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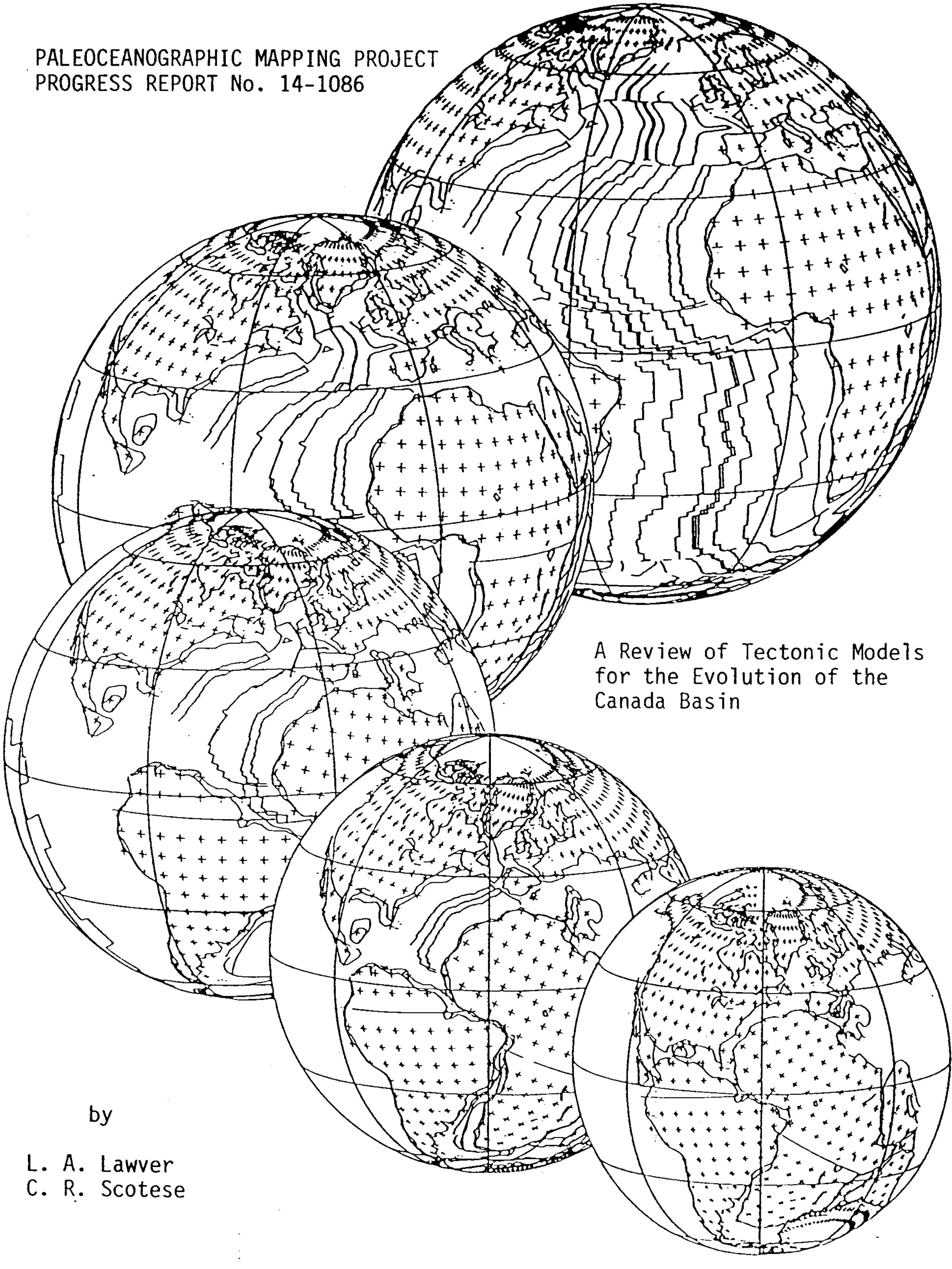

A Review of Tectonic Models for the Evolution of the Canada Basin

by

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Introduction

The Arctic Ocean is the least-explored ocean on earth with a nearly continuous ice cover that makes collection of shipborne geological and geophysical data almost impossible. As late as 1907 (Mikkelsen, 1955), expeditions were still being sponsored to discover the elusive northern continent thought to occupy all or part of the Arctic Ocean. Since the plate tectonic revolution of the sixties, numerous theories concerning the tectonic origin of the Arctic Ocean, and the Canada Basin in particular (Figure 1), have been proposed.

Tectonic models for the Canada Basin can be separated into three broad categories: oceanization of continental crust, entrapment of old oceanic crust, and the *in-situ* formation of the oceanic crust by seafloor spreading. The first category consists of the tectonic model originally suggested by Shatskiy in 1935 and later given prominence by Beloussov in the 1950's and 60's (Shatskiy, 1935; Beloussov, 1970). They argued that the Canada Basin was a cratonic high that shed debris southward, particularly along Arctic Canada and the north slope of Alaska. This high was later oceanized by mantle convection that eroded the root and caused the area to subside. Pogrebitskiy (1976) and Pushcharovskiy (1976) both used the oceanization of continental crust to explain the tectonic evolution of the Canada Basin. Recently such models have been modified (Pogrebitskiy et al., 1984), and the formation of the Canada Basin has been explained by a combination of lithospheric oceanization and granitization (endogenic differentiation).

The second category of models suggests that much of the Canada Basin resulted from entrapment of older oceanic crust (Churkin, 1970; Churkin and Trexler, 1980; Karasik et al., 1984). Early Mesozoic oceanic lithosphere, travelling northward on the Kula plate, was inserted into the Arctic and during the mid-Cretaceous was cut off from the Pacific by the suturing of North America, the Kolyma terrane, and Eurasia (see figure 2).

Others have suggested that only parts of the Canada and Makarov basin are composed of trapped oceanic crust of Paleozoic age (Jones, 1980; Rowley et al., 1985).

The tectonic models that comprise the third category, *in-situ* sea floor spreading, can be subdivided four ways. The first subdivision consists of models that can be characterized as the "rotational model" (Carey, 1955, 1958; Grantz, 1966; Hamilton, 1967, 1968; Tailleur, 1969; Tailleur and Snelson, 1969; Rickwood, 1970; Tailleur and Brosgé, 1970; Freeland and Dietz, 1973; Tailleur, 1973; Johnson et al., 1978; Sweeney et al., 1978; Grantz et al., 1979; Grantz et al., 1981; Mair and Forsyth, 1982; Vogt *et al.*, 1982; May and Grantz, 1983; Sweeney, 1983; Burke, 1984; Green et al., 1984; Harland, et al. 1984; Embry, 1985; Sweeney, 1985; McWhae, 1986). The rotational model suggests that the North Slope block rotated away from the Canadian Arctic Islands about a pole near the Mackenzie Delta (figure 3). The second subdivision of *in-situ* seafloor spreading models (figure 4) is based on the assumption that the Alpha and Mendeleev ridges were once an active spreading center (Johnson and Heezen, 1967; Beal, 1968; Vogt and Ostenso, 1970; Ostenso and Wold, 1971; Hall, 1970, 1973; Ostenso, 1974; Christie, 1979; Crane, in press; Smith, in press). This subdivision, characterized as the "Arctic Islands strike-slip" model, consists of models that predict that the North Slope is a passive margin that rifted either from the Lomonosov Ridge or the Alpha and Mendeleev ridges. In these models, the margin of the Canadian Arctic Islands acted as a left-lateral transform fault. The third subdivision of seafloor spreading models can be characterized as the "North Slope strike-slip" model (Herron et al., 1974; Vogt et al.,1982; Metz et al., 1982; Rowley et al., 1985). In these models (figure 5), northeastern Siberia or the Chukchi Plateau rifts away from the Canadian Arctic Islands along a transform fault that parallels the margin of the North Slope. These models predict little or no motion of the North Slope with respect to cratonic North America. Finally, comprising the fourth subdivision is the model of the Canada Basin proposed by Jones (1980, 1982,1983). His model consists of a combination of trapped Paleozoic oceanic crust, dextral strike-slip movement along the

North Slope margin, and sea floor spreading along the Alpha Ridge. These four models along with other seafloor spreading models for the tectonic evolution of the Canada Basin will be discussed in the following sections.

Historical Development

The first mobile model for the *in-situ* formation of the Canada Basin was the sphenochasm model (Carey, 1955, 1958). Carey cited the bend in the trend from the Canadian Rockies and Coast Ranges through the Alaska Range into the Alaska Peninsula and categorized the bend as an orocline. Carey's model was the predecessor of the true "rotational model". The next step came when Grantz (1966) was working on the structure and tectonics of western Alaska. He realized that the position and trends of the known and suspected strike-slip faults in western Alaska could be explained by a modification of Carey's (1958) oroclinal bending model. By 1967, it was also realized that there was a good paleogeographic fit between Arctic Alaska and Arctic Canada (Tailleur, 1973). Hamilton (1967, 1968) discussed the rotation of northern Alaska away from the Canadian Arctic Islands and felt that the opening of the Canada Basin could be accommodated by the deflection of the Cordilleran front and with strike-slip motion between Siberia and the Chukchi Shelf. At the same time, Tailleur et al. (1967) presented a talk at the International Symposium on the Devonian System where they suggested that if Arctic Alaska was rotated clockwise about a pole south of the Mackenzie Delta then Early Mesozoic Alaska was placed against Banks Island in the Canadian Arctic. They presented a slide titled 'possible paleogeography in the Late Devonian' which showed the Devonian clastic wedges on the Amerasian continental edge juxtaposed with those in the Canadian Arctic Islands. Tailleur et al. felt that it was more likely that the Devonian clastic wedges had been shed off opposite flanks of a single linear uplift than off the southern flank of a 3,500 km long semi-circular uplift whose northern flank was an ocean deep.

In an unpublished abstract for the Alaska Science Congress (August, 1967), Tailleur specified 30° to 40° of clockwise pivoting of Alaska about the northern end of the

Canadian Rockies to restore "the counterclockwise drift suggested by Grantz and by Hamilton". By closing the Canada Basin, Tailleur believed the facies and structural grain at the margin of the Cordillera would be straightened and would place the northerly-derived clastic deposits of Late Devonian age now in the Brooks Range and Wrangel Island on opposite flanks of a linear uplift from those in the Canadian Arctic Islands.

By 1969, Tailleur (1969) and Tailleur and Snelson (1969) described what they saw as large-scale horizontal displacements in the Brooks Range and speculated that the Siberian-Chukchi shelf had drifted southeastward and that northern Alaska and the Arctic Islands had earlier rifted apart and rotated out of the Canada Basin. Tailleur (1969) showed a 30° rotational opening of the Canada Basin about a pole 500 km south of the Mackenzie Delta. Hamilton (1970) in a manuscript submitted in December, 1969, showed a rotational opening of the Canada Basin of about 50° about a pole that appears to be located 300 or 400 km south of the Mackenzie Delta. While Hamilton (1970) references Carey (1958), his support for this model includes the need for a northern source for the Carboniferous through Neocomian clastic rocks of northern Alaska and the northeastward trend of lower Paleozoic rocks in the northern Yukon Territory.

Rickwood (1970) discussed the Prudhoe Bay field and concluded that the Canada Basin opened 67° about a pole of rotation located in the Mackenzie Delta. In the same symposium volume, Tailleur and Brosgé (1970) summarized the geology of the North Slope and used it to illustrate the tectonic evolution of the Arctic and the rotational opening of the Canada Basin between the Neocomian and the late Albian. The ages they assigned were based on the changes in deposition that they observed in the geological record of the North Slope.

By 1970, the extension of the mid-ocean ridge in the Atlantic through the Norwegian-Greenland Sea and into the Eurasia Basin had been recognized (Heezen and Ewing, 1961; Wilson, 1963; and Vogt et al., 1970). Vogt and Ostenso (1970) utilized the Russian aeromagnetic data to assign an age of 40 to 0 Ma to the Eurasia Basin. They also assigned a seafloor spreading origin to the Alpha and Mendeleev ridges, and an age for them of 60 to 40 Ma. Magnetic anomalies parallel to the Alpha Ridge had first been noticed by King et al. (1966) while Ostenso (1962) had noted the high amplitude magnetic anomalies associated with the Alpha Ridge. While the U.S. Geological Survey people were studyingthe geological framework of Arctic Alaska, Siberia and the Canadian Arctic Islands, marine geologists were looking at the Eurasia Basin as an extension of the Mid-Atlantic seafloor spreading ridge. Tailleur and Brosgé (1970) rotated all of the Canada Basin closed about a pole south of the Mackenzie Delta while Vogt and Ostenso (1970) had seafloor spreading along the Alpha and Mendeleev ridges but left the tectonic evolution of the Canada Basin undecided.

Churkin (1973) in a paper submitted in 1971, concluded that the available data in the Arctic required opening of the modern Canada Basin (Late Jurassic or Early Cretaceous), development of the deep Canada Basin (Late Cretaceous), and opening of the Eurasian Basin in connection with Cenozoic seafloor spreading from the Arctic Mid-Ocean Ridge [Gakkel Ridge]. Churkin (1973) combined the inferred Canada Basin tectonics of Vogt and Ostenso (1970), who had opening on the Arctic Mid-Ocean Ridge between 40 Ma and present, seafloor spreading on the Alpha and Mendeleev ridges between 60 and 40 Ma and opening of the deep Canada Basin prior to 60 Ma, with the idea of a suggested spreading axis that opened the Canada Basin about a pole in the Mackenzie Delta.

In 1972, Pitman and Talwani (1972) published their definitive paper on sea-floor spreading in the North Atlantic. This paper seems to have prompted a number of authors (Freeland and Dietz, 1973; Herron et al., 1974) to begin speculation on how to place the Canada Basin into a global plate tectonic framework. The location of the Pitman and Talwani (1972) pole of opening for North America-Eurasia for 63 Ma to present, was actually used to explain the opening of the Eurasia Basin between 63 Ma and the present (Herron et al., 1974) prior to the identification of the seafloor spreading anomalies by Karasik (1974). Lineated magnetic anomalies were first observed in the Eurasia Basin in

1968 (Karasik, 1968) while Vogt et al., (1979) updated and confirmed Karasik's (1974) work with additional aeromagnetic data.

Freeland and Dietz (1973) wrote a paper in 1972 which used the ideas of Grantz (1966), Tailleur (1969), Tailleur and Brosgé (1970),Vogt and Ostenso (1970), and Pitman and Talwani (1972) to develop a model for the rotational history of Alaskan tectonic blocks. While the idea of rotational tectonic blocks are used in some of the later models, Freeland and Dietz (1973) also incorporated the translation of northeastern Siberia up against the Canadian Islands by strike-slip motion along the northern edge of Alaska and along the Lomonosov Ridge (figure 6). While Churkin (1973) assumed the Alpha Ridge to have been an active seafloor spreading center, Freeland and Dietz (1973) seemed to have ignored the Alpha and Mendeleev ridges since the strike-slip motion of the Siberian block rifting away from Arctic Canada can not be reconciled with seafloor spreading along the Alpha and Mendeleev ridges. While Freeland and Dietz (1973) still incorporated the rotation of Alaska in their model, they in fact suggested the first major variation on the tectonic evolution of the Canada Basin.

Herron et al. (1974) also utilized the Pitman and Talwani (1972) history of seafloor spreading in the North Atlantic and their poles of opening for North America-Eurasia to explain the tectonic evolution of the Eurasia Basin. For the Canada Basin, they postulated that during the Early Paleozoic, the Kolymski block collided with Arctic Canada. Herron et al. (1974) then modified the Freeland and Dietz (1973) idea to have all of the Kolymski Block rifting away from Arctic Canada during the Jurassic along parallel strike-slip faults along the Lomonosov Ridge and along the North Slope of Alaska (figure 5). Their model was the first one to propose a tectonic history of the Canada Basin that did not include a rotational opening of the Canada Basin that resulted in passive margins on both Arctic Alaska and Arctic Canada. When the pole of rotation for North America and Eurasia shifted to the north coast of Greenland during the Cretaceous, Herron et al. (1974) postulated that the extension in the North Atlantic resulted in compression in the Canada

Basin on the opposite side of the pole of rotation between 81 Ma and 63 Ma. This made the Alpha and Mendeleev ridges arc-related features rather than seafloor spreading features as postulated by Vogt et al. (1970). Vogt and Ostenso (1970) had earlier mentioned the possibility that the Alpha Ridge might be arc-related but their idea was based on a superficial resemblance between the Alpha Ridge and the Beata Ridge in the Caribbean, which was also believed to be arc-related.

With the exception of the 1975 Canadian Society of Petroleum Geologists Memoir 4, there was virtually nothing new written about the tectonic evolution of the Canada Basin until the 1978 Arctic Geophysical Review (Sweeney, 1978). Yorath and Norris (1975) did present a slight modification of the Herron et al. (1974) idea, that included extremely asymmetrical spreading with the spreading center that rifted the Kolymski block off Arctic Canada having remained along Arctic Canada. Sweeney et al. (1978) utilized the latest geophysical results from the Arctic to produce support for the original Hamilton (1970) and Tailleur and Brosgé (1970) model for the rotational opening of the Canada Basin. De Laurier (1978) summarized and expanded the arguments that Herron et al. (1974) and Clark (1975) had used to argue that the Alpha and Mendeleev ridges were not produced by normal mid-ocean sea floor spreading. De Laurier (1978) cited both the age versus depth relationship of Parsons and Sclater (1977) which would imply that if the Alpha Ridge is at least 70 Ma old (based on the age of silicoflagellates dredged from its crest; Ling et al. (1973), Clark (1974)), its relief should have decayed by 2900 meters and the fact that the present minimum depth of the Alpha Ridge ranges between 1200 meters and a saddle on the Mendeleev Ridge of just below 2500 meters, which is well above the average depth for active sea floor spreading ridges. De Laurier (1978) also pointed that a 70 Ma old ridge should have only 500 meters of relief while the Alpha Ridge has 2900±500 meters of relief.

Starting in 1979, a whole new series of papers concerning the tectonic evolution of the Canada Basin were published. Christie (1979) published a paper that he had presented some time before on the relationship of Svalbard to the Franklinian Geosyncline in the Canadian Arctic. He utilized the shore-based geology to constrain the tectonic evolution of the Arctic. In his model (figure 7) the Canada Basin opened with either spreading along the Alpha Ridge or parallel to the Alpha Ridge, resulting in transform fault motion along the Canadian Arctic. The Lomonosov Ridge, North Slope of Alaska and "Bering Splinter" (part of Northeast Siberia) were all rifted margins. After the Canada Basin opened in the Late Paleozoic or earliest Mesozoic, Cenozoic opening in the North Atlantic produced closure between the "Bering and Kolymski Splinters" and Siberia so that the opposite transform margin to Arctic Canada was obscured. Christie (1979; personal communication, 1986) was primarily concerned with a model that would allow juxtaposition of the Franklin Geosyncline and Svalbard but he did introduce a new variation on the evolution of the Arctic that was later exploited by others.

Vogt et al. (1979) found complex, sublinear, high-amplitude anomalies over the Alpha Ridge that correlate with topography and with free-air gravity. In the northern Canada Basin they found several prominent linear anomalies subparallel to the Alpha Ridge (Cordillera) which if they were produced by sea-floor spreading indicate that the spreading axis cannot have paralleled either the Canadian continental margin (as Herron et al. (1974) suggested) or the Alpha Ridge (as Christie (1979) suggested) but instead lay parallel to the Northwind Ridge (Escarpment). Vogt et al. (1982) further developed this model.

In 1979, the first offshore seismic reflection data from the continental margin north of Alaska was published (Eittreim and Grantz, 1979; Grantz et al., 1979). On the bases of these data, Grantz et al. (1979) concluded that the continental margin north of Alaska was a passive margin of the Atlantic type. In the west the Chukchi sector is characterized by the deep late Mesozoic and Tertiary North Chukchi basins and the Chukchi Plateau (Continental Borderland). They speculate that the Chukchi Plateau which has continental affinities (Hunkins et al., 1962; Shaver and Hunkins, 1964) may have been rifted out of the region of the North Chukchi Basin. If the scattered continental fragments of the

Chukchi Plateau are brought together, Grantz et al. (1979) suggest that they would fit within the structurally deeper regions of the North Chukchi Basin. The linear Northwind Ridge could have functioned as a strike-slip fault as the Canada Basin opened and the Chukchi Plateau could be stretched and intruded continental crust.

Jones (1980) presented a new model that could not be classified with any of the previous models. He based his model on data collected during petroleum exploration along the margin of the Canada Basin. His model assumes that the southern part of the Canada Basin is Paleozoic in age. Thousands of kilometers of dextral strike-slip were accommodated along the Tintina Fault parallel to the Canadian Cordillera and continuing to the Lomonosov Ridge region along the Beaufort-Laptev Sea continental margin. When the Alpha and Mendeleev ridges began to spread in the Early Cretaceous, an additional dextral strike-slip fault developed along Arctic Canada. By Late Cretaceous, dextral strike-slip motion along the Kaltag Fault-Porcupine lineament continued from Western Alaska along Arctic Canada. Jones (1980) proposed more than 500 kilometers of offset along this fault system which displaced the Tintina Fault from its continuation along the Beaufort-Laptev Sea. In this model the Lomonosov Ridge can be considered a passive margin as well as an indistinct passive margin in the deep Canada Basin while the sense of strike-slip motion along Arctic Alaska is opposite to that proposed by Vogt et al. (1982) or Herron et al. (1974). The sense of strike-slip motion along Arctic Canada is also opposite to that proposed by Christie (1979).

After Jones (1980), the more recent papers that discuss *in-situ* formation of the Canada Basin have presented data and interpretations that support one of the four previous models or can be considered to be only slight modifications of the four. Of particular importance to our understanding of tectonic features in the Canada Basin have been the data presented from the CESAR experiment (Jackson et al., 1985) which studied the Alpha Ridge. Even though they collected seismic refraction, heat flow, magnetics, gravity and bathymetry data they were able only to conclude that the Alpha Ridge is an oceanic plateau of problematic origin like the Ontong-Java and Manihiki plateaus of the Pacific (Forsyth et al., 1986). The data also support the earlier idea of Vogt et al. (1979) that the Alpha and Mendeleev ridges were formed similar to the present-day Icelandic hotspot. Lawver et al. (1983) suggested that the Alpha and Mendeleev Ridges may have been formed by a hot spot that started near the Siberian side, migrated across the active ridge that was opening the Canada Basin, and ended near Arctic Canada. Their model would explain the apparent necking of the Mendeleev Ridge near 81° N and the change in strike between the Alpha and Mendeleev ridges.

An important constraint on the movement of the North Slope of Alaska with respect to North America would be reliable paleomagnetic results. Newman et al. (1977) presented an abstract concerning paleopoles that they determined from Late Devonian and Mississippian strata from the Brooks Range. They incorporated into their results paleomagnetic data released by Exxon Corporation on twelve major stratigraphic sections and an oriented core from Prudhoe Bay. Newman et al. (1977) found that the measured paleopoles are "highly divergent" from coeval North American poles and show a counterclockwise rotation of about 70° for a continental plate that included all of the North Slope and Brooks Range of Alaska and adjacent Yukon Territory.

Hillhouse and Grommé (1983) found that Upper Devonian and Mississippian sedimentary rocks in a large part of the Brooks Range had been remagnetized following a major episode of thrusting and folding during the Cretaceous. Consequently they concluded that paleomagnetic results from the Brooks Range could not be used to confirm a rotational opening of the Canada Basin. They did report on two additional oriented cores taken from the Lower Triassic Ivishak Formation and the pre-Mississippian argillite from East Simpson No. 2, an NPRA well on the coast about 250 kilometers west-northwest of Prudhoe Bay. While the Lower Triassic Ivishak Formation core gave a poorly defined paleomagnetic pole of probable post-Triassic age, the other core, taken in the pre-Mississippian argillite, carried a stable magnetic component (in hematite) that probably originated during deposition of the overlying Mississippian redbeds (Hillhouse and Grommé, 1983). They found that the hematite zone gives a pole consistent with large-scale counterclockwise rotation of Arctic Alaska.

Finally, Halgedahl and Jarrard (in press), undertook a paleomagnetic study using fully oriented drill cores from two ARCO wells in the Kuparuk River oil field, immediately west of Prudhoe Bay. Unlike the earlier studies which were uncertain of the timing of the rotational opening of the Canada Basin, the ARCO study concentrated on the Kuparuk River formation, a Lower Cretaceous clastic shelf sequence of Valangian to Barremian, possibly the youngest pre-emplacement formation on the North Slope. Their results are only compatible with the 70° counterclockwise rotation of the North Slope block away from Arctic Canada about a pole of rotation in the Mackenzie Delta. Furthermore, they conclude that the rotation began at approximately 130 Ma and concluded no later than about 100 Ma when collision between the North Slope block and the South Anyui-Yukon-Koyukuk trench triggered the Brookian orogeny.

The major aeromagnetic programs of the U.S. Navy were reported in 1981 (Taylor et al., 1981; Vogt et al., 1981) and 1982 (Vogt et al., 1982). While Taylor et al. (1981) interpreted the Canada Basin aeromagnetic results as indicating seafloor spreading which is Jurassic in age (153 Ma to 127 Ma: DNAG timescale, Palmer (1983)) and supportive of a rotational opening of the Canada Basin, Vogt et al. (1982) reinterpreted the data and concluded that such questions (of tectonic evolution) "cannot be resolved with existing data, or even with more of the same". They suggest that using the tectonic models as guides, multi-year, multi-disciplinary air-lifted experiments deployed on ice flows will be needed to make major progress in our understanding of the tectonic evolution of the Canada Basin.

Tectonic Setting of the Canada Basin

In order to provide a proper framework to study the evolution of the Canada Basin, the North Atlantic and Eurasian basins must be closed, restoring North America and Eurasia to their pre-drift configuration. This exercise itself is not without controversy. Though numerous reconstructions of the North Atlantic have been proposed (Bullard et al., 1965; Sclater et al., 1977; Srivastava, 1978; Unternehr, 1982; Srivastava and Tapscott, 1986), most investigations have focused on the evolution of the Atlantic region and little attention has been paid to the fit between North America and northeastern Eurasia. Indeed, most of these reconstructions require 1000-2000 km of east-west closure between Alaska and northeast Eurasia as a consequence of sea floor spreading in the North Atlantic during the Tertiary. It is difficult to find evidence for compression of this magnitude.

Another unresolved problem is the fit of Greenland and North America, and the implied offset across the Nares Strait (Dawes and Kerr, 1982). Geologic and structural arguments have been made suggesting that the offset along the Nares Strait fault is less than 50 km (Dawes and Kerr, 1982); however, complete closure of Baffin Bay and the Labrador Sea requires at least 250 km of sinistral strike-slip movement (Wilson, 1963; Johnson and Srivastava, 1982).

In an attempt to solve these problems, we propose the North Atlantic reconstruction illustrated in Figure 8. In this reassembly, North America and northeastern Eurasia are nearly contiguous. The closure between these regions, required by the opening of the North Atlantic and Eurasian basins, is about 500 km and can be accommodated by compression along the Delong Mountains in northwestern Alaska and in the Verkhoyansk foldbelt between Kolyma and Siberia. Greenland is fitted tightly against Baffin Island and Labrador. The offset along the Nares Strait fault is kept to a minimum by undeforming the Eurekan foldbelt and by unstretching the grabens in the Lawrence, Jones, and Viscount-Melville Sounds. Also, in this reconstruction the Lomonosov Ridge has been rotated independently with respect to North America. Approximately 300 km of right-lateral displacement is required between the southern end of the Lomonosov Ridge and northernmost Ellesmere Island (Vogt et al., 1982). The poles of rotation used to produce the reconstruction illustrated in Figure 8 are listed in Table I.

Tectonic Features of the Canada Basin

The major tectonic features of the Canada Basin that must be accounted for in any tectonic model are the Alpha Ridge, the Mendeleev Ridge, the Chukchi Plateau and the Northwind Ridge (Figure 1). Most authors agree that the crust of the Chukchi Plateau and Northwind Ridge is stretched continental crust or transitional crust (Sweeney et al., 1978). These latter features are thought to be derived from either the North Chukchi Basin (Grantz and May, 1983) or from the continental margin adjacent to Banks Island (Metz et al., 1982; Mair and Forsyth, 1982; Vogt et al., 1982; Rowley et al., 1985).

More problematic are the Alpha and Mendeleev ridges which have been interpreted to be: 1) an extinct spreading center (Johnson and Heezen, 1967; Beal, 1968; Vogt and Ostenso, 1970; Ostenso and Wold, 1971; Hall, 1970, 1973; Christie, 1979; Jones, 1980) ; 2) a thin sliver of continental crust like the Lomonosov Ridge (Johnson et al., 1978); 3) a stretched fragment of continental or transitional crust (King et al., 1966; Kerr, 1980; Karasik et al., 1984; Crane (in press)); 4) an island arc (Herron et al., 1974; Taylor, 1978; Churkin and Trexler, 1980; Rowley et al., 1985); 5) a oceanic plateau (Vogt et al., 1981; Jackson et al. (in press)); 6) a 'hot spot' trace (Vogt et al., 1979; Lawver et al., 1983); 7) a "leaky transform" (Embry, 1985); or 8) the result of excess ridge axis volcanism, as in the case of Iceland (Vogt et al., 1982; Forsyth et al., 1986; Smith (in press)).

The presence of Late Cretaceous sediments along the axis of the Alpha Ridge indicates that if it was a spreading center, it was not active during the Tertiary. A Mesozoic age for spreading is also unlikely because the corrected depth to basement (2.5 km) is far too shallow, since a spreading center of Cretaceous age would have subsided to a depth of 4 to 5 km (DeLaurier, 1978). Recent results of the Canadian Expedition to Study the Alpha Ridge (CESAR) indicate that the topography of the ridge is complex and unlike the Lomonosov Ridge (Jackson and Johnson, 1984). The axial valley of the Alpha Ridge is an elongate graben with a thick cover of sediments (>400 m). Samples dredged from the steep northeastern flank of the valley have been identified as vesicular alkali basalt (Van Wagoner and Robinson, 1985), indicating that at one time at least part of the ridge was very shallow. Though the evidence is not conclusive, recent discussions of the Alpha and Mendeleev ridges (Jackson et al. (in press), Smith (in press)) tend to favor an oceanic origin, similar to Iceland or the high -standing plateaus of the Pacific.

Classification Scheme

As shown in figure 8, the Canada Basin can be considered to have four sides: 1) Arctic Canada, 2) the North Slope of Alaska, 3) Siberia and 4) either the Lomonosov Ridge or the Alpha and Mendeleev ridges. One of the most important features of the various models for the Canada Basin is the prediction that is made as to whether these margins have acted as passive or strike-slip boundaries. We have classified the tectonic models for the Canada Basin according to a scheme where (P) indicates a passive, extensional margin and (F) represents a strike-slip, transform margin (Table 2). The annotation (c) indicates the few cases where the margins have been characterized as compressive.

The four circum-Arctic margins can be classified as passive (P) or transform (F) boundaries in 16 different ways. The number of likely configurations, however, is less because according to the rules of plate tectonics each passive margin requires a conjugate margin eliminating PFFF, FPFF, FFPF, and FFFP. Two other possible configurations seem highly unlikely PPPP or FFFF. As an example, the model first proposed by Carey (1958) as the oroclinal bending model, and more recently referred to as the "rotational" model, would be classified as a PPPF, because in this model, a combined North Slope (P) and Siberian (P) block rotates away from Arctic Canada (P), along a transform fault formed by the Alpha and Mendeleev ridges or Lomonosov Ridge (F). Four of the remaining ten models (PPPF, PPFP, PFPP, FPPP) are variations of the "rotational" model with the pivot point simply changed from the Mackenzie Delta to the other corners.

Many of the evolutionary models for the Canada Basin that have been proposed in the past two decades are contradictory. Even so these models can be grouped into four subdivisions. Most of the models assume the same boundaries as we show in figure 8, although some consider the North Slope of Alaska to be continuous with the Siberian margin. A few of the models combine trapped oceanic crust with crust formed *in-situ* which leads to over simplification in order to place every model into the four boundary schemes. The models generally address at least two of the four boundaries of the Canada Basin and are tabulated in Table 2. Since none of the models have suggested compressional boundries for the Canadian Arctic, North Slope, Siberian or Lomonosov Ridge all margins were considered to have been rifted passive (P) or strike-slip transform fault (F) margins.

Model A. Rotational (PPPF)

(Carey, 1955, 1958; Grantz, 1966; Hamilton, 1967,1968; Tailleur, 1969; Tailleur and Snelson, 1969; Taillleur and Brosge, 1970; Rickwood, 1970; Tailleur, 1973; Freeland and Dietz, 1973; Johnson *et al.*, 1978; Sweeney *et al.*, 1978; Grantz *et al.*, 1979; Grantz *et al.*, 1981; Mair and Forsyth, 1982; Sweeney *et al.*, 1982; Vogt *et al.*, 1982; May and Grantz, 1983; Sweeney, 1983; Burke, 1984; Green *et al.*, 1984; Harland,*et al.* 1984; Embry, 1985; Sweeney, 1985; McWhae, 1986)

A rotational opening of the Canada Basin was first proposed by Carey (1955) based on his concept of oroclinal bending, and which he later related to plate tectonics. Hamilton (1968), Tailleur (1969), Tailleur and Brosgé (1970), following the suggestion of Grantz (1966), applied the concept of rotational opening of the Canada Basin to explain the change in provenance directions of North Slope sediments.

Prior to the uplift of the Brooks Range, sediments on the North Slope had a northern source and prograded southward. The tectonic land of the Innutian foldbelt was the source for the clastic deposits on Wrangell Island and for the clastic wedge of the Endicott Group in northern Alaska (Tailleur and Brosgé, 1970). The pre-rifting phase of the Canada Basin was thought to coincide with 193 Ma diabase intrusives that were emplaced into a condensed sequence of Early and Middle Jurassic chert, limestone, and oil shale (Kingak) . The "pebble shale" which unconformably overlies the Kingak shale was considered by Tailleur and Brosgé (1970) to indicate the last strong influence of the Innutian landmass. They dated the rotational opening of the Canada Basin as Aptian-Albian (119 to 97 Ma), with a pole of rotation located approximately 500 kilometers south of the Mackenzie Delta.

Rickwood (1970) produced a fit of the Barrow Arch section of the North Slope of Alaska to the Banks Island section of Arctic Canada in which he estimated that roughly 67°

of rotational opening had taken place about a pole in the southern part of the Mackenzie Delta. He suggested that the opening of the Canada Basin was contemporaneous with the observed faulting along the margin that ranged in age from Late Neocomian to Barremian, just slightly older than the Tailleur and Brosgé (1970) estimate. Rickwood (1970) also pointed out that it was at this time that the Brooks Range began to rise, perhaps as a consequence of the opening.

Grantz et al. (1979) rotated the 1000 m isobaths by 66°, about a pole at 69.1° N, 130.5° W and found that the coastlines from the Mackenzie Delta west to the Northwind Escarpment fit well against the Canadian Arctic Islands (figure 3). The authors noted that the Lomonosov Ridge fell on a small circle about this pole of rotation. In the same study, Grantz et al. (1979) summarized the depositional characteristics of the North Slope strata between the Mackenzie Delta and Camden Bay. West of Camden Bay, the northern source continued to shed debris, but waningly so through the Late Jurassic and the Neocomian. They concluded that initial rifting may have begun in the Mackenzie Delta region as early as Middle Jurassic, but that actual opening of the Canada Basin was delayed until late Neocomian time.

Vogt et al. (1982) suggested a similar scenario for the opening based on a fan-shaped set of magnetic anomalies in the Canada Basin (Taylor et al., 1981). In this model, the North Slope of Alaska first rotated away from Arctic Canada about a pole in the Mackenzie Delta, with a younger rift splitting the Chukchi Plateau away from Arctic Canada (figure 9).

Other workers have also preferred the rotational model (Sweeney, et al., 1978, 1982; Mair and Forsyth, 1982; Burke, 1984; Green et al., 1984; Harland, et al. 1984; Embry, 1985; McWhae, 1986). These models are similar in that they rift the North Slope block from along the margins of the Canadian Arctic Islands; however, they differ in the exact timing of the motion and the presumed extent of the reconstructed 'rotational' block.

Harland et al. (1984) utilized the rotational model to explain formation of the Canada Basin during the Late Jurassic to earliest Cretaceous. In their model, the North Slope of Alaska was originally located adjacent to Ellesmere Island-Northern Greenland during the Middle Devonian. They suggest that at least 1000 kilometers of left-lateral strike-slip motion along Arctic Canada occurred before late Carboniferous to bring the North Slope of Alaska into its pre-drift position. The existence of a major inactive strike-slip fault may have been the cause for the later rifting along the same boundary.

Embry (1985) noted four regional unconformities in Arctic Canada that he related to the tectonic development of the Canada Basin: 1) a late Aalenian (middle Jurassic) unconformity, followed by the development of grabens (e.g. Eglinton graben) parallel to the future margin of the Canada Basin, related to the onset of rifting; 2) a Callovian (latest Middle Jurassic) unconformity, caused by a subsequent episode of rifting and graben development; 3) a widespread late Valangian and early Hauterivian (Early Cretaceous) unconformity that Embry (1985) relates to the onset of seafloor spreading (during this later phase, subsidence rates along the Arctic margin increased rapidly and basalt flows appeared for the first time in the Mesozoic succession); and 4) the final stage (earliest Late Cretaceous), during which uplift occurred, was coincident with the final phase of volcanism and collision. Embry suggests that seafloor spreading in the Canada Basin ceased at this time and that the continental margin began to undergo thermal subsidence.

Embry (in press) also suggests that the rotational model restores the continuity of pre-drift facies trends. The axis of deposition of pre-drift Mesozoic strata (Triassic-Hauterivian) crosses the Canadian Arctic Islands and is truncated by the continental margin in the vicinity of Banks Island. The rotation of the North Slope block restores this truncated axis with a similar truncated basin axis (Hanna Trough) on the Chukchi Shelf (figure 10).

McWhae (1986) also advocates a rotational opening of the Canada Basin (between 125 and 85 Ma) about a pole in the Mackenzie Delta. When spreading ceased in the Canada

Basin, McWhae (1986) suggests that during the Late Cretaceous, movement along the Kaltag and associated strike-slip faults severed the North Slope of Alaska from the North American plate and it became part of the northeasterly moving Eurasian plate.

Though the rotational model has been popular until recently, paleomagnetic evidence documenting the rotation of the North Slope has been hard to come by. Earlier workers were frustrated by both the lack of suitable rock types (few red beds or volcanic rocks) and the presence of a pervasive Cretaceous overprint (Newman et al., 1977; Hillhouse and Grommé, 1983). The most recent effort, Halgedahl and Jarrard (in press), clearly supports the rotational model. By studying fully-oriented drill cores from the North Slope, Halgedahl and Jarrard (in press) determined a pole position for the Valanginian (chrons M14 through M11An; 138 to 133 MA) section of the Kuparuk River formation (49.1° N and 146.1° W). When compared with paleomagnetic poles for cratonic North America, the Kuparuk pole suggests significant relative motion between North America and the North Slope block. As illustrated in figure 11, the rotational model is compatible with these new data.

Model B. Arctic Islands Strike-Slip (FPFP)

(Ostenso, 1974; Christie, 1979; Kerr, 1981; Dutro, 1981; Crane, in press; Smith, in press)

Model B, like the rotational model, also predicts that the North Slope of Alaska is a passive margin; however, the conjugate margin is not the Canadian Arctic, but rather the Lomonosov Ridge or the Alpha and Mendeleev ridges. In this scenario, the Canadian Arctic margin acted as a left-lateral transform fault. Though strike-slip movement along the margin of the Arctic Islands was implicit in many of the early suggestions that the Alpha Ridge was a spreading center (Johnson and Heezen, 1967; Beal, 1968; Vogt and Ostenso, 1970; Ostenso and Wold, 1971; Hall, 1970, 1973), Christie (1979) was one of the first workers to use this framework to explain the tectonic development of the Canada Basin (figure 7).

Set in the context of a general discussion of the Franklinian orogenic belt, Christie's (1979) model suggests that during the Late Paleozoic-earliest Mesozoic, rifting began in the Canada Basin either on, or parallel to, the Alpha and Mendeleev ridges. This opening produced a rifted margin along the Lomonosov Ridge, North Slope of Alaska and Bering Sea splinter, and resulted in transform motion along the margin of the Canadian Arctic (figure 7).

Dutro (1981) and Kerr (1981) supported the interpretation that the Canadian Arctic margin was bounded by a transform fault, noting that the margin is remarkably straight and might be an extension of the Kaltag/Porcupine fault system as suggested by Yorath and Norris, (1975). Kerr (1981) concluded that the Canada Basin is an ancient ocean basin that formed during a rifting episode in the Late Paleozoic (Mississippian). Dutro (1981) indicates a substantial Canada Basin predating early Mexozoic that was later enlarged by rifting during the Jurassic. The Alpha Ridge was considered by both of them to be the spreading center that created the basin (figure 4).

Recently, two similar models for the evolution of the Canada Basin have been proposed by Smith (in press) and Crane (in press). Both models use approximately the same tectonic elements and begin to open the Canada Basin at about the same time (150 Ma). In both Crane (in press) and Smith (in press), the Chukchi Plateau and Mendeleev Ridge are foundered continental fragments. Crane also considers the Alpha Ridge to be of continental origin; however, Smith is less certain and allows that the inclusion or exclusion of it would not 'substantially' affect the major features of the reconstruction. The reconstructed positions of these fragments against the Lomonosov Ridge is somewhat tighter in the fit (figure 12) of Smith (in press), and the shape and extent of the North Slope and Chukotka blocks, in both models, are quite different. The North Slope block in the Crane (in press) model is larger, and includes Wrangel Island (figure 13). According to Smith, Wrangell Island is part of the Chukotka block, as is the Seward Peninsula. In

Crane (in press), the Seward Peninsula is a separate block that travels independently of the North Slope and Chukotka terranes.

The tectonic scenario outlined by both models is very similar. The Canada Basin began to open in the Late Jurassic (150 Ma) as the North Slope terrane rifted away from the Alpha Ridge and the Chukotka terrane translated dextrally with respect to the Siberian margin. By the mid-Cretaceous the Chukchi Plateau and Mendeleev Ridge had been stretched and rifted away from the Lomonosov margin. The Canada Basin had finished spreading by 80 Ma (at the latest), and the focus of rifting shifted to the North Atlantic. Both Crane and Smith suggest that the Makarov Basin formed in the early Tertiary, and was a precursor to spreading along the Arctic Mid-Ocean Ridge. Halgedahl and Jarrard (In press) referred to this as the Lomonosov Rifting model in their paper. The paleomagnetic results cannot be rectified for the Kuparuk River formation with the pole for cratonic North America, given the motion shown in figure 14.

Model C. North Slope Transform (PFPF)

(Herron et al., 1974; Vogt et al., 1982; Metz et al., 1982; Rowley et al., 1985)

Model C is the converse of Model B; the assignment of passive and transform margins have been switched. In the resulting model, the Canadian Arctic is a passive margin, as is the Siberian shelf edge (including the Chukchi Plateau). Consquently, the North Slope margin and Lomonosov Ridge are the transform faults that bound the basin.

The most familiar model that falls into this category was proposed by Herron et al. (1974). In this model, the Kolymski block collides with Arctic Canada during the early-mid Paleozoic (Franklinian orogeny) (figure 5). The same block rifts away during Middle Jurassic (187 to 163 Ma) with transform motion parallel to Arctic Alaska and the Lomonosov Ridge (figure 5). The Canada Basin was fully opened when the Kolymski block collided with Siberia along the Verkhoyansk fold belt in Early Cretaceous time. During the period 81 Ma to 63 Ma the pole of opening between North America and Eurasia was in northern Greenland (Pitman and Talwani, 1972). Herron et al. (1974) assumed that such a pole would necessitate compression north of Greenland and suggested that the compression was accommodated, in part, by subduction along the Alpha and Mendeleev ridges.

Recently, modified versions of Model C (PFPF) have been proposed (Vogt et al., 1982; Metz et al., 1982; Rowley et al., 1985). In these models, as in Herron et al. (1974), the North Slope margin is a left-lateral strike-slip fault and the Canadian Arctic is a passive margin. However, the Chukchi Plateau, rather than the Kolymski block, is the terrane that rifts away from the Arctic Islands (figure 15). This interpretation is in best agreement with the trend of linear magnetic anomalies in the Canadian Basin (Vogt et al., 1982) and crustal structure inferred from seismic refraction studies (Mair and Lyons, 1981). Rowley et al. (1985) take this model one step further and argue that the Canada Basin is, in effect, a back-arc basin that opened as a result of subduction to the east beneath the Alpha and Mendeleev ridges.

Model D. Yukon Strike Slip (FFFP)

(Jones, 1980, 1982, 1983)

Jones (1980, 1982,1983) postulated a model for the development of the Canada Basin based on petroleum exploration data collected in the Mackenzie Delta region. He assumed that much of the crust in the Canada Basin was Paleozoic in age and was attached to Arctic Canada as part of the North American plate. The North Slope of Alaska and northeast Siberia formed a single terrane and were offset with respect to North America by a large right-lateral strike-slip fault that aligned the Tintina fault, the margin of the North Slope, and the Arctic margin of northeastern Siberia (figure 16).

During the Permo-Triassic the North Slope terrane translated northward (right-lateral motion) with respect to North America along this mega-fault zone (figure 16). Strike-slip motion continued and during the Early Cretaceous the Makarov and northernmost half of the Canada Basin opened as Alaska continued to translate northward (figure 16). During the Late Cretaceous and Early Tertiary, extension in the North Atlantic resulted in compression in Alaska, and the North Slope/NE Siberian block moved northeastward with respect to cratonic North America along a dextral strike-slip fault that ran along the Kaltag fault and margin of the Canadian Arctic Islands. The Yukon strike-slip model as used in Halgedahl and Jarrad's paleomagnetic study (in press) produces a solution that cannot be rectified with the observed paleomagnetic data collected.

Discussion

In the thirty years since Carey (1955) first discussed oroclinical bending and its implication for the opening of the Arctic Ocean, hundreds of papers have been written about the tectonics, marine geology and marine geophysics of the Arctic region. Knowledge of the Arctic has increased tremendously but is still meager compared to most of the other oceans of the world. Of the three main modes of formation for the Canada Basin, oceanization of continental crust, entrapment of old Paleozoic oceanic crust, and *in-situ* formation of Mesozoic or Cenozoic oceanic crust, only the last seems to have withstood the increased available data.

The seismic refraction results of Mair and Forsyth (1981) showed that while the crust of the Canada Basin may be covered with a thick sedimentary sequence, it is true oceanic crust. The entrapment of older oceanic crust (Churkin, 1970; Churkin and Trexler, 1980; Karasik, et al., 1984) as shown in figure 2 cannot be supported by the heat flow data (Lachenbruch and Marshall, 1966; Lachenbruch, 1969; Langseth and Lachenbruch, this volume) and the depth-to-basement calculations (Lawver and Baggeroer, 1983) since both suggest an age for the Canada Basin of Cretaceous or younger, consistent with the geology of the North Slope of Alaska (Brosgé and Tailleur, 1970) and the Canadian Arctic Islands (McWhae, 1986). Consequently only the models for the tectonic evolution of the Arctic that suggest *in-situ* formation of oceanic crust have been tabulated in table 2.

For the first fifteen years after Carey's (1955) paper, virtually all models of the evolution of the Canada Basin relied exclusively on the surrounding land geology to produce tectonic models. It was not until Beal (1968), Lachenbruch (1969), Hall (1970) and Vogt and Ostenso (1970) that much of the early geophysical data from the Canada Basin became widely published. Later aeromagnetic data (Vogt et al., 1979) produced new interpretations but were eventually termed inadequate to resolve the problem (Vogt et al., 1982). With the exception of the CESAR results (Jackson et al., 1986) which determined that the Alpha Ridge is not an abandoned spreading center but more probably is of oceanic plateau origin, no new data from the Canada Basin has resulted. Even some of the CESAR results remain ambiguous as to whether the Alpha Ridge is an oceanic plateau, a hot spot trace similar to Iceland or contains continental fragments (Sweeney and Weber, in press).

Since the marine geological and geophysical data is unable to resolve the tectonic evolution of the Canada Basin, new data from the land and continental margins must be utilized. Two important contributions have been the multi-channel seismic reflection results from the Beaufort and Chukchi Seas (Grantz et al., 1979; Grantz and May, 1983) and paleomagnetic results from the North Slope (Newman et al., 1977; Hillhouse and Grommé,1983; Halgedahl and Jarrard, in press). Grantz et al. (1979) concluded that the North Slope of Alaska had to have been a rifted "Atlantic-type" continental margin with no evidence of strike-slip motion along the Alaskan continental margin. The paleomagnetic results (Halgedahl and Jarrard, in press) are only compatible with a rotational opening of the Canada Basin.

Since Carey's (1955) paper, many authors have used depositional paleocurrents from the surrounding margins to support a rotational opening of the Canada Basin, particularly Tailleur and Brosgé (1970), Hamilton (1970), and Freeland and Dietz (1973). Objections to the rotational model have been raised by some based on the fact that the depositional trends are east to west on both Arctic Alaska and the Canadian Arctic and rotation would produce opposing depositional directions (Churkin and Trexler, 1980).

Others have objected that Arctic Alaska needs to be positioned closer to the Northern Canadian Arctic Islands and that simply rotating Alaska into Banks Island does not place it close enough to Ellesmere Island (Crane, in press). Smith (in press) points out that the geology of the pivot area in the Mackenzie Delta is not consistent with a rotational opening of the Canada Basin because Jurassic sediments prograded north and west towards the present-day position of Alaska, when they should have faced an open ocean. Supporters of the rotational model cite the paleomagnetic results of Halgedahl and Jarrard (in press) and the seismic reflection results of Grantz et al. (1979) as support for the rotational model. They would reply that the depositional directions on the North Slope and Canadian Arctic Islands may not be of the same formation and that the pre-rift high may have had opposing depositional directions on different sides of it. Sweeney (1986, personal communication) addresses the concern of Crane (in press) by suggesting that Arctic Alaska may have been against northern Ellesmere Island and Greenland during the early Paleozoic. In mid-Paleozoic time Arctic Alaska was sheared sinistrally along the Canadian margin to its Jurassic pre-rotated position opposite Banks Island. Unfortunately Sweeney does not suggest a cause for the major sinistral shear that would have displaced Arctic Alaska from near Greenland to opposite Banks Island. Finally, in pre-rotation time the region of the Mackenzie Delta could have in fact been facing an extension of an open ocean because the rotated Arctic Alaska block cannot be considered to have been very wide. Certainly the Yukon-Koyukuk region is presumably Jurassic or older trapped oceanic crust just as Churkin and Trexler (1980) show it to have been in figure 2.

Model B which generally presumes sea floor spreading on or parallel to the Alpha and Mendeleev Ridges was suggested by Ostenso (1974) and elaborated upon by Christie (1979) and used by Dutro (1981), Crane (in press) and Smith (in press). Their model solves the problem of the northern Ellesmere-Greenland source for North Slope Alaska while maintaining the North Slope as a passive Atlantic-type margin as Grantz et al. (1979) requires. So little multi-channel seismic reflection data is available along the Canadian

Arctic margin that it cannot be classified as either passive or faulted on the basis of geophysical data. Perhaps the most difficult objections to overcome for this model are the recent paleomagnetic results of Halgedahl and Jarrard (in press). Figure 14 indicates that the paleomagnetic pole for the Model B Early Cretaceous North Slope would not coincide at all with that for North America.

Model C, which was first suggested by Herron et al. (1974) in order to explain the Early Cretaceous Verkhoyansk foldbelt, has since been discussed by many others including Vogt et al. (1982). The folding resulted from the collision of a piece (Kolymski Block) rifted off Arctic Canada that collided with Eurasia. Vogt et al. (1982) believed that the best fit to the magnetic lineations that they found in the Canada Basin could only have been produced by a spreading ridge parallel to the Chukchi Plateau. Rowley et al. (1985) believed that the North Slope of Alaska has not changed appreciatively since Paleozoic time. It is difficult to reconcile the requirement of Model C for a strike-slip fault boundary along the North Slope of Alaska with the MCS results and the interpretations of Grantz et al. (1979). Halgedahl and Jarrard (in press) did not show the results of a fixed Alaska with respect to North America but it is obvious that such a scenario would not agree with the paleomagnetic pole they found for the North Slope, since a 70° counterclockwise rotation is required for it to be in agreement with the pole for North America.

Model D, suggested by Jones (1980, 1983), requires far greater offset on many of the faults in Alaska than can be documented by workers in northern Alaska. Even though Brosgé (1982, personal communication) is often referenced for the continuation of the Kaltag fault into the Porcupine lineation of the Yukon, he agrees that there is no observeable field evidence to support such a continuation across the Yukon-Porcupine lowlands.

The question of timing for the opening of the Canada Basin has not been extensively dealt with in this paper. Tailleur and Brosgé (1970) suggested rotational opening of Aptian and Albian age (119 Ma to 97 Ma). Lawver and Baggeroer (1983) suggested post-Neocomian to about Campanian (125 Ma to 80 Ma) based on heat flow versus age and depth versus age calculations. Finally Halgedahl and Jarrard (in press) have suggested an age of 130 Ma to 100 Ma based on their paleomagnetic results. They constrain the beginning of rotation with their Kuparuk Formation results and they assume the age of the thrusting in the Brooks Range constrains the cessation of motion. Unfortunately there are no reliable data to constrain the age better than the general time frame of mid to Late Cretaceous.

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TABLE 1

Continent	Latitude	Longitude	Angle
North America	0.00	0.00	0.00
Greenland	-50.07	6.29	7.74
Europe	-69.34	-33.20	23.61
Iberia	-74.43	176.23	49.76
Ellesmere Island	-68.72	77.34	11.36

*fixed with respect to North America

TABLE 2

Models by Author	Classification			
	Arctic	North Slope	Siberia	Lomonosov
Grantz (1966)	P	P	P	F
Hamilton (1967,1968)	P	P	P	F
Tailleur (1969)	P	P	P	F
Tailleur and Snelson (1969)	P	P	P	F
Tailleur and Brosge (1970)	P	P	P	F
Tailleur (1973)	P	P	P	F
Freeland and Dietz (1973)	P	P	P	F
Sweeney et al. (1978)	P	P	P	F
Johnson et al. (1978)	P	P	-	F-P[1]
Grantz et al (1979)	P	P	P	F
Green et al. (1982)	P	P	P	F
Sweeney (1982)	P	P	P	F
Vogt et al. (1982)	P	P	-	F
May and Grantz (1983)	-	P	-	-[2]
Sweeney (1983)	-	P	-	-[2]
Burke (1984)	P	P	P	F
Harland (1984)	P	P	P	F
Embry (1985)	P	P	P	F
Sweeney (1985)	P	P	P	F
McWhae (1986)	P	P	P	F
Ostenso (1974)	F	P	F	P[3]
Christie (1979)	F	P	-	P
Crane (in press)	F	P	F	P
Smith (in press)	F	P	F	P
Herron et al. (1974)	P	F	P	F(c)[4]
Vogt et al. (1982)	P	F	-	F[5]
Metz et al. (1982)	P	F	P	F
Rowley et al. (1985)	P	F	-	(c)[5]
Jones (1980)	F	F	F	P[6]
Jones (1983)	F	F	F	P

classification: F = strike-slip faulting
P = passive
(c) = compressive
(o) = older

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1 F during early history (Cretaceous), in Tertiary opening of Makarov Basin is precursor to opening along Nansen-Gakkel Ridge.

2 Classification of North Slope as passive margin consistent with PPPF and FPFP models.

3 Implied from assignment of Alpha Cordillera as Cretaceous spreading center.

4 F during early history (Cretaceous), in Tertiary (c) due to opening of North Atlantic.

5 Though similar to Herron et al. (1974) model and Metz et al. (1982) model, in these models it is only the Chukchi Borderland that rifts away from Arctic Canada.

6 In this model, part of the Canada basin consists of trapped Late Paleozoic ocean crust.

Figure 1. Location map of the Arctic Ocean region. Light weight lines indicate outer continental margins, dashed where uncertain. Heavyweight line is the presently active seafloor spreading ridge in the North Atlantic and Eurasia Basin. Hatchered lines in the Canadian Arctic Islands indicate graben-like features that can be closed in reconstructions of the Arctic region. Bathymetric features taken from Perry *et al.* (1985).

Figure 2. Entrapment of older oceanic crust model taken from Churkin and Trexler (1980). Paleogeographic reconstructions of the Arctic showing northward drift, collision, and accretion. Projection is flat polar, and shelf areas are not shown so that the land areas can be recognized. Maps are not intended to show rigorous geographic locations but rather the process of terrane accretion and Kula plate capture. (l) indicates trapped Canada Basin. (2) indicates trapped Yukon-Koyukuk region. and (3) indicates trapped Bering Sea.

Figure 3. Rotational model for the development of the Canada Basin taken from Grantz *et al.* (1979). The 1000-meter bathymetric contour from the Canadian side has been rotated 66° about a pole at 69.1°N, 130.5°W. The Lomonosov Ridge lies nearly on a small circle about the pole of rotation as does the Northwind Escarpment. Hypothetical spreading center in the North Chukchi Basin indicates region from which Grantz *et al.* (1979) suggest the Chukchi Plateau could have extended.

Figure 4. Figure illustrating the Arctic Islands strike-slip (FPFP) taken from Dutro (1981) and showing the hypothetical development of the Arctic Ocean Basin and adjacent regions in post-Paleozoic time. A=northern Alaska; Ch=Chukchi Peninsula; CP=Chukchi Plateau; E=Ellesmere Island; FJ=Franz Josef Land; GR=Greenland; I=Iceland; Lo=Lomonosov Ridge; NS=New Siberian Islands; NZ=Novaya Zemlya; Sc=Scandinavia; Sp=Spitzbergen; St=St. Lawrence Island; SZ=Severna Zemlya; W=Wrangel Island. Dashed outlines with underlined letters indicate approximate positions during early Mesozoic time. Large arrows show directions of relative transport. Small arrows show relative transcurrent movements.

Figure 5. Figure taken from Herron *et al.* (1974) showing the North Slope transform (PFPF) model. Heavy dashed lines with arrows=major plate boundaries and direction of movement relative to North America. (a) closure of proto-Amerasian Basin in early Paleozoic time. This motion culminated with mid-Paleozoic folding of Franklinian geoclinal sediments and shedding of clastic rocks onto Canadian Arctic Islands, Brooks Range, and Wrangel Island north of Chukotka. (b) opening of the Amerasian Basin during Jurassic magnetic quiet period, as Kolymshi broke away from North America.

Figure 6. Tectonic reconstruction of the Canada Basin using the multiblock fanning model of Freeland and Dietz (1973). While Arctic Alaska is rotated against Banks Island, northeastern Siberia is translated away from Arctic Canada along transform faults parallel to the Lomonosov Ridge and the northern margin of Alaska.

Figure 7. Taken from Christie (1979). Stages in a hypothetical reconstruction of continents of the Arctic region using an FPFP model for the evolution of the Canada Basin. Bg=Bering splinter; K=Kolymski splinter; dotted line indicates late Paleozoic-Mesozoic successor basin; double-line indicates an active spreading center; dashed double line indicates 'fossil spreading center'; wiggly arrow indicates direction of sedimentary transport.

Figure 8. The Arctic region restored to its configuration prior to opening in the Eurasia Basin and Labrador Sea. Lightweight line in northern Alaska is the assumed boundary between Arctic Alaska, which moved as an independent piece, and the remainder of Alaska which is not considered to have been involved in the tectonic evolution of the Canada Basin.

Figure 9. Variation on the rotational model taken from Vogt *et al.* (1982). The initial rifting between the Canadian Arctic Islands and Arctic Alaska only extends between the Mackenzie Delta region and the Chukchi Plateau with the remainder of the extension occuring between the Chukchi Plateau and Alaska and Siberia as Hamilton (1970) suggested. In T2 the Chukchi Plateau block also begins to move away from Arctic Canada as Alaska continues to rotate away. While they show the Alpha Ridge in existence at the time of these scenerios, it is not essential to their hypothesis.

Figure 10. Provided by Embry (1986, personal communication). The depocenter axis of the pre-drift Mesozoic strata can be traced through the Canadian Arctic Islands to where it is truncated perpendicular to the Canada Basin margin. Clockwise rotation of northern Alaska and adjacent northeastern Siberia about the pivot in the Mackenzie Delta restores this truncated axis with a similarly truncated basin axis on the Chukchi Shelf.

Figure 11. Taken from Halgedahl and Jarrard (1987). Comparisons of the mean Kuparuk River paleomagnetic pole to the 120 Ma pole for cratonic North America using the PPPF model for the evolution of the Canada Basin.

Figure 12. Figures taken from Smith (1987) illustrating a modification of the Arctic Islands strike-slip (FPFP) model. Ax=Axel Heiberg; CHK=Chukotka block; ELL=Ellesmere; NSI=New Siberian Islands; OM=Omolon block; PR=Prikolymsk block; YT-NF=Yukon-Koyukok block; Sew=Seward Peninsula. (a) reconstruction of the Canada Basin region at 150 Ma prior to the opening of the Canada Basin. (b) mid-Cretaceous reconstruction of the region showing active spreading occuring parallel to the Alpha Ridge. (c) Late Cretaceous reconstruction showing continued motion along strike-slip faults bordering the Canada Basin.

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Figure 15. Modification of North Slope transform (PFPF) model taken from Vogt *et al.* (1982). (a) Jurassic to Lower Cretaceous rifting breaks up Chukchi Plateau and detaches it from Kolyma Block, which begins to separate from the Canadian Arctic Islands along a line roughly paralleling the Banks-Eglinton-Sverdrup basins. At this time there is still southward sediment transport (arrows) into northern Alaska. (b) the first phase of spreading ends and the plate boundary begins to reorient itself and becomes extinct at time shown in (c).

Figure 16. Yukon strike-slip (FFFP) model taken from Jones (1980). The evolution of the Amerasian Basin is shown with the associated displacements along the Tintina and Kaltag faults.

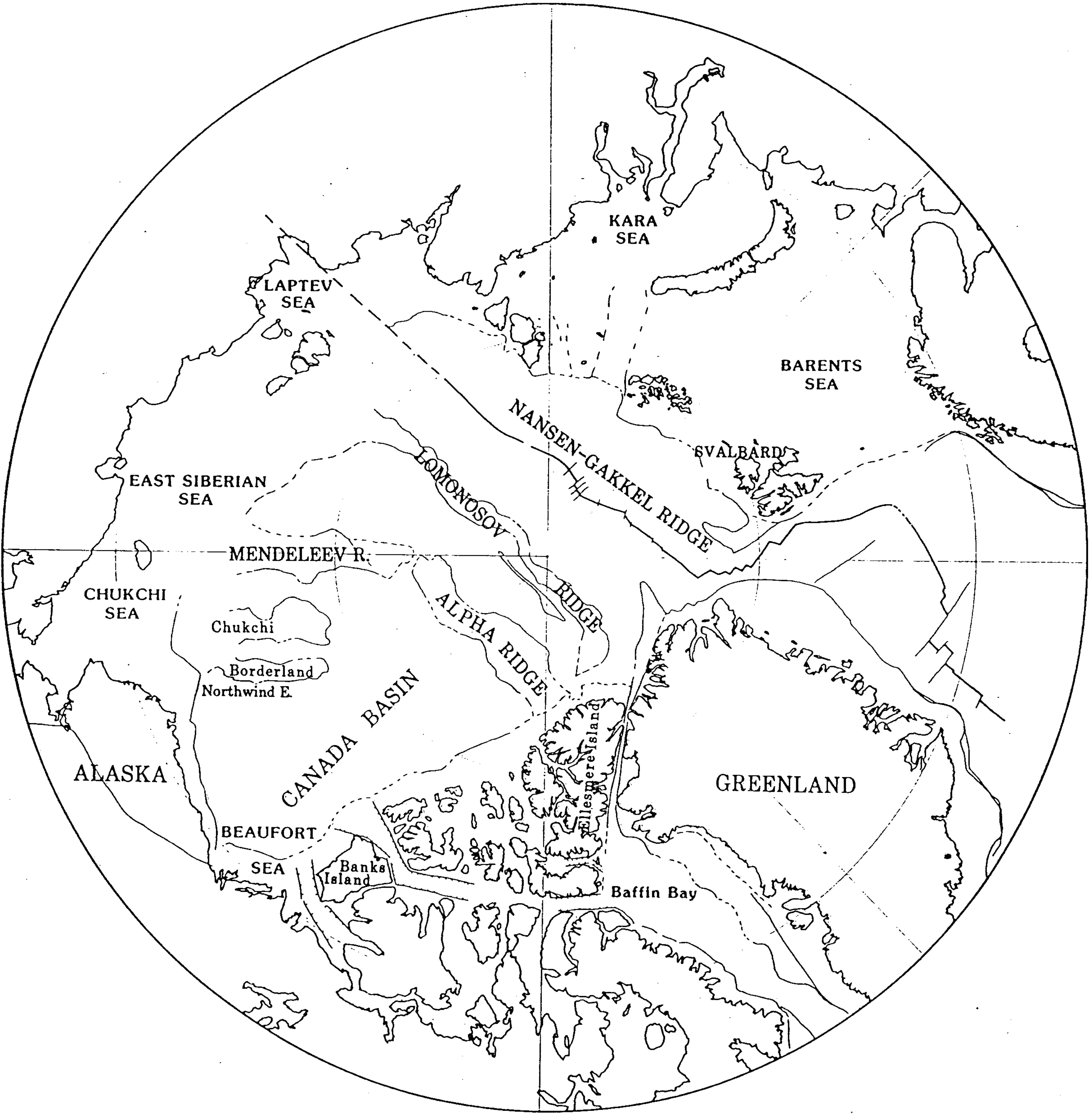
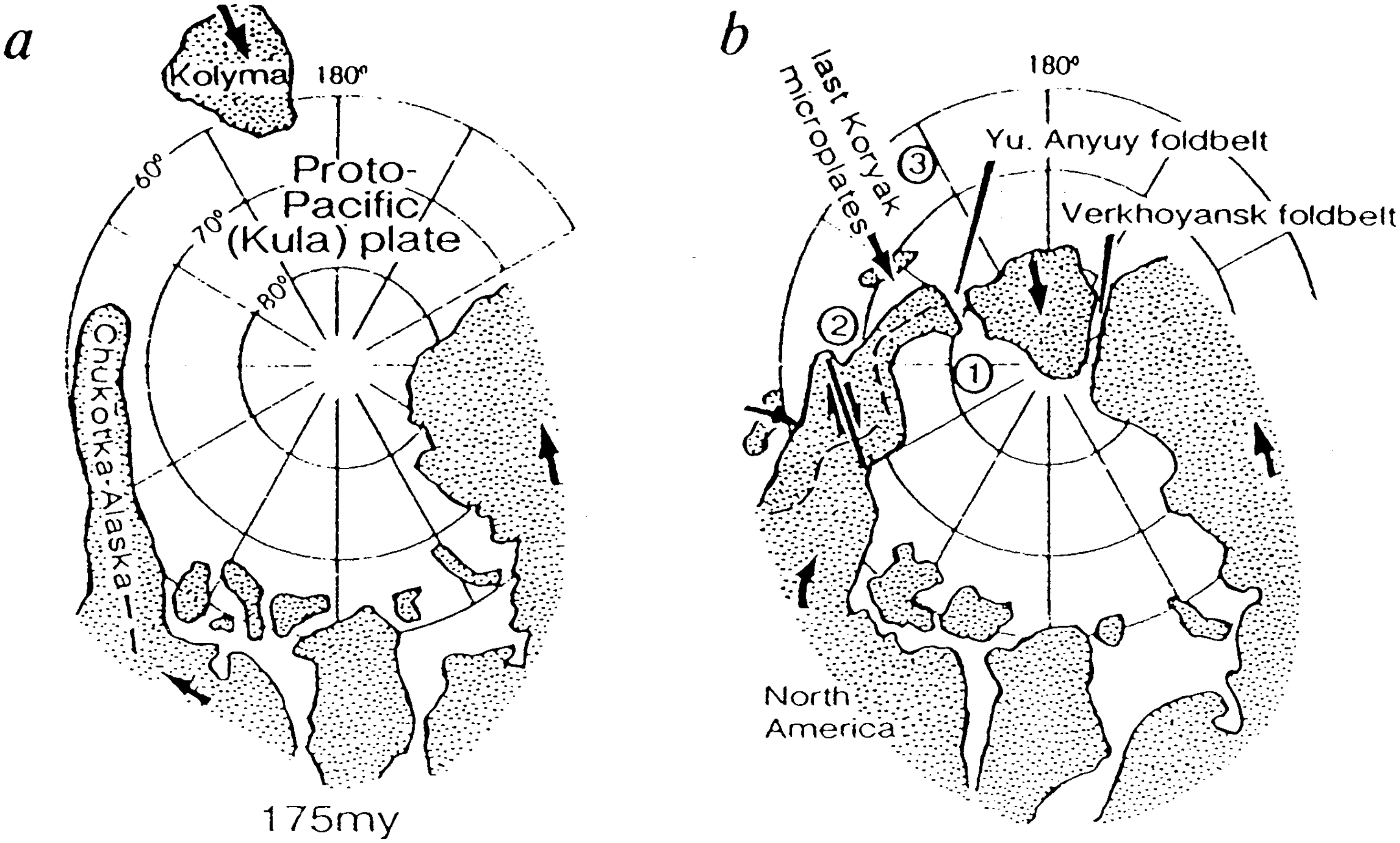
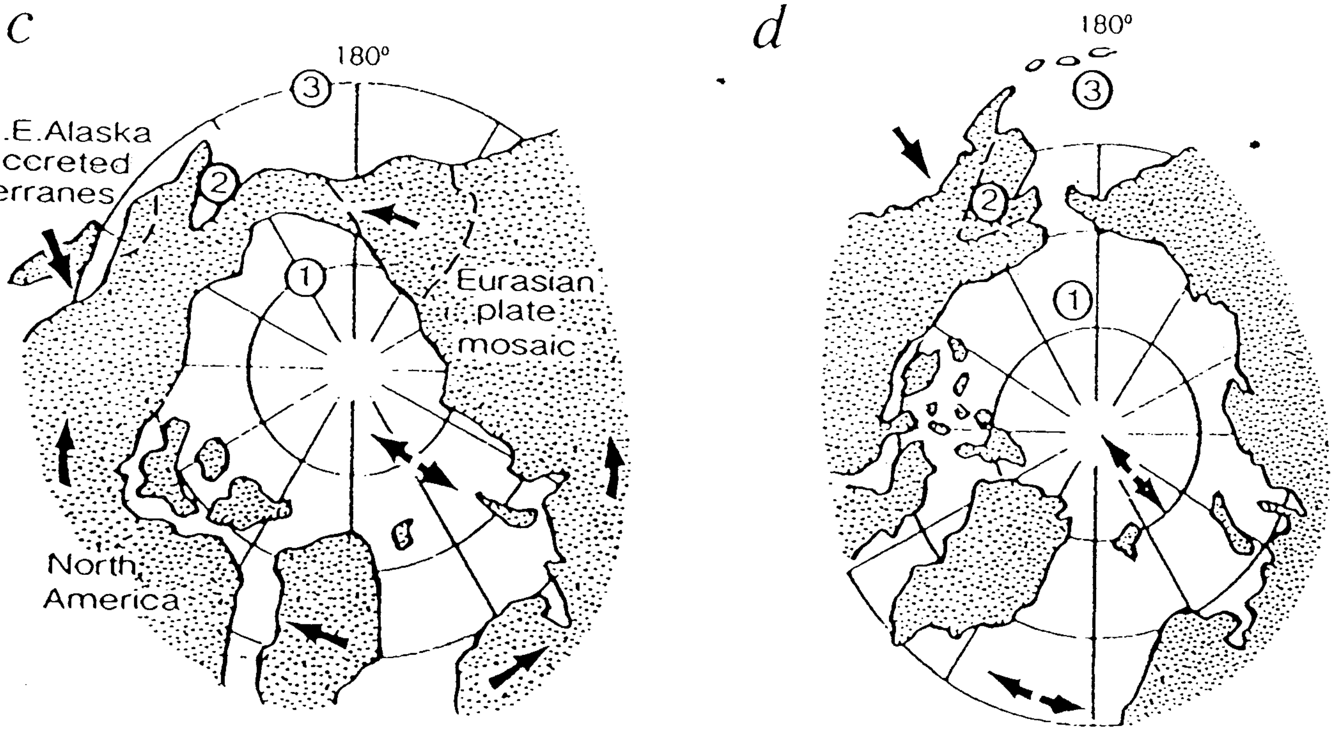

KARA SEA
LAPTEV SEA
BARENTS SEA
NANSEN-GAKKEL RIDGE
SVALBARD
LOMONOSOV RIDGE
EAST SIBERIAN SEA
MENDELEEV R.
CHUKCHI SEA
Chukchi Borderland
Northwind E.
ALPHA RIDGE
CANADA BASIN
ALASKA
Ellesmere Island
GREENLAND
BEAUFORT SEA
Banks Island
Baffin Bay

Figure 1



175my
(Early Jurassic)

125my
(Early Cretaceous)



50my
(Eocene)

Present

Figure 2

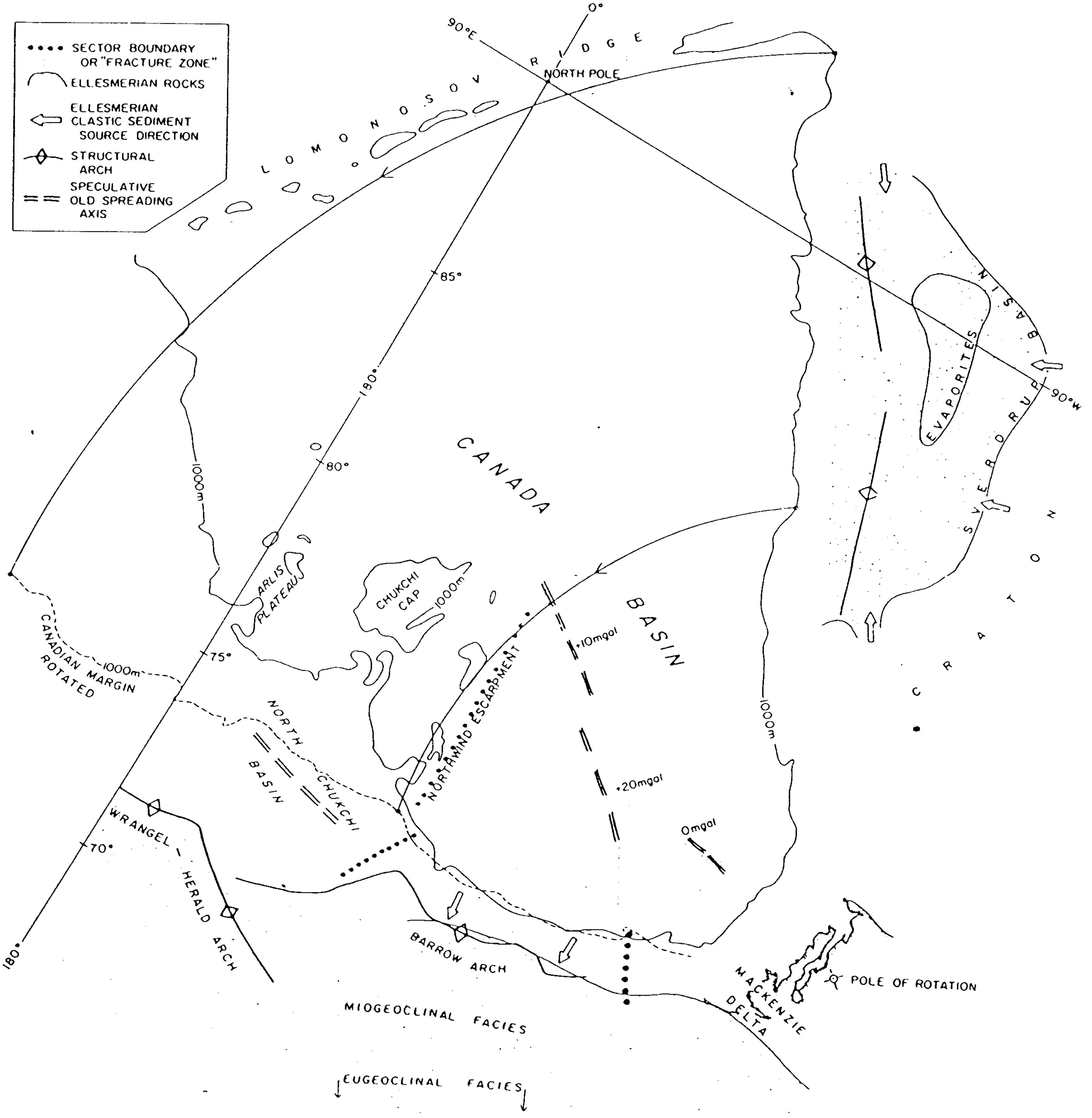

SECTOR BOUNDARY OR "FRACTURE ZONE"
ELLESMERIAN ROCKS
ELLESMERIAN CLASTIC SEDIMENT SOURCE DIRECTION
STRUCTURAL ARCH
SPECULATIVE OLD SPREADING AXIS
0°
90°E
LOMONOSOV RIDGE
NORTH POLE
85°
180°
80°
75°
70°
180°
90°W
1000m
CANADA BASIN
ARLIS PLATEAU
CHUKCHI CAP
1000m
+10mgal
+20mgal
0mgal
NORTHWIND ESCARPMENT
CANADIAN MARGIN ROTATED
1000m
NORTH CHUKCHI BASIN
WRANGEL - HERALD ARCH
BARROW ARCH
MIOGEOCLINAL FACIES
EUGEOCLINAL FACIES
MACKENZIE DELTA
POLE OF ROTATION
1000m
EVAPORITES
SVERDRUP BASIN
CRATON

Figure 3

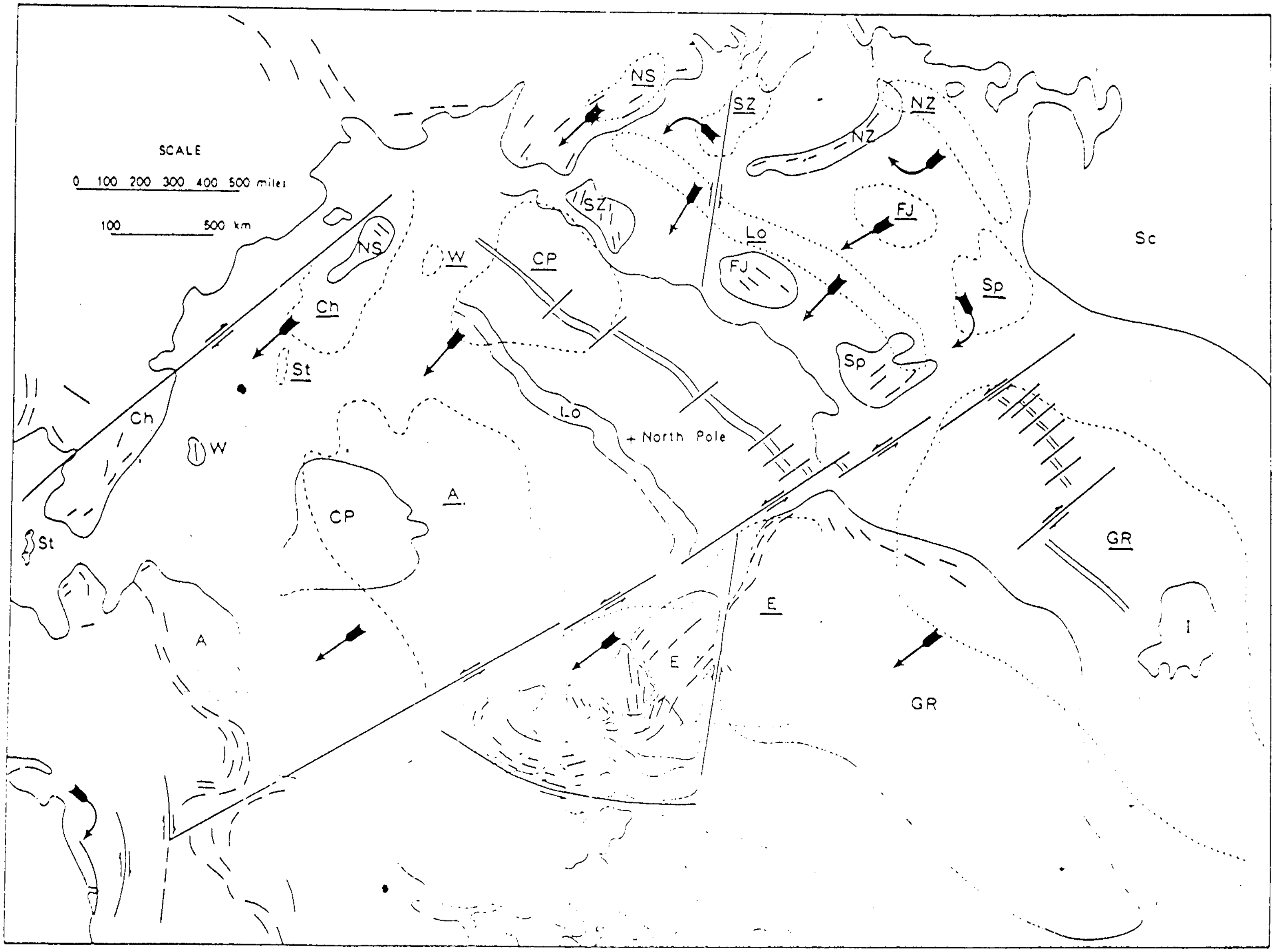

SCALE
0 100 200 300 400 500 miles
100 500 km
NS
SZ
NZ
NZ
Sc
SZ
FJ
Lo
FJ
Sp
Sp
Sp
W
CP
NS
Ch
St
Lo
+ North Pole
Ch
W
St
CP
A
A
E
E
GR
GR
I

Figure 4

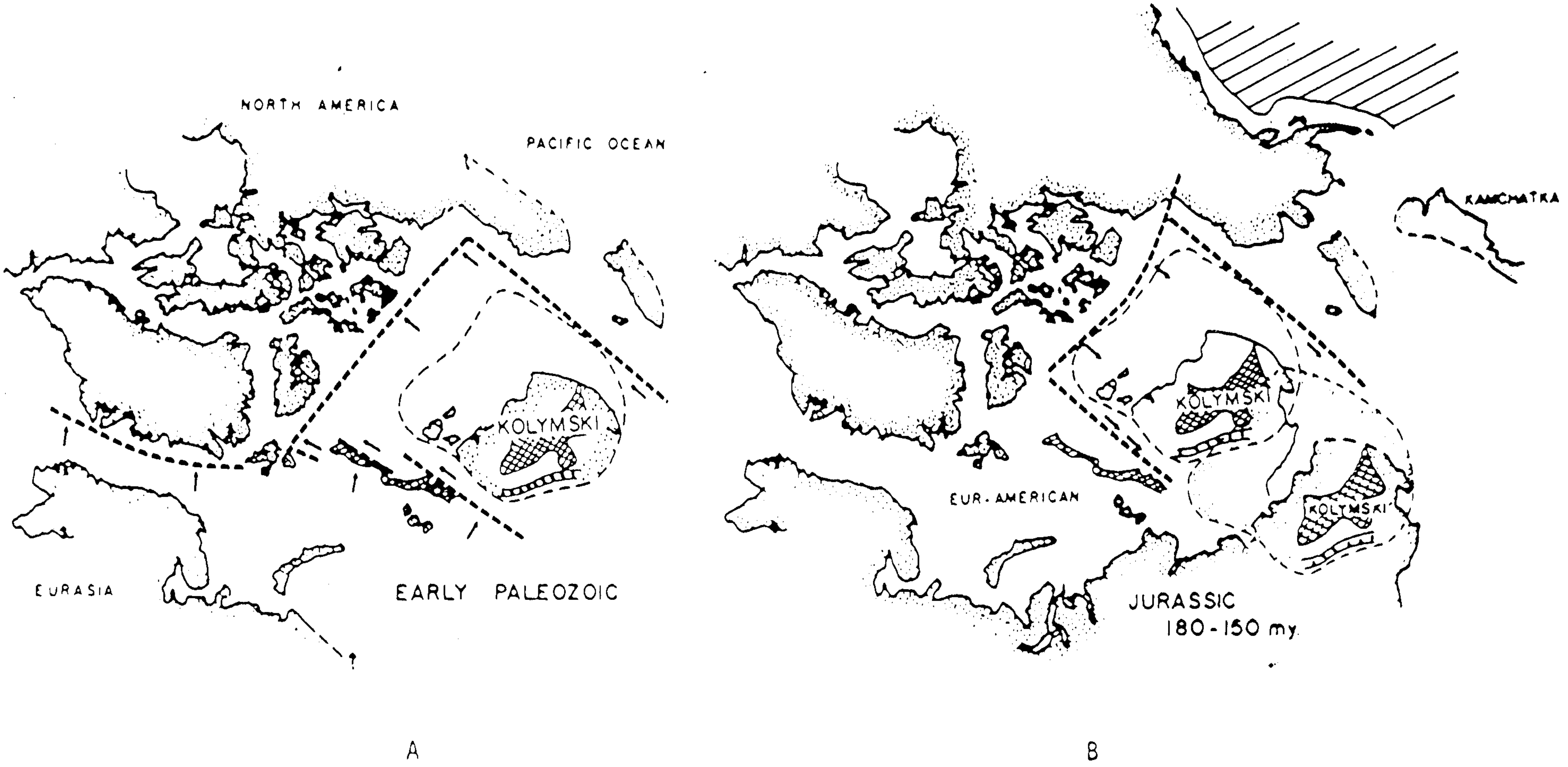

NORTH AMERICA
PACIFIC OCEAN
KOLYMSKI
EURASIA
EARLY PALEOZOIC
A
KAMCHATKA
KOLYMSKI
EUR-AMERICAN
KOLYMSKI
JURASSIC
180-150 my
B

Figure 5

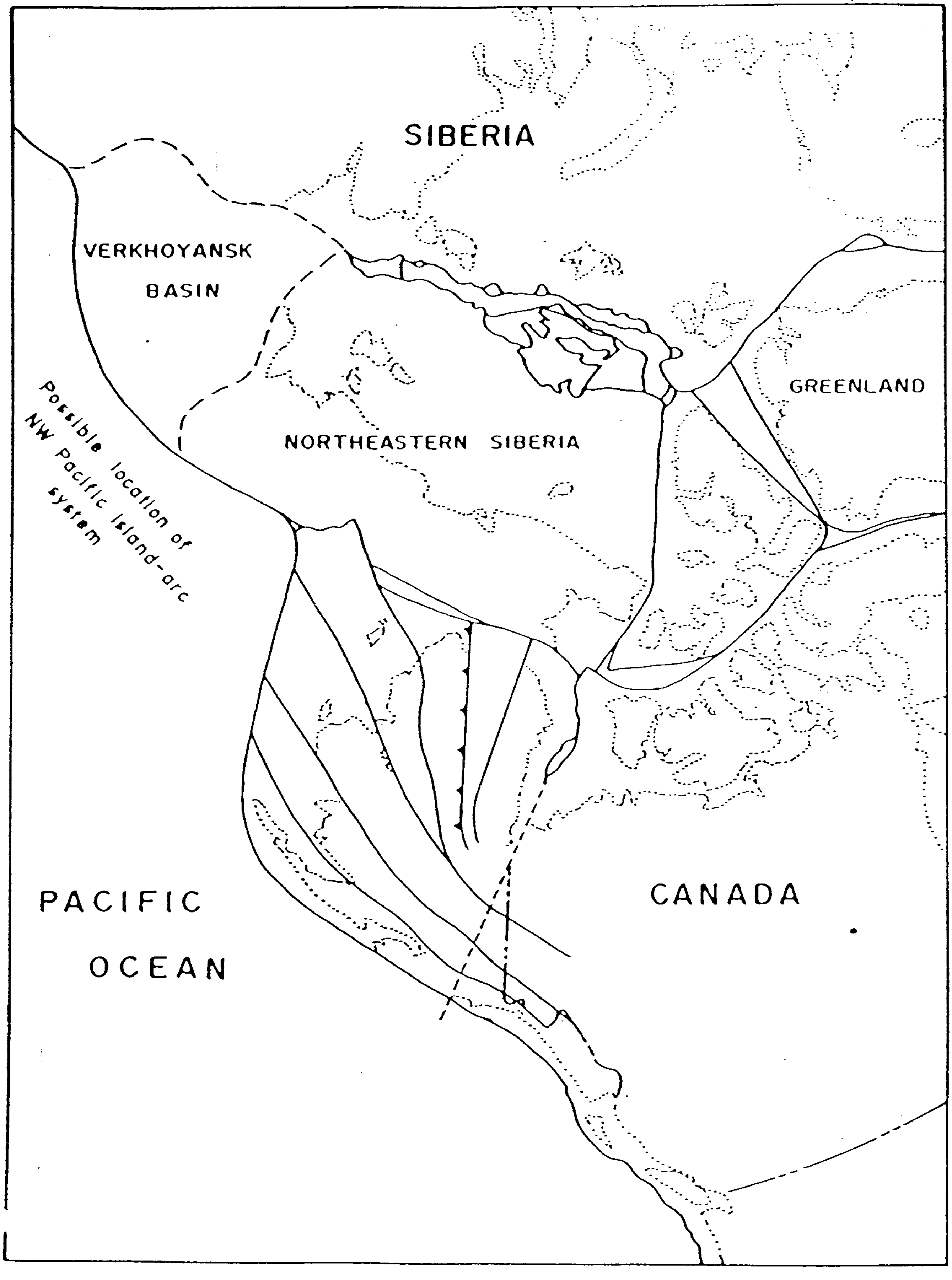
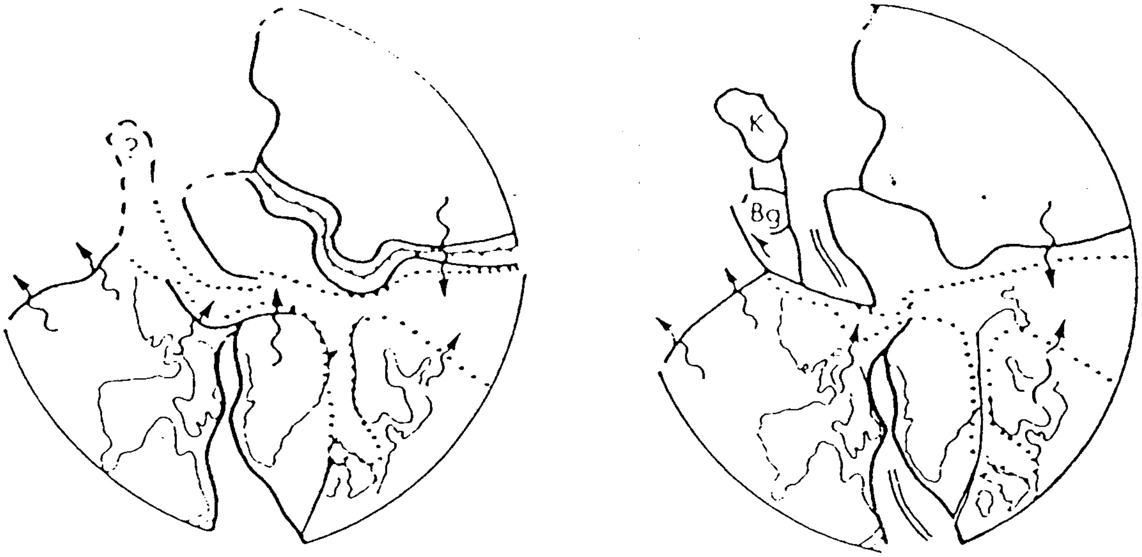

SIBERIA
VERKHOYANSK BASIN
Possible location of NW Pacific island-arc system
NORTHEASTERN SIBERIA
GREENLAND
PACIFIC OCEAN
CANADA

Figure 6

D late Paleozoic: Variscan

E late Paleozoic - earliest Mesozoic: rifting



F mid to late Mesozoic: rifting

G late Cretaceous-early Cenozoic: rifting, volcanism

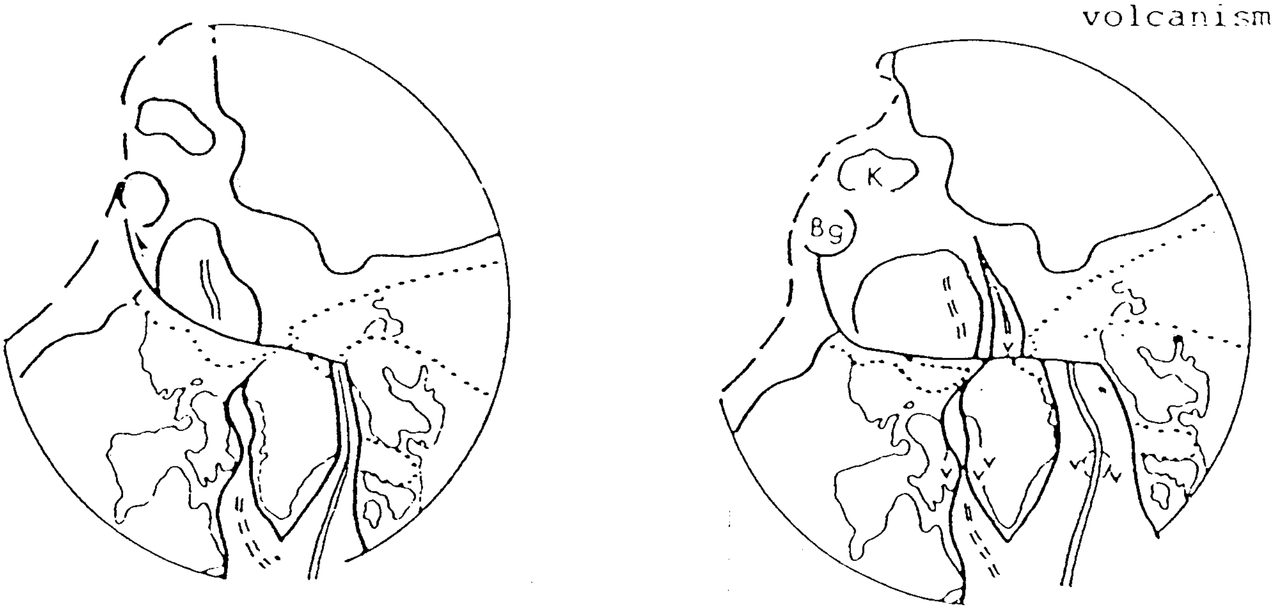


Figure 7

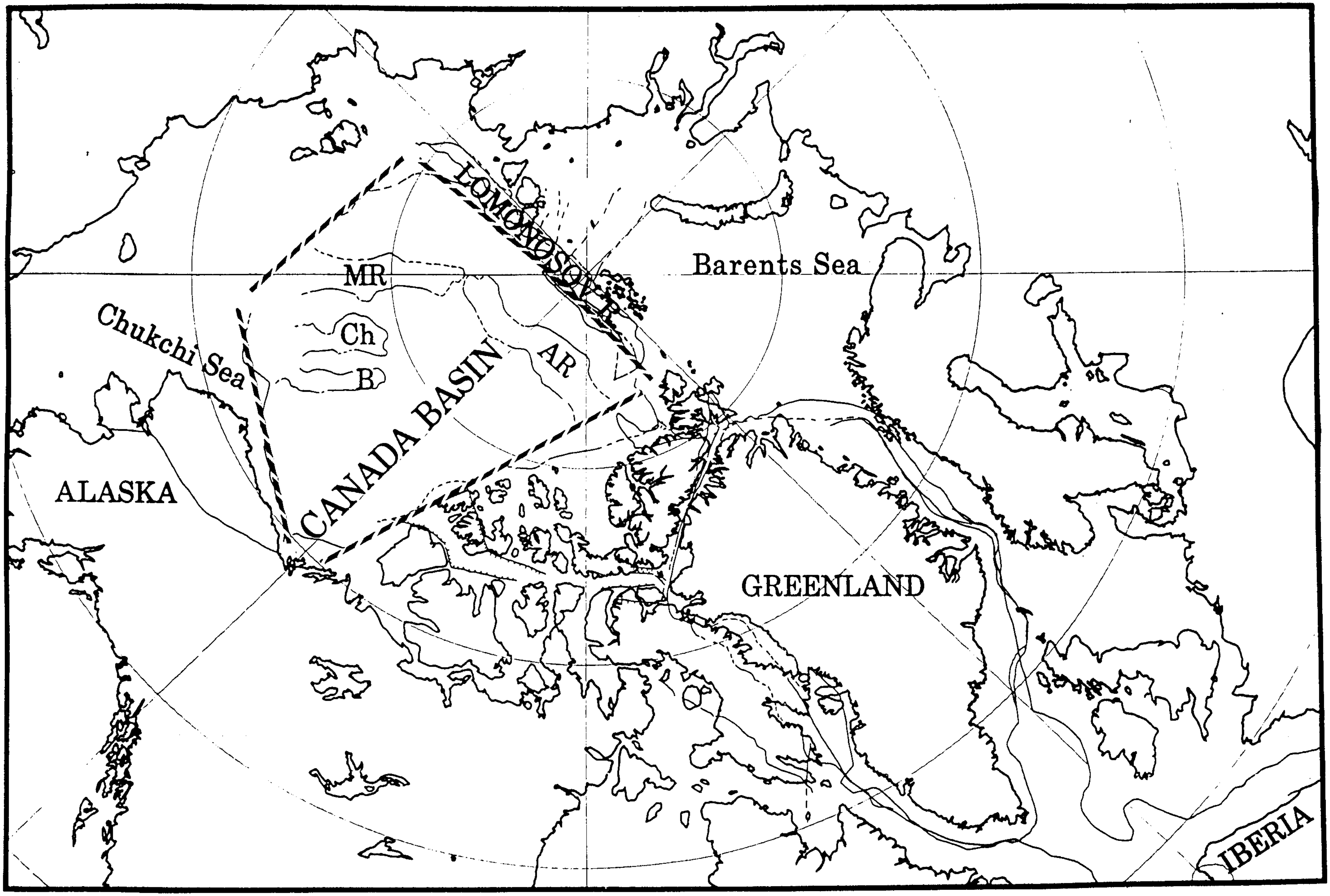

LOMONOSOV R.
Barents Sea
MR
Ch
B
AR
Chukchi Sea
CANADA BASIN
ALASKA
GREENLAND
IBERIA

Figure 8

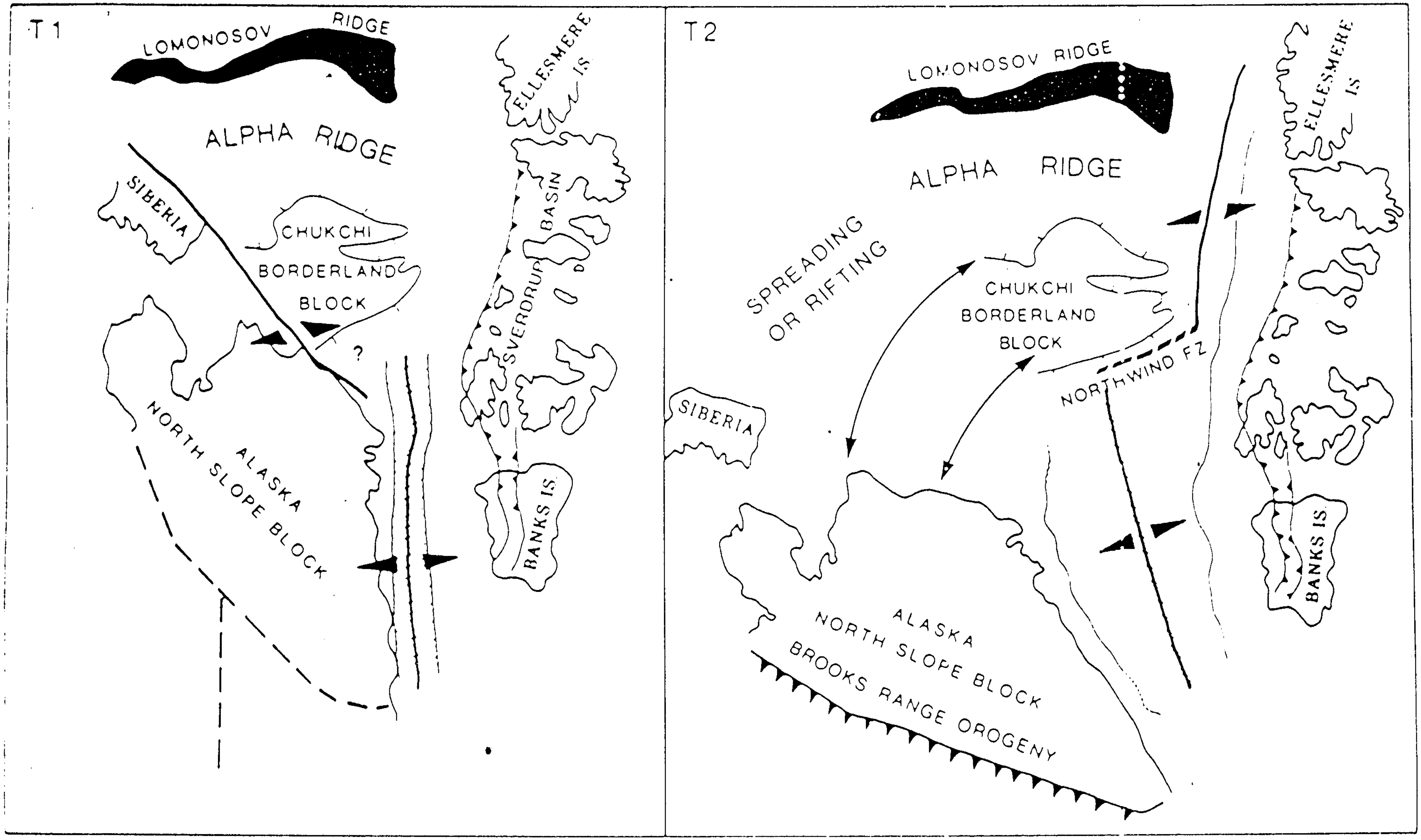
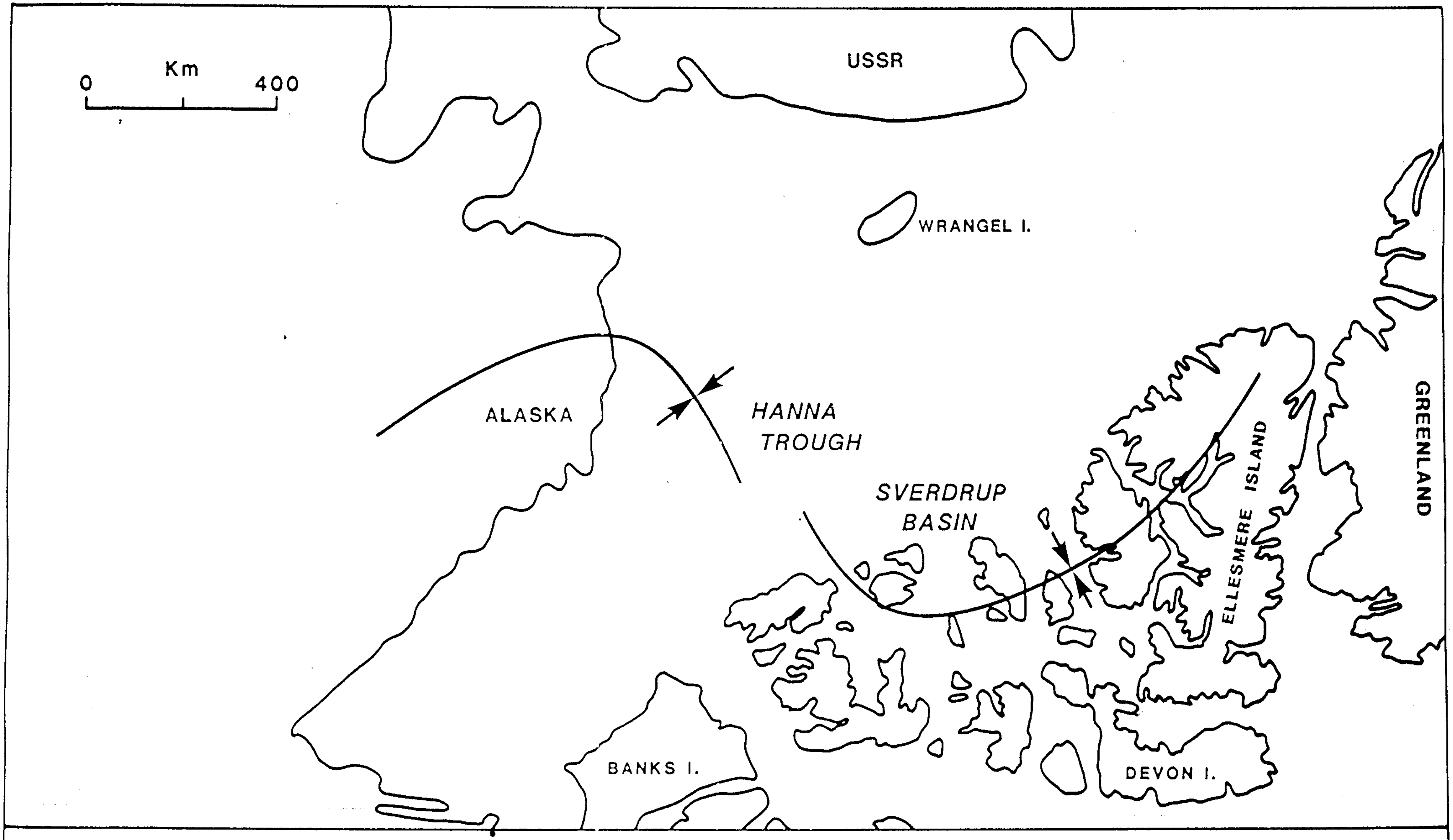

T1
LOMONOSOV RIDGE
ALPHA RIDGE
ELLESMERE IS
SIBERIA
CHUKCHI BORDERLAND BLOCK
?
SVERDRUP BASIN
ALASKA NORTH SLOPE BLOCK
BANKS IS
T2
LOMONOSOV RIDGE
ALPHA RIDGE
ELLESMERE IS
SPREADING OR RIFTING
CHUKCHI BORDERLAND BLOCK
NORTHWIND FZ
SIBERIA
ALASKA NORTH SLOPE BLOCK
BROOKS RANGE OROGENY
BANKS IS

Figure 9



RESTORATION OF BASIN AXIS BY ROTATION

Figure 10

SVERDRUP RIM RIFTING MODEL

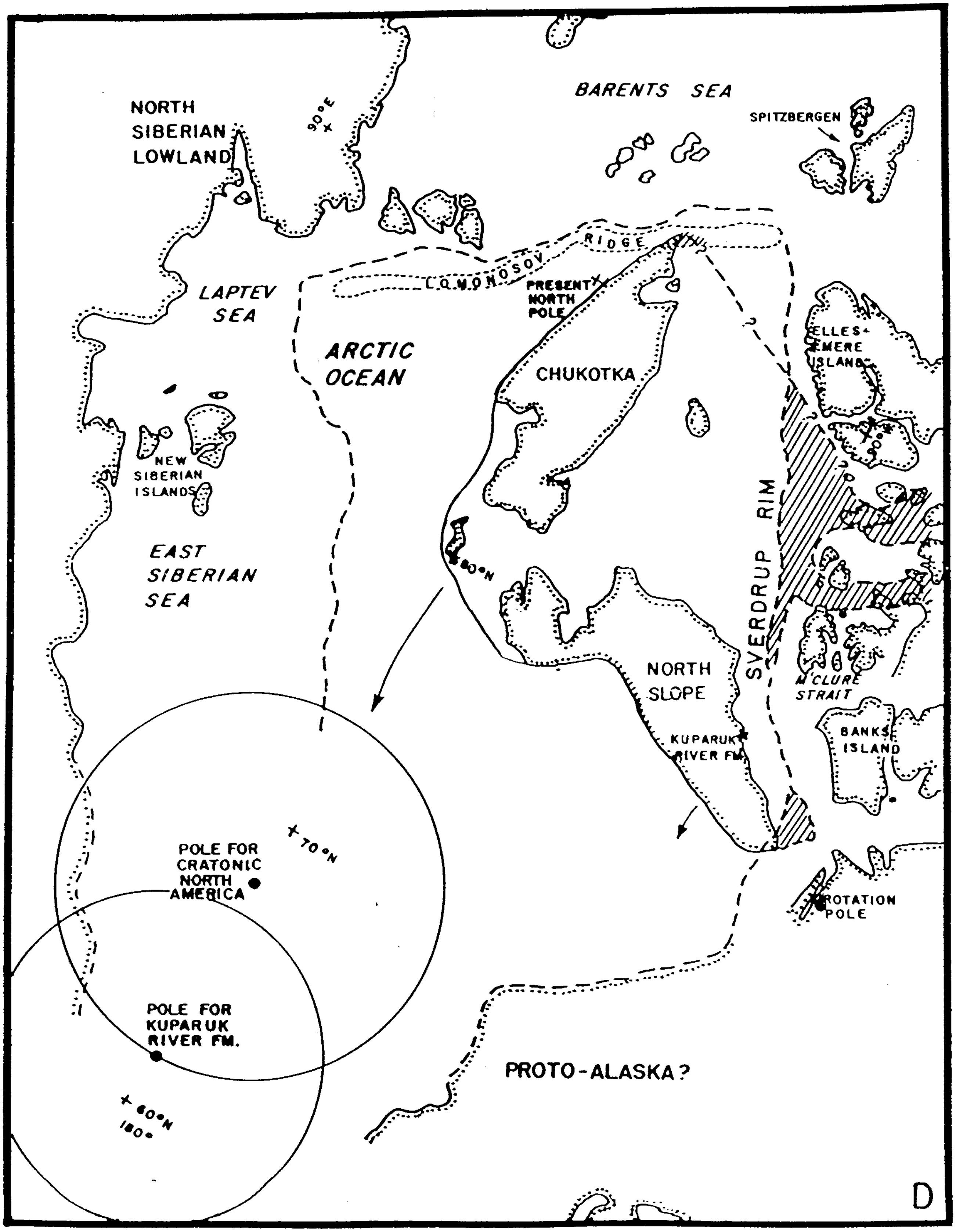


Figure 11

LATE JURASSIC (150Ma)

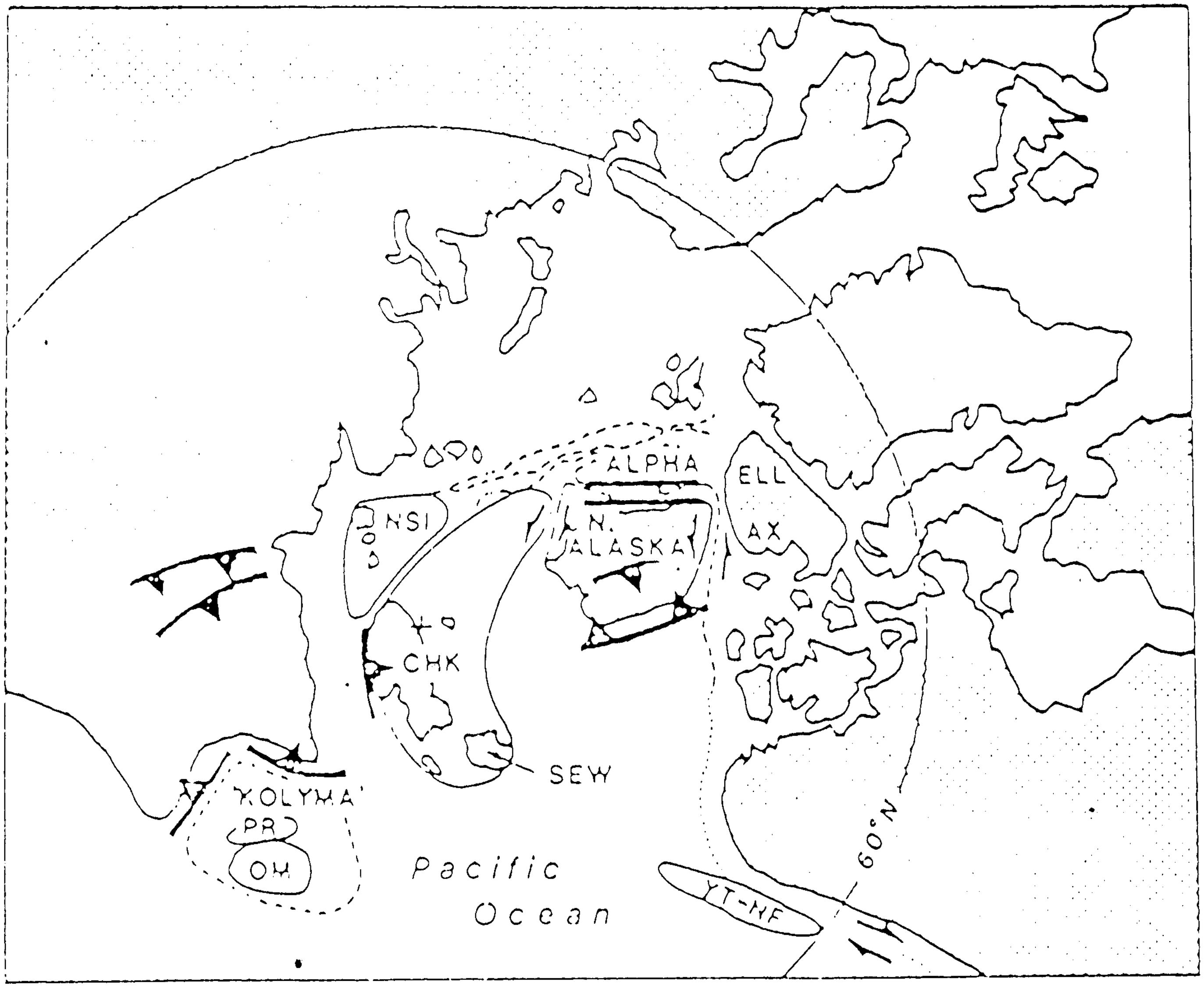


Figure 12a

MID CRETACEOUS (110Ma)

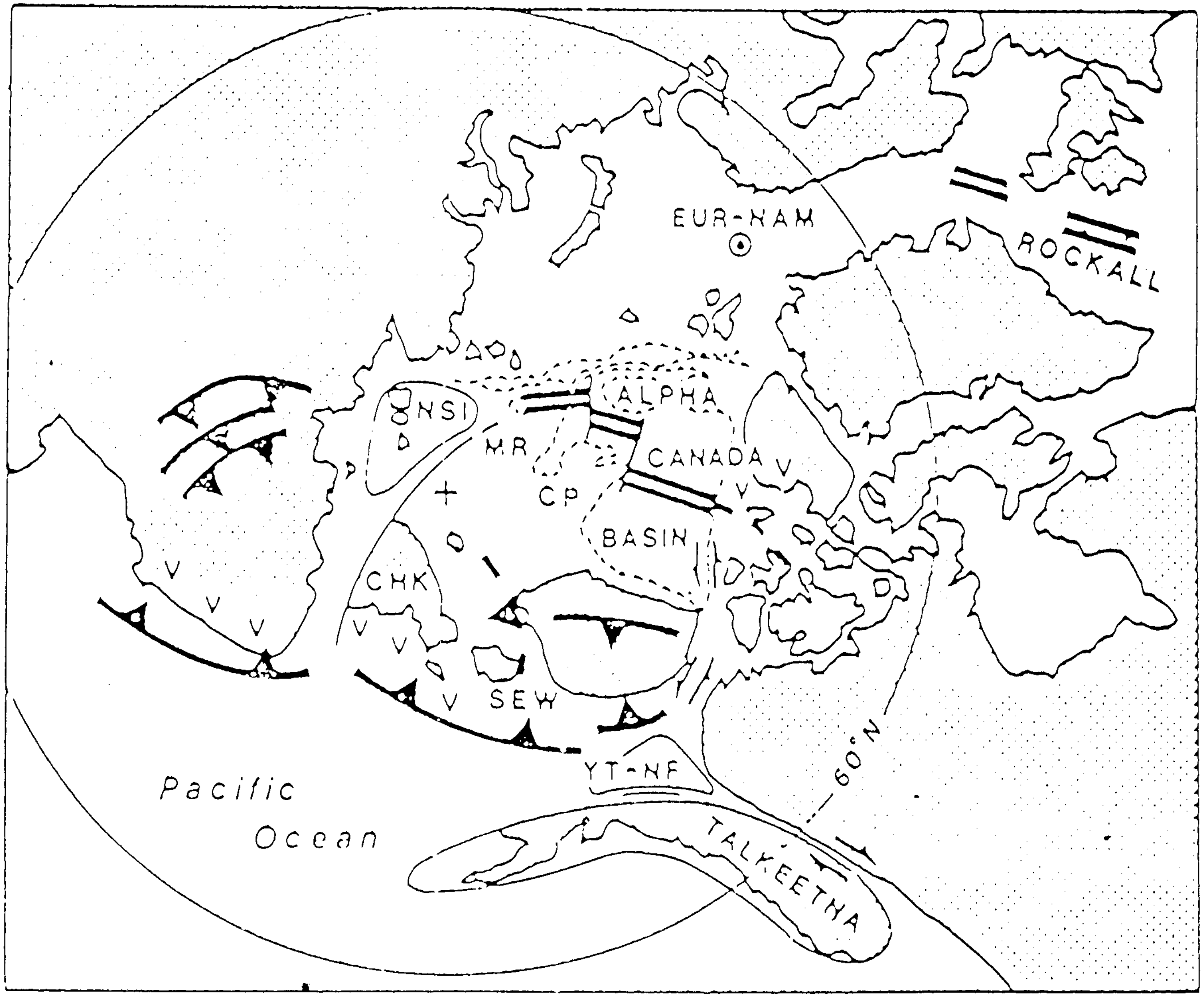


Figure 12b

LATE CRETACEOUS (76Ma)

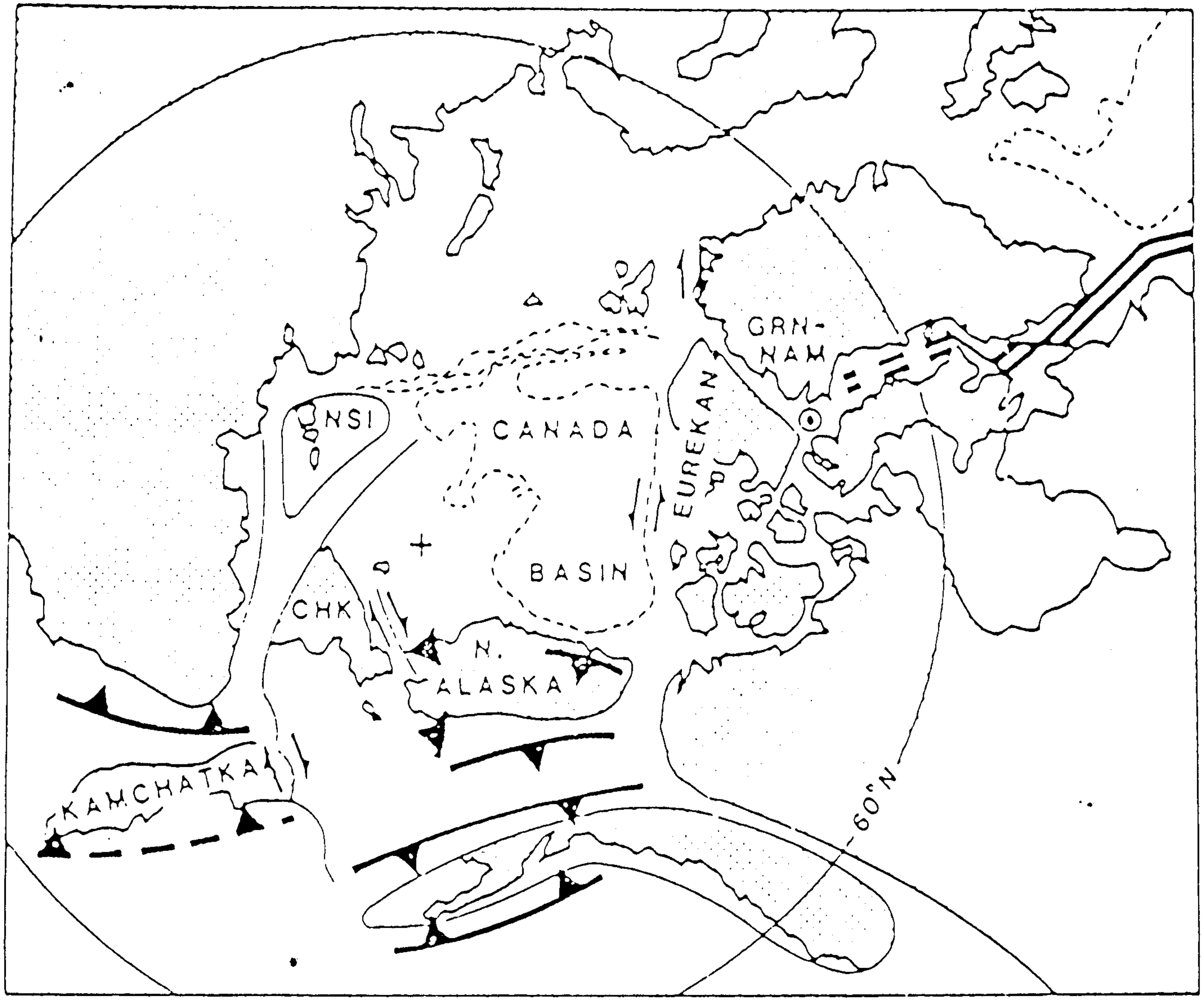


Figure 12c

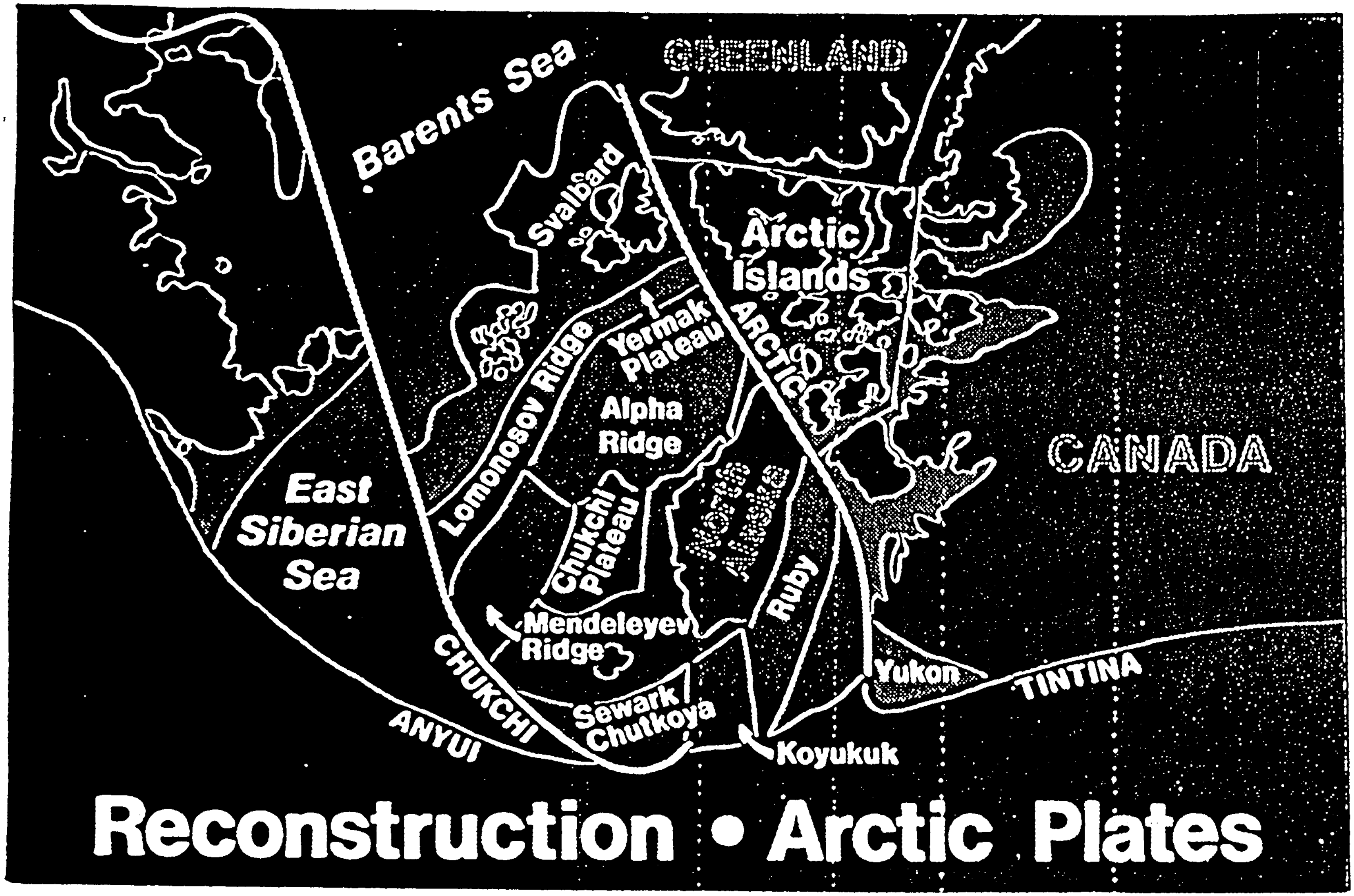

GREENLAND
Barents Sea
Svalbard
Arctic Islands
ARCTIC
Yermak Plateau
Lomonosov Ridge
Alpha Ridge
CANADA
East Siberian Sea
Chukchi Plateau
North Alaska
Ruby
Mendeleyev Ridge
CHUKCHI
Sewark Chutkoya
Yukon
TINTINA
ANYUI
Koyukuk
Reconstruction • Arctic Plates

Figure 13

LOMONOSOV RIFTING MODEL

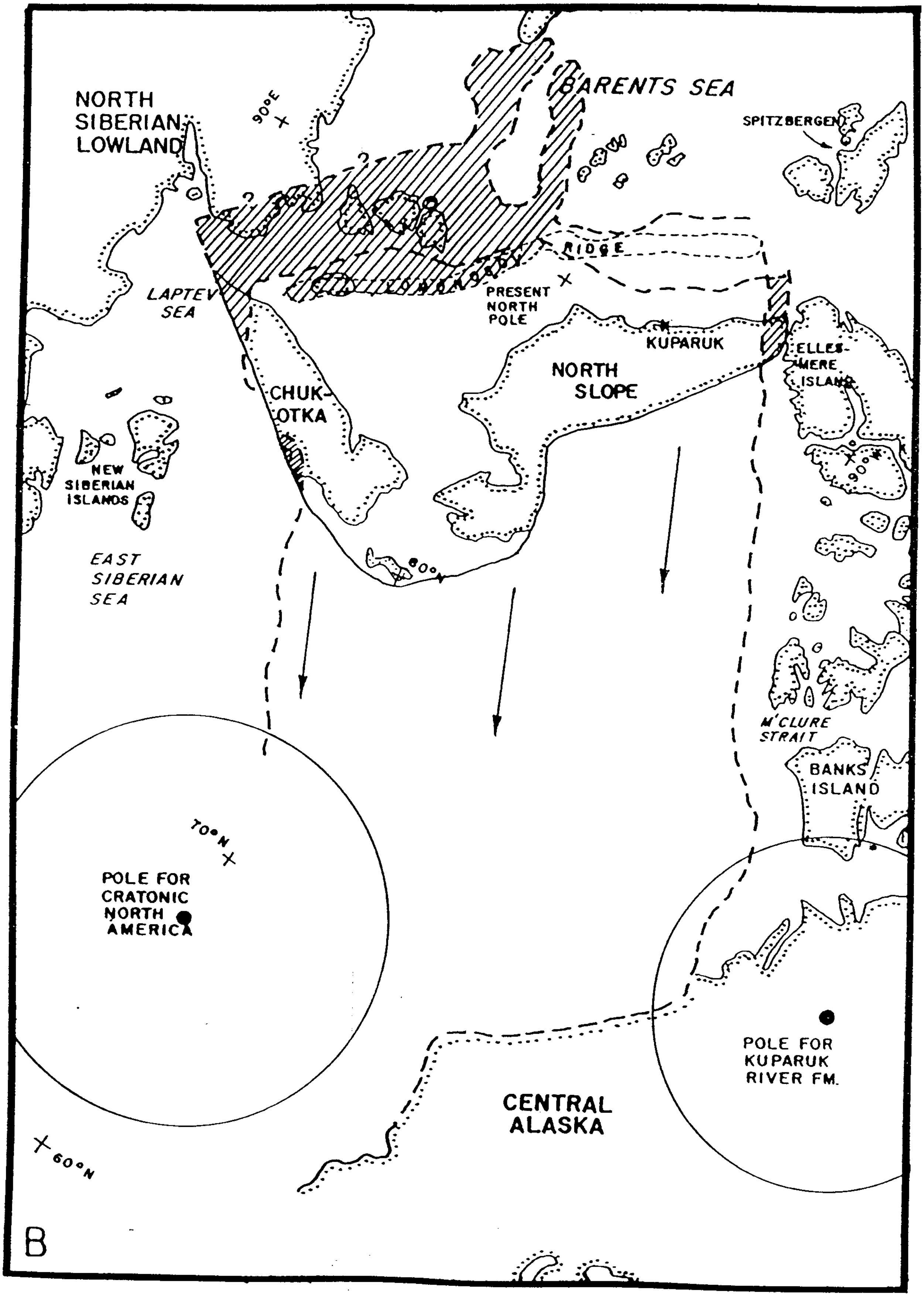


Figure 14

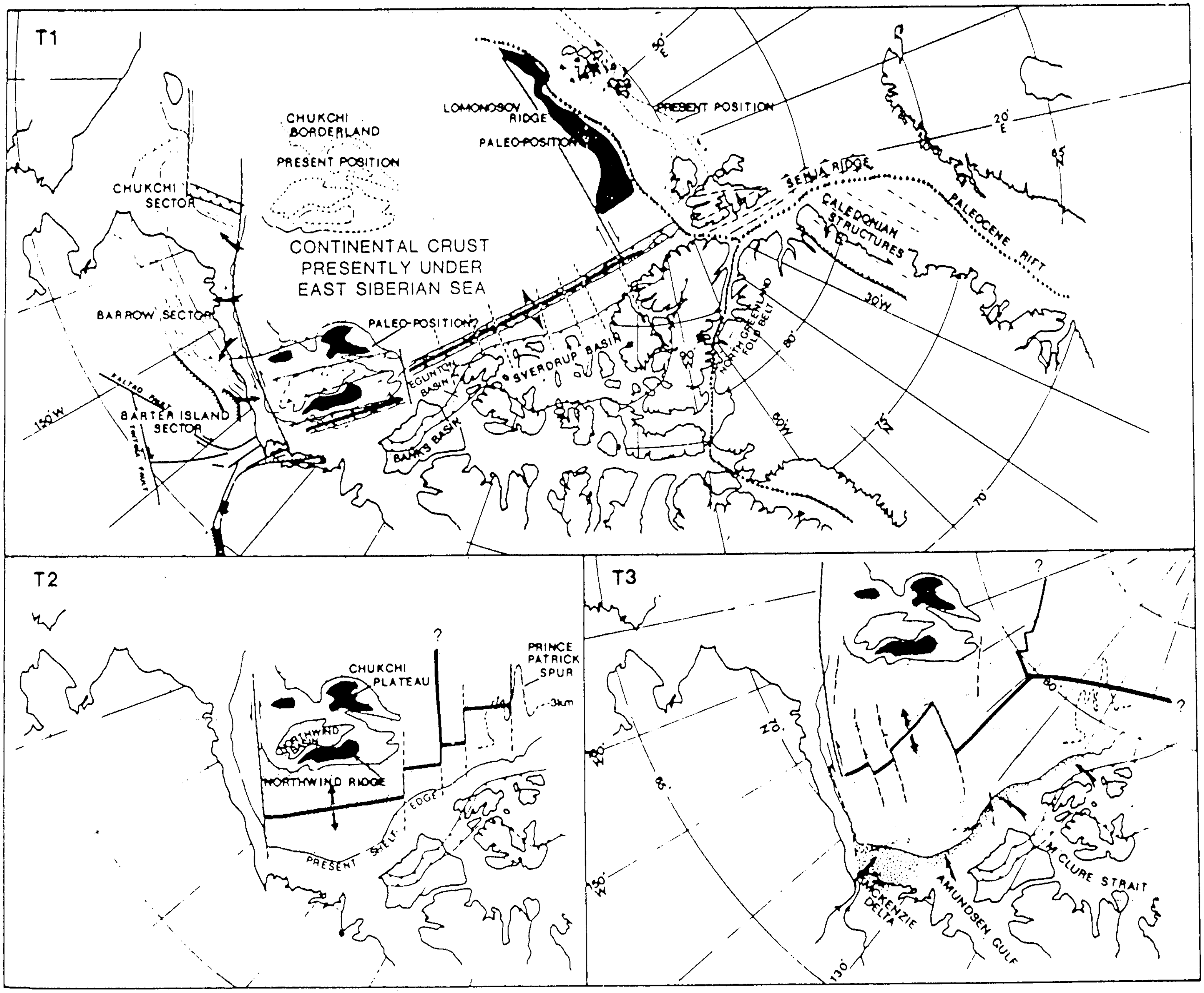
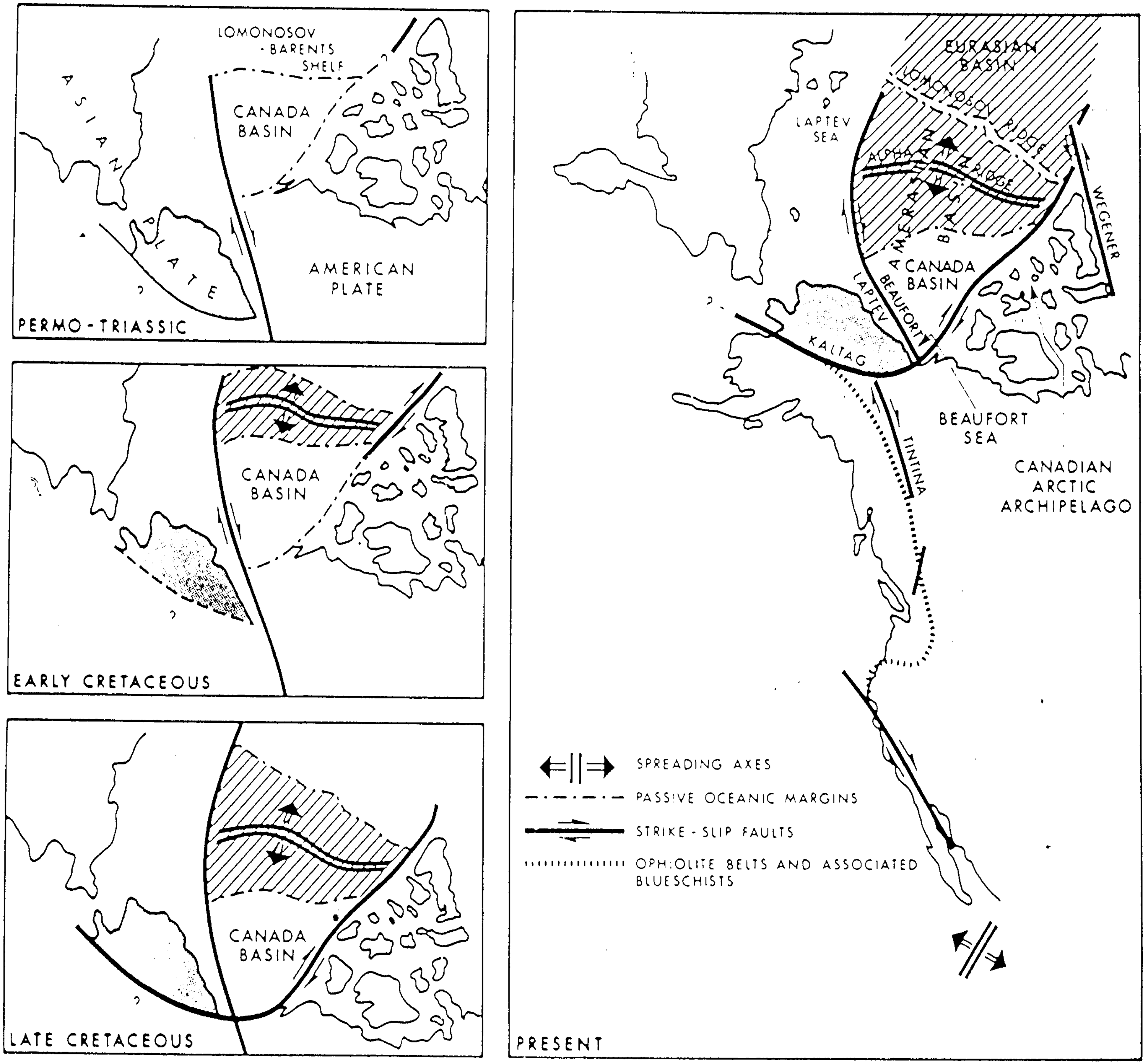

T1
CHUKCHI BORDERLAND
PRESENT POSITION
LOMONOSOV RIDGE
PALEO-POSITION
PRESENT POSITION
30°E
20°E
85°N
CHUKCHI SECTOR
SENJA RIDGE
CALEDONIAN STRUCTURES
PALEOCENE RIFT
CONTINENTAL CRUST PRESENTLY UNDER EAST SIBERIAN SEA
BARROW SECTOR
PALEO-POSITION?
EGLINTON BASIN
SVERDRUP BASIN
NORTH GREENLAND FOLD BELT
30°W
80°
KALTAG FAULT
150°W
BARTER ISLAND SECTOR
TINTINA FAULT
BANKS BASIN
60°W
75°N
70°
T2
CHUKCHI PLATEAU
PRINCE PATRICK SPUR
3km
NORTHWIND BASIN
NORTHWIND RIDGE
PRESENT SHELF EDGE
?
T3
?
80°
?
70°N
180°W
85°
150°W
M'CLURE STRAIT
MACKENZIE DELTA
AMUNDSEN GULF
130°

Figure 15



LOMONOSOV
-BARENTS
SHELF
ASIAN PLATE
CANADA BASIN
AMERICAN PLATE
PERMO-TRIASSIC
CANADA BASIN
EARLY CRETACEOUS
CANADA BASIN
LATE CRETACEOUS
EURASIAN BASIN
LOMONOSOV RIDGE
ALPHA RIDGE
AMERASIAN BASIN
LAPTEV SEA
CANADA BASIN
LAPTEV
BEAUFORT
KALTAG
WEGENER
TINTINA
BEAUFORT SEA
CANADIAN ARCTIC ARCHIPELAGO
SPREADING AXES
PASSIVE OCEANIC MARGINS
STRIKE - SLIP FAULTS
OPHIOLITE BELTS AND ASSOCIATED BLUESCHISTS
PRESENT

Figure 16