular to the syn-accretionary segment. The role of Alpha Ridge in the evolution of the Canada Basin will be discussed more fully later (Lane, in prep.), but the foregoing suggests that the eruption of a mantle plume in the Late Cretaceous produced a westward ridge jump (Fig.3) that caused cessation of Stage 2 spreading as well as the fragmentation of the Arctic Plate (Fig.3) into two short-lived microplates (Fig.4). The Alpha Ridge plume drove northwest spreading in northern Canada Basin and created an anomalous crustal thickness straddling the mid-ocean ridge (Fig.4). When the North American plate passed too far west over the plume, it could no longer sustain ocean spreading and began penetrating the older oceanic crust as the post-accretionary eastern Alpha Ridge (Figs.1,4). When that happened, the entire ridge system in the Canada Basin died out. According to this scenario, the Mendeleyev Ridge and central Alpha Ridge (Fig.1) are the oldest; western Alpha Ridge is syn-accretionary and younger than the adjacent segments. The eastern post-

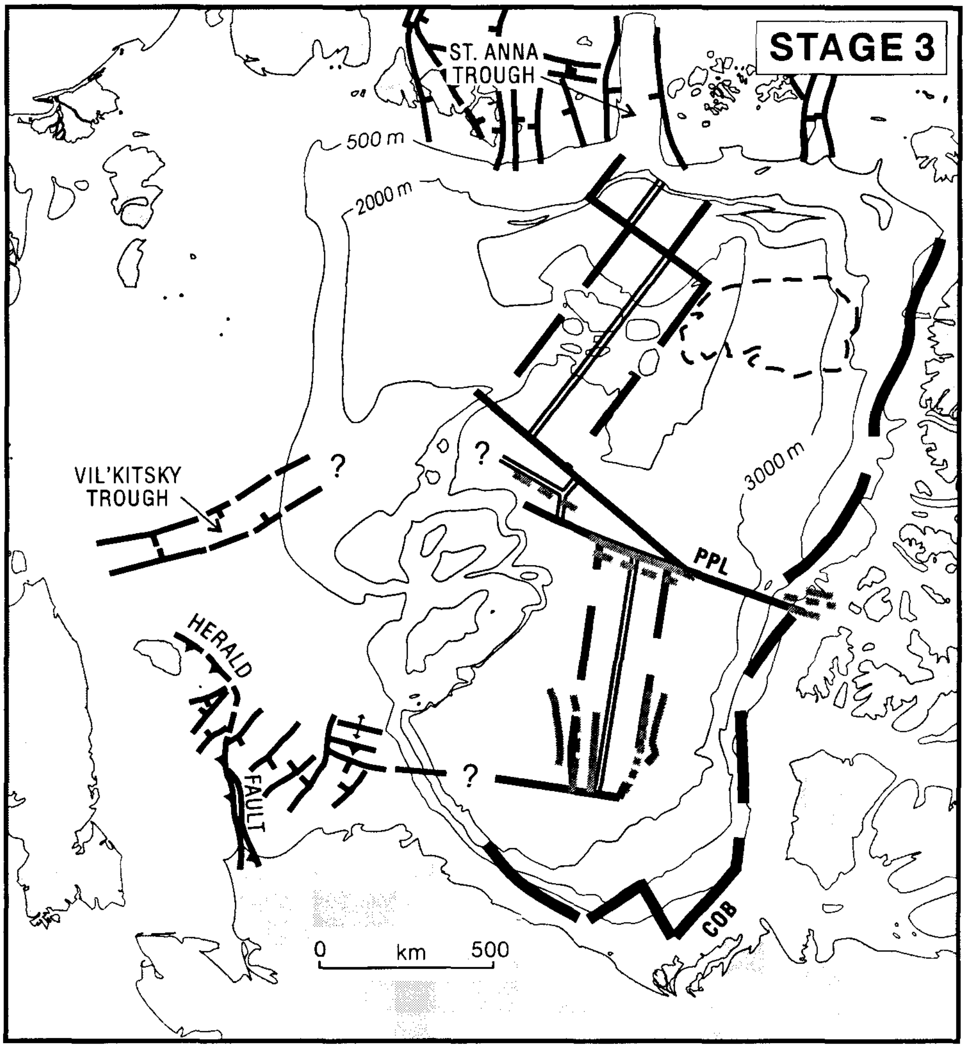

Fig.4. East-west Stage 3 spreading in the southern Canada Basin, synchronous with NW-SE spreading in the northern Canada Basin. Triple junction in the central basin is schematic, representing a geometrically required zone accommodating differing simultaneous displacements. Continental accommodation in bordering regions is speculative but consistent with available data (Thurston and Theiss, 1987; Grantz et al., 1990b, 1990c; Zonenshain et al., 1990). The Prince Patrick Lineament (PPL) is shown, double lines are spreading axes, and long dashed lines bracket Stage 3 oceanic crust (shaded). Dashed outline in northern Canada Basin is the site of the future post-accretionary Alpha Ridge.

accretionary part (Fig.1) is the youngest and records the Late Cretaceous track of the North American plate over the Alpha Ridge plume.

CONCLUSIONS

Existing data require a multistage kinematic evolution. Most of the preserved Canada and eastern Makarov basins formed by northwestward Stage 2 spreading away from Arctic Canada. Constraints include the Beaufort Fracture zone, the bathymetry of western Alpha Ridge and Chukchi borderland, the continent-ocean transition of parts of the Canadian polar margin, and aeromagnetic anomaly trends in both northern and southern Canada Basin. Stage 3 in the southern Canada Basin is based on several north-south trending magnetic anomalies that truncate Stage 2 anomalies in both southern and northern Canada Basin. East-west Stage 3 spreading is confined to the southern Canada Basin and occurred while northwest-southeast spreading continued in the northern Canada Basin. Fragmentation and divergent spreading of the two Arctic oceanic microplates were presumably accommodated in a complex zone north of Chukchi Borderland. Stage 1 evolution is poorly defined but is required to accommodate the timing of Alaska margin formation and Chukotkan deformation.

The northern Mendeleyev and Alpha ridges were partly syn-accretionary and partly post-accretionary. The syn-accretionary parts help to define the kinematics of Canada Basin evolution. The post-accretionary part defines the local track of the North American plate over the mantle during the Late Cretaceous.

Reliable aeromagnetic and gravity data in the Canada and Makarov basins are required to document any plate-tectonic model. The acquisition of high-quality data in the Beaufort-Mackenzie region has shown that even limited areas of reliable coverage can produce valuable data to constrain Arctic Ocean evolution.

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