PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Evolution of Sedimentary Basins in the Canadian Arctic [and Discussion]

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Evolution of sedimentary basins in the Canadian Arctic

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Since middle Proterozoic time, two long-lasting phases affected the Canadian Arctic Archipelago, each forming a different sedimentary basin.

The Franklinian Basin, which was floored by continental or quasi-continental crust, received 10 km or more of clastic, carbonate and volcanic rocks from the mid-Proterozoic to Devonian. Internal parts of the basin were deformed, intruded and metamorphosed locally, and external parts were folded and thrust cratonward by compressional episodes of the Ellesmerian Orogeny, which culminated in the late Devonian. This marked the end of a phase, at which time the entire region may have been emergent. The nature of plate interactions that produced Ellesmerian deformation are unknown.

The second phase began in the early Carboniferous, when plate movements of the Boreal Rifting Episode created the proto-Canada Basin by left-hand transform motion of a plate along the modern continental margin and the location of the Kaltag Fault of northern Alaska. As a marginal side effect of that motion, the Sverdrup Basin developed as a peri-cratonic incipient rift. From the Carboniferous to late Cretaceous the basin received about 13 km of cratonic-derived clastic detritus.

From late Cretaceous to early Tertiary time, the Arctic Archipelago was disrupted by the interference of two plate movements originating in the Arctic and North Atlantic regions. Those events had three main effects: the craton was extended and a graben-filled depression formed in the southeastern part of the archipelago; the eastern and central parts of the Sverdrup Basin were compressed and uplifted (Eurekan Orogeny); and resultant clastics prograded northwestward toward the Canada Basin, to form the Arctic continental terrace wedge.

Introduction

Several of my recent papers have dealt with different aspects of the geology of the Canadian Arctic (Kerr 1980*a*, *b*, *c*, 1981*a*, *b*). Together they describe the evolution of the sedimentary basins there. That evolution is briefly summarized here by the use of figures published in the earlier papers.

Two long-lasting phases affected the Canadian Arctic. The constructional phase involved formation of a supercontinent, Pangaea. Nearly all of the present Arctic lands was part of Pangaea, including the present lands and marine areas. The subsequent fragmentation phase involved the break-up of that supercontinent by plate tectonic processes to form the present oceans, continents, islands and channels.

Constructional phase

The constructional phase included all of early Palaeozoic time and ended at the end of the Ellesmerian Orogeny in late Devonian or early Mississippian time. The configuration of the Canadian Arctic at the end of this phase is shown in figure 1 (from Kerr 1980*a*, fig. 3). The area of the present Canada Basin, Canadian Arctic Islands, and nearby seaways apparently was made

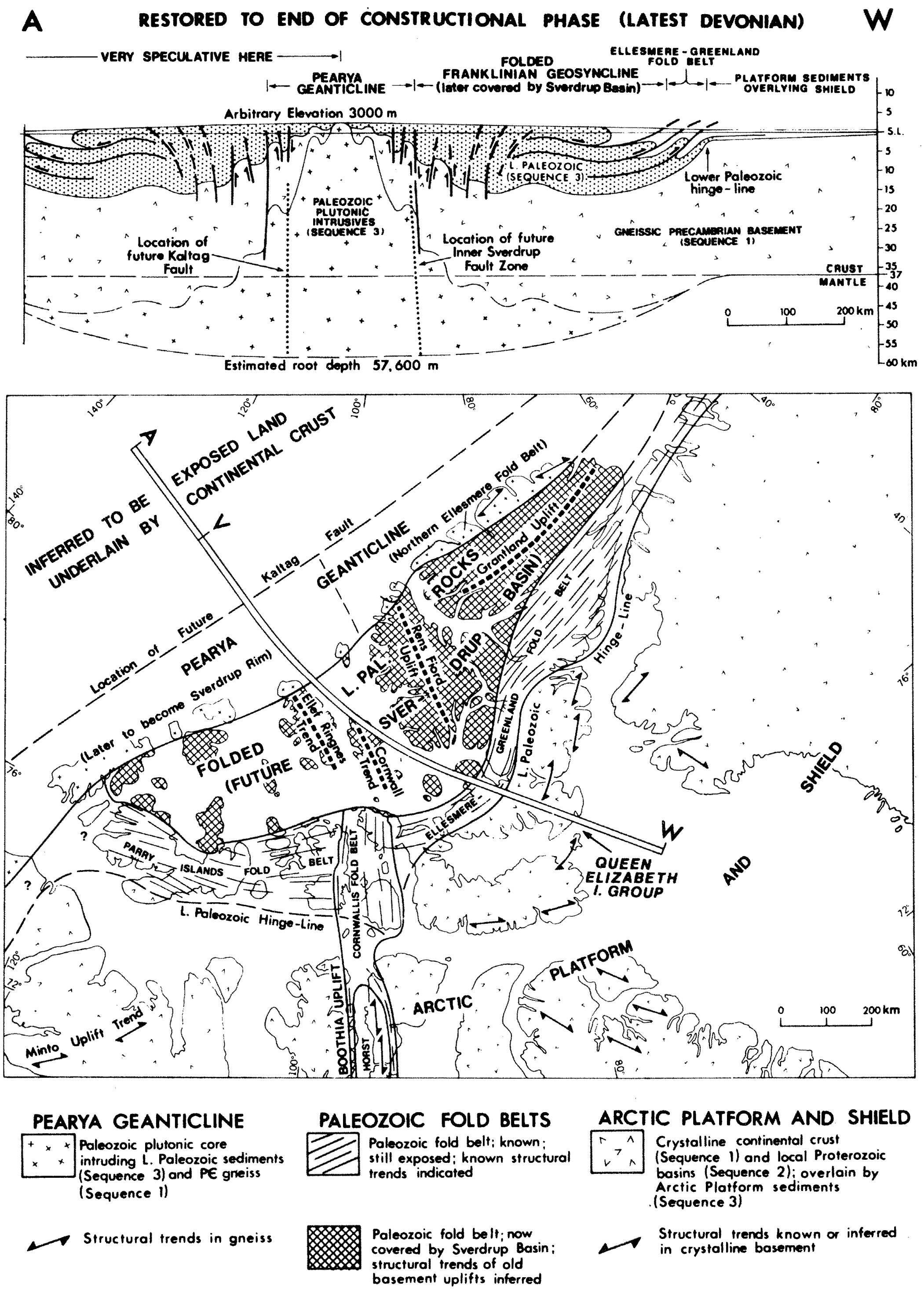

FIGURE 1. Structural configuration of the Canadian Arctic in latest Devonian time, at the end of the constructional phase. For location see figure 3.

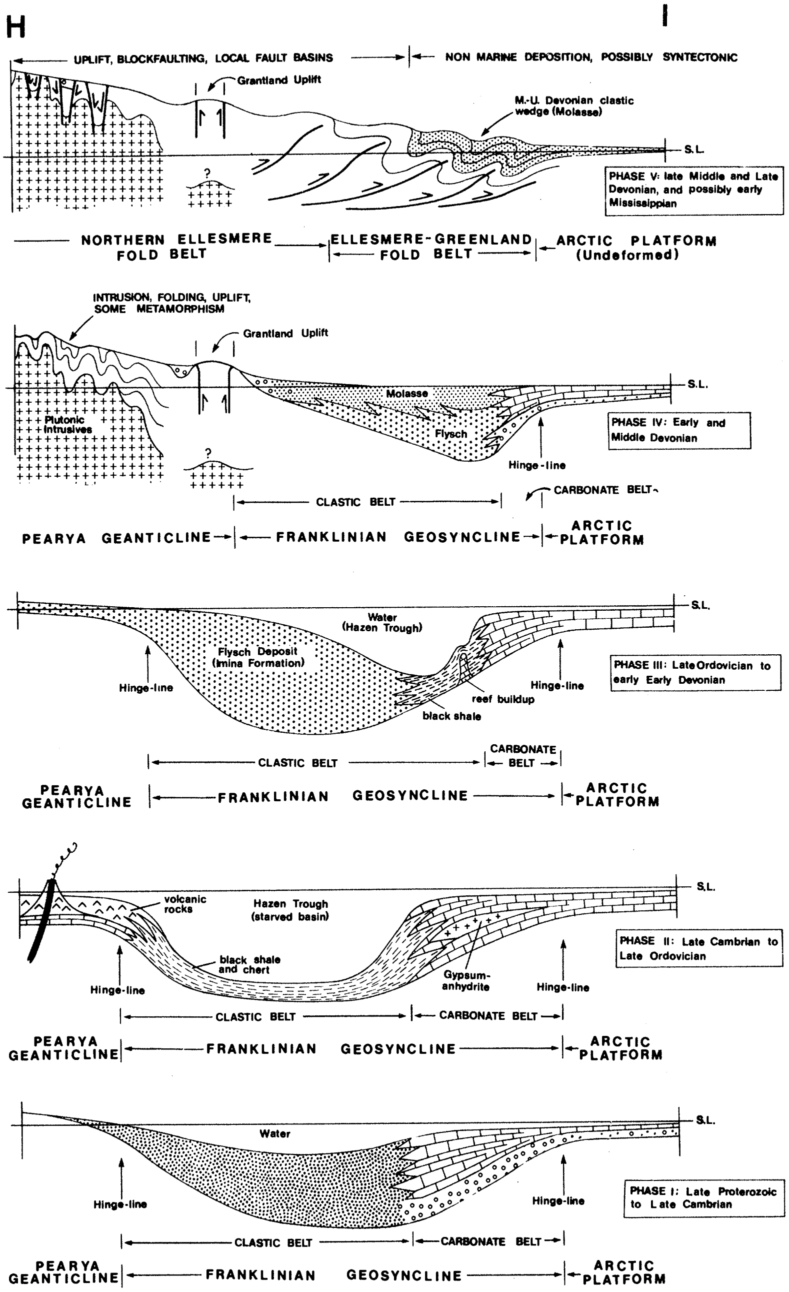

FIGURE 2. Evolution of the Franklinian Geosyncline (sequence 3, figure 1), showing the five phases of its development, with the youngest at the top.

up of a continental crust. A linear tectonic belt extending NE–SW through this region was the Pearya Geanticline. It had been active through much of previous Palaeozoic time. At the end of the constructional phase the geanticline was a topographically high region that had been deformed, intruded and metamorphosed by the Ellesmerian Orogeny. This thick rigid geanticline was to have a major control on structures that would develop in the later phase.

The Lower Palaeozoic Franklinian Geosyncline lay southeast of the Pearya Geanticline, and presumably formed on continental crust (figure 1). It developed simultaneously with the Pearya

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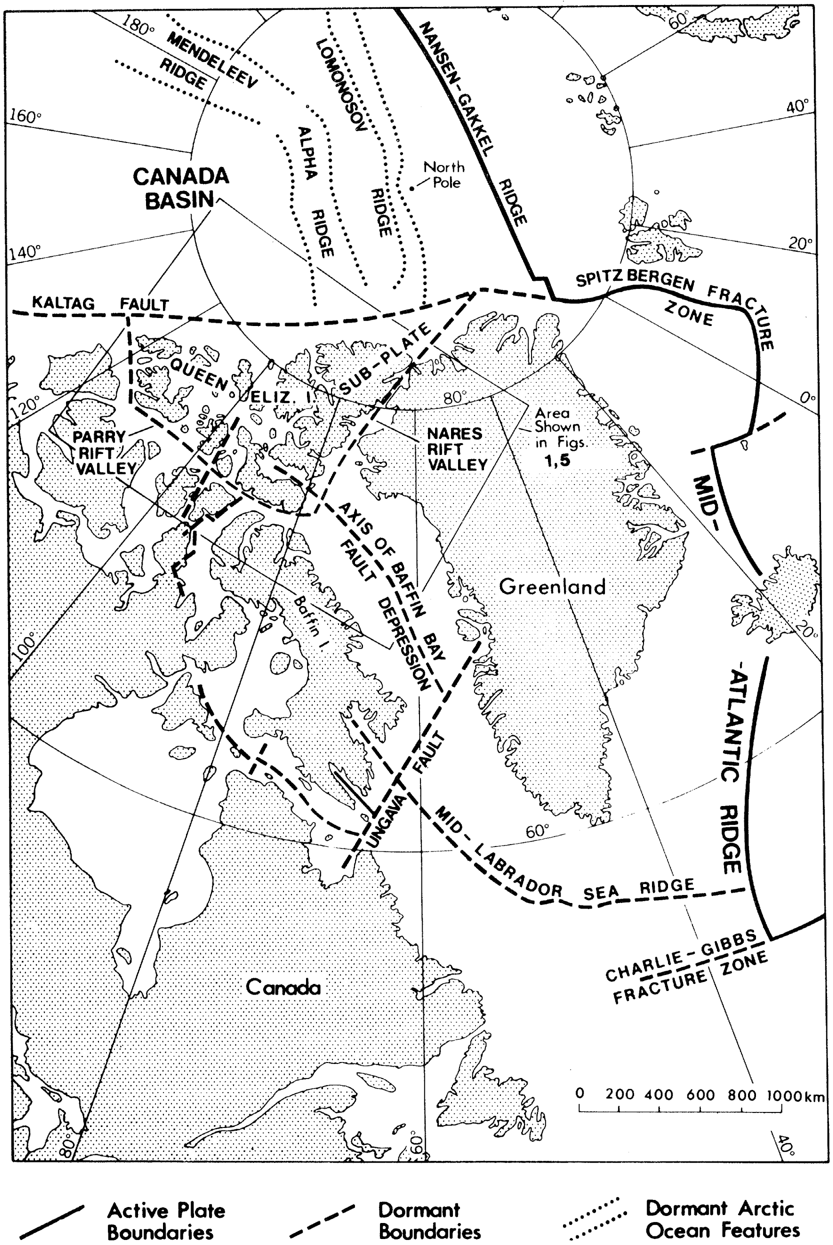

FIGURE 3. Present-day geography of the North American Arctic, showing the major plate-related structures.

Geanticline. The five phases in the development of the Franklinian Geosyncline are shown in figure 2 (from Kerr 1981*a*, fig. 7).

FRAGMENTATION PHASE

The fragmentation phase of the Canadian Arctic involved plate tectonic processes that broke apart the supercontinent to form the present-day lands, seas and structures that are shown in figure 3 (after Kerr 1980*a*, fig. 1). Fragmentation resulted from the interplay of two plate tectonic events that were largely restricted to opposite sides of the present continent. Each of these events

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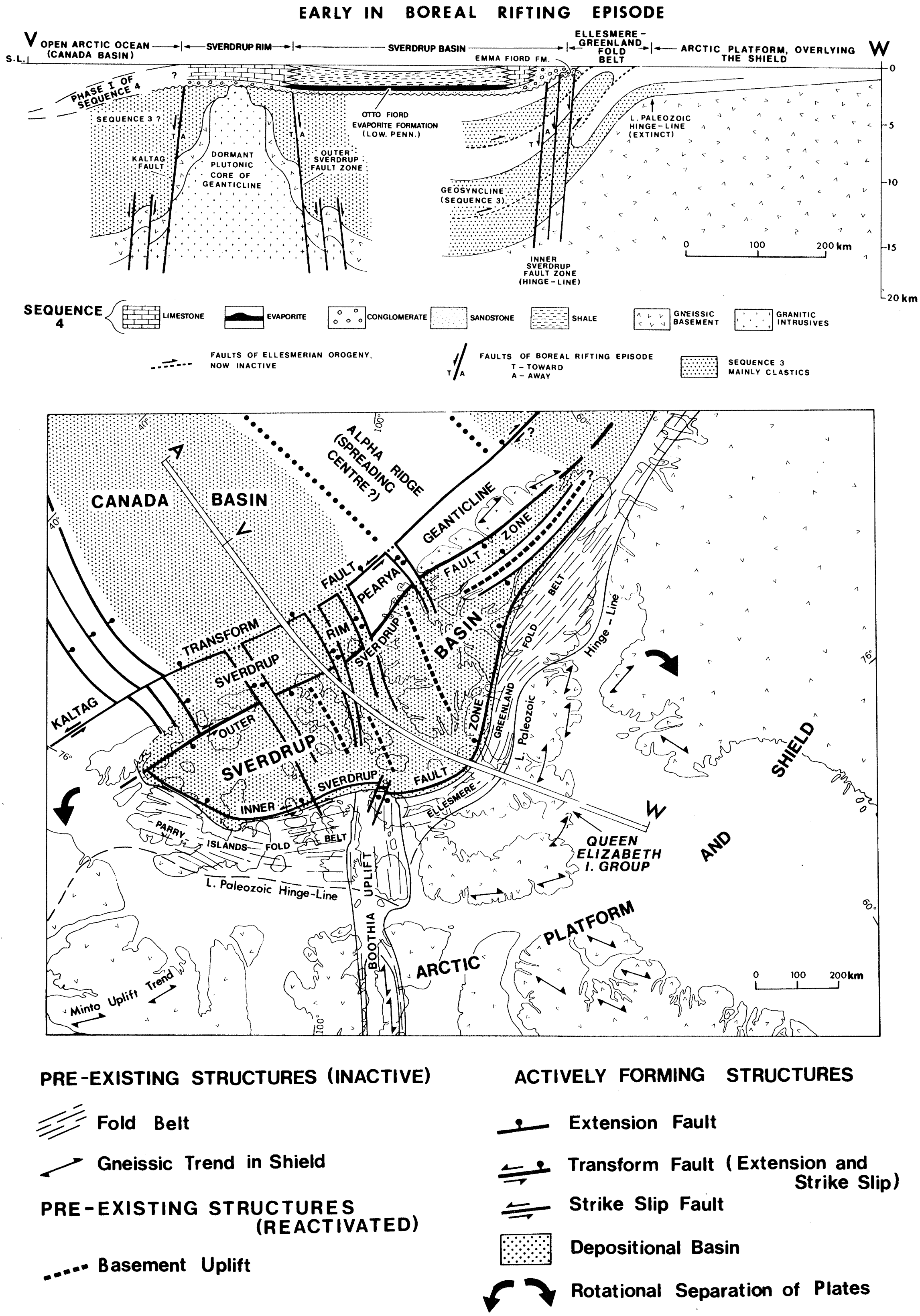

FIGURE 4. Initial fragmentation of the Canadian Arctic to form early stages of the Canada Basin and the Sverdrup Basin. This represents late Palaeozoic time (Carboniferous to Permian) in an early stage of the Boreal Rifting Episode. The islands had not yet formed (cf. figure 3). The structures in the map and cross section were controlled by the older structures shown in figure 1.

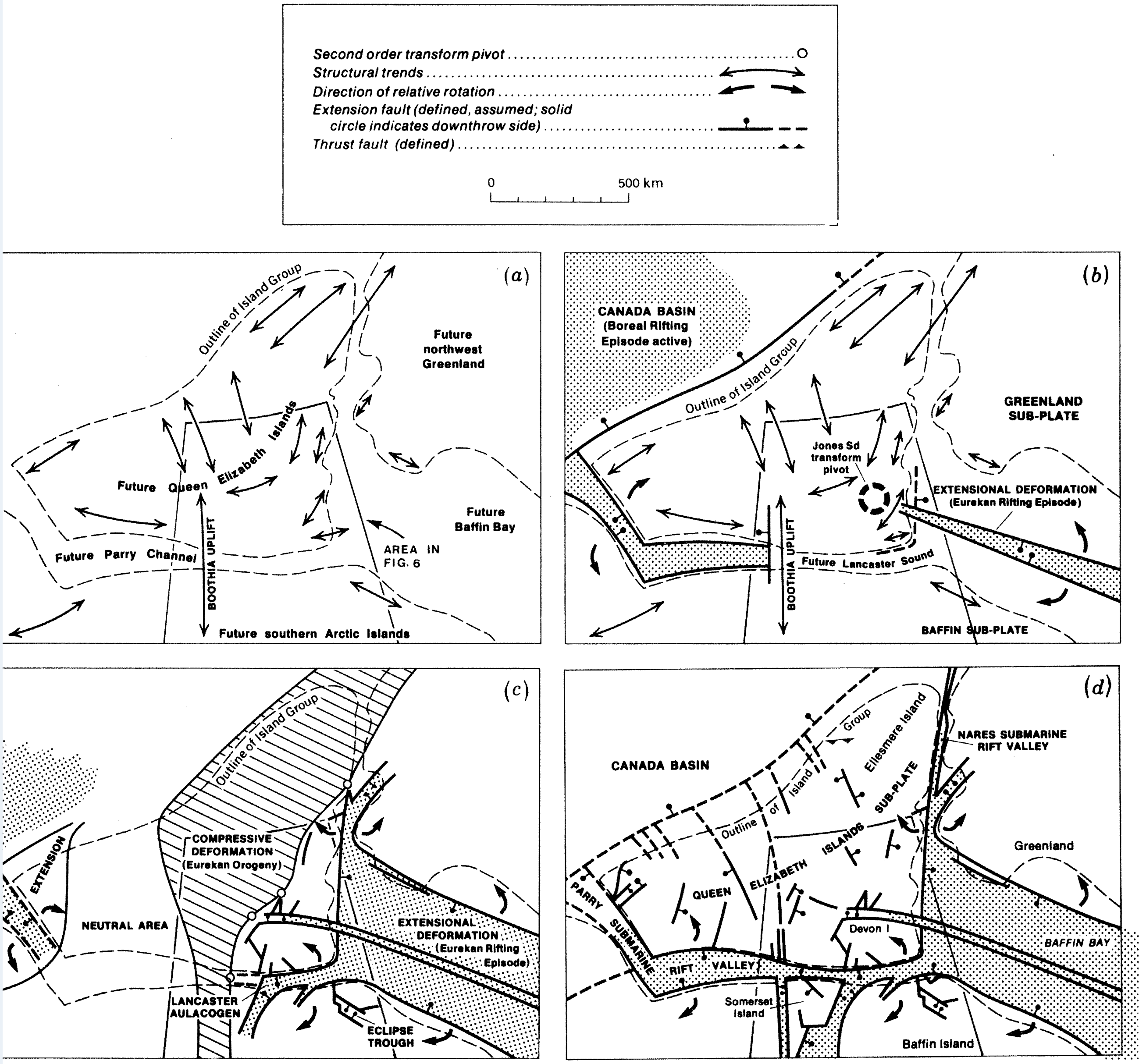

FIGURE 5. Sequence of plate tectonic events in the Canadian Arctic (after Kerr 1981 *b*), with the area shown in figure 6 outlined. (*a*) Structural trends of the Precambrian Shield and folded sedimentary cover that influenced plate and sub-plate boundaries and movements. (*b*) Latest Cretaceous to early Tertiary time. The Boreal Rifting Episode was active, emanating from the northwest (cf. figure 4). The Eurekan Deformation was in an early phase, and northwest propagating extension faults began to separate the Greenland and Baffin Island sub-plates. These sub-plates rotated apart about the Jones Sound first-order transform pivot in the future Queen Elizabeth Islands. (*c*) Climactic phase of the Eurekan Deformation in early to mid-Tertiary time (for more detail of this phase see figure 6). Extension in the southeast (Eurekan Rifting Episode) was transformed to compression in the northwest (Eurekan Orogeny) by means of several second-order transform pivots. The Boreal Rifting Episode was diminishing, presumably as a result of the increasing activity of the Eurekan Deformation. (*d*) Final phase of plate movements in the Canadian Arctic, in Miocene or Pliocene time, when faults emanating from the Atlantic Ocean were able to break northwestward through the continent to connect with older faults of the Arctic Ocean, obliterating the transform pivots. This structural configuration of sub-plates exists today, modified by erosion.

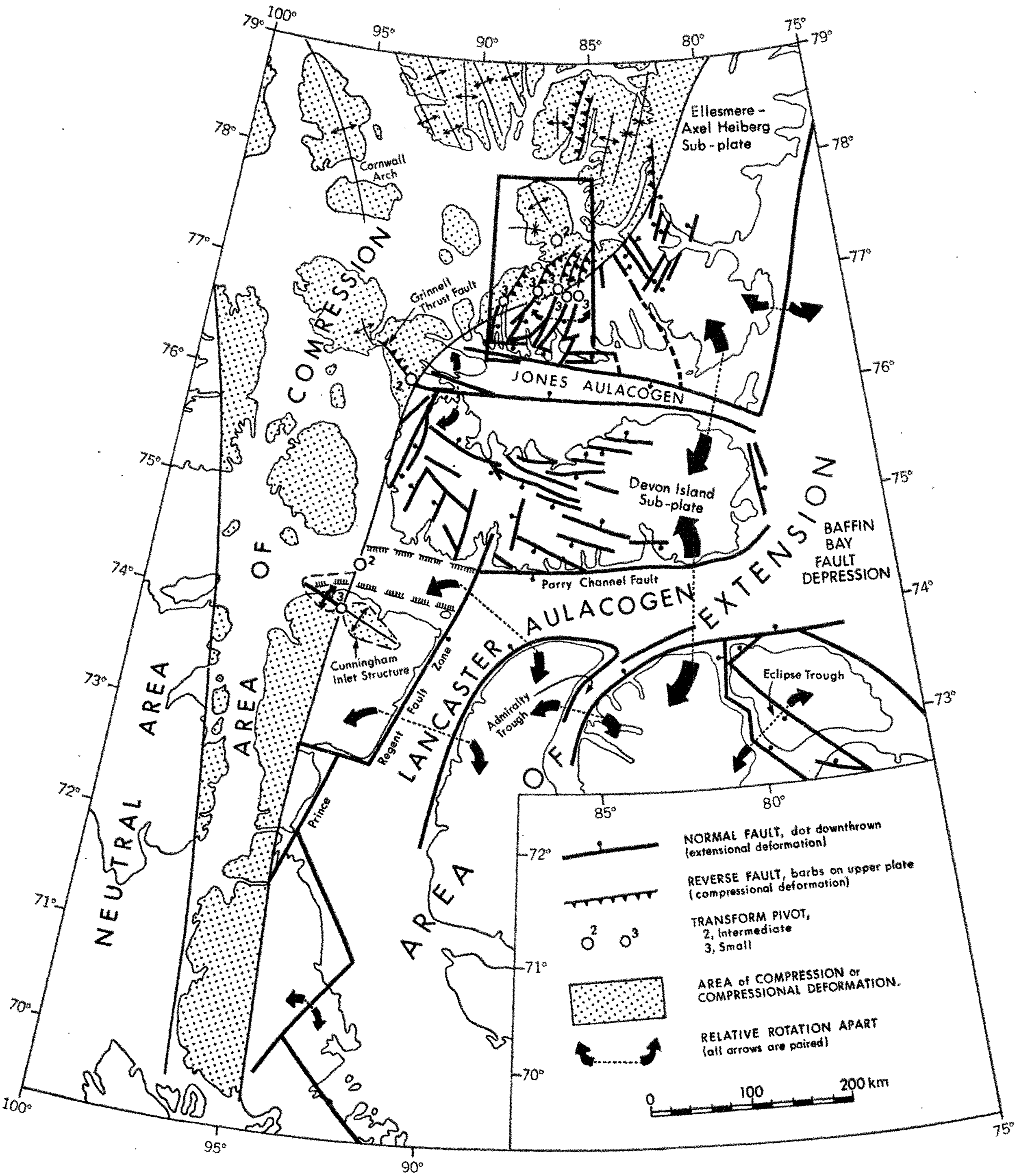

Figure 6. Movements that may have occurred at the terminus of the Canadian Arctic Rift System during the climactic phase of the Eurekan Deformation. Figure 5*c* shows the larger region during the same phase. For explanation of sub-plate movements see Kerr (1981*b*).

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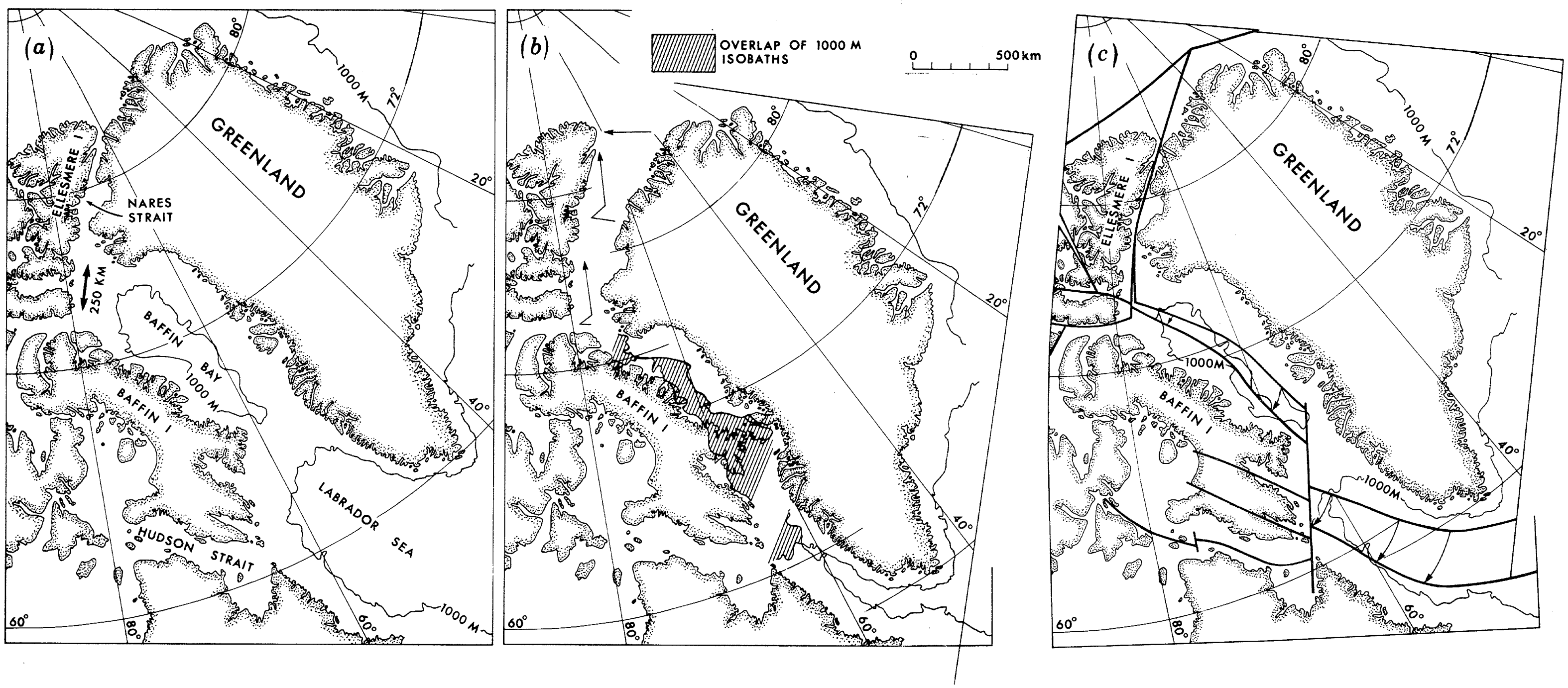

Figure 7. Current theories of tectonics that explain the relation of Greenland to the rest of North America (from Kerr 1981*b*). (*a*) Fixist theories in which there has been no lateral movement of Greenland. (*b*) Conventional plate tectonic theories (moving continents or moving plates) in which most modern-day workers consider that Greenland moved about 250 km along Nares Strait. The conventional reconstruction shown (after Srivastava 1978) considers that Greenland first moved toward Ellesmere Island, closing up Nares Strait (horizontal arrows) and later had northward strike-slip displacement (vertical arrows). (*c*) Restoration according to the integrated theory of plate tectonics (Kerr 1967*a*, *b*, 1980*a*, 1981*a*, *b*, and herein). Greenland and Canada rotated apart, with the lateral movement increasing to the southeast from Nares Strait to Baffin Bay to the Labrador Sea. The amount of restoration made here is shown by curving arrows. Much of the great movement apart in Labrador Sea is accounted for by minor rotational opening in southern Nares Strait. The 1000 m isobaths in Baffin Bay and Labrador Sea cannot be brought back together. The gap between them that appears at first to be missing continental material can be accounted for by a foundered remnant of continental crust (Kerr 1967*b*).

was largely responsible for the formation of the oceanic area on one side of the present continent, as well as for certain deformations within the adjacent continental margin.

The Boreal Rifting Episode began in the present-day Arctic Ocean, apparently in about mid-Mississippian time, as shown in figure 4 (from Kerr 1980*a*, fig. 4). This resulted from movement of plates away from a spreading centre occupying the present Alpha Ridge. The Canada Basin and Makarov Basin formed on either side of the spreading centre. Extension faults of this spreading event apparently had a tendency to advance southeastward. Their advance was largely impeded by the thick plutonic core of the now-dormant Pearya Geanticline, and this caused the Kaltag Transform Fault to form along the northwest margin of that core. A small amount of extension affected the geanticline, which subsided slightly to form the Sverdrup Rim. The Sverdrup Basin formed southeast of the geanticline, located on an older folded geosyncline. The existence of that older basin may have made the crust more amenable to subsidence there, and was responsible therefore for the location of the Sverdrup Basin.

The sequence of events in the fragmentation history of the Canadian Arctic Islands is shown in figure 5 (after Kerr 1981*b*, fig. 7). The old structural grains that were present at the end of the constructional phase (figure 5*a*) had a major influence in controlling the pattern of fragmentation. The fragmentation phase began with the Boreal Rifting Episode, which apparently had a basically similar stress pattern from mid-Mississippian to late Cretaceous time (figure 5*b*). It appears that during this time the Canada Basin widened progressively, as the plate moving southwestward from the Alpha Ridge travelled progressively farther. The Sverdrup Basin formed on the adjacent continent as a side effect of events emanating from the Canada Basin. As the Canada Basin widened by the southwestward movement of a plate, a wider area of the adjacent continent became affected, and Parry Rift Valley began to form (figure 5*b*). The Eurekan Rifting Episode then began to develop, and in late Cretaceous time was in a very early stage (figure 5*b*). It began to rotate the Greenland and the Baffin Island sub-plates apart about a transform pivot. The rotation was accommodated by the northwestward advance of extension faults.

As the Eurekan Deformation progressed, it continued to separate and rotate apart the blocks on either side of Baffin Bay. The extension faults, however, could not readily advance northwestward because of the impediment caused by pre-existing structures. A bifurcation developed with branches deflected westward and northward. This episode reached its climactic phase (figure 5*c*) in mid-Tertiary time (between middle Eocene and early Miocene). Extension in the southeast (Eurekan Rifting Episode) caused compressional deformation farther northwest (Eurekan Orogeny).

As the Boreal Rifting Episode and the Eurekan Rifting Episode were being propagated toward each other, a plate tectonic contest developed (figure 5*c*, after Kerr 1980*a*, fig. 8). The Eurekan Rifting Episode was stronger and dominated. It produced a large area of compressional deformation in the central Canadian Arctic (figure 5*c*), which replaced the earlier extensional deformation that had emanated from the Canada Basin. Still farther west there was a large neutral area. In the extreme west, however, extension of the Boreal Rifting Episode continued uninterrupted, presumably because this was too far west to be affected by the Eurekan Deformation. The effects of the plate tectonic contest are shown in more detail in figure 6 (after Kerr 1981*b*, fig. 6). The Canadian Arctic was being fragmented into large sub-plates, each of which was itself fragmented into numerous smaller and smaller sub-plates. Extensional–compressional couples formed, in which areas of extensional deformation were transformed through pivots into areas of compressional deformation. The large area of continental lithosphere in the southeast was being stretched on a grand scale, by means of listric normal faults in upper levels of the crust and flow at greater depth. Lancaster Aulacogen developed in this stage as a westward projection into the continent, and has been documented in detail (Kerr 1980*b*).

The final severing of the North American Continent in the Arctic (figure 5*d*) resulted from the final pulse of the Eurekan Rifting Episode. This occurred in early Miocene or later time (figure 5*d*). For the first time the Queen Elizabeth Islands Sub-plate became completely surrounded by fault zones. This was achieved as faults of the Eurekan Rifting Episode broke northwestward through the continent to connect with faults that had formed earlier in the northwest by the Boreal Rifting Episode.

The Canadian Arctic Rift System is now dormant (figure 3). It became dormant when the Eurekan Deformation ceased after its final Miocene or younger pulse (figure 5*d*). Activity may have continued at sea in a minor way where the major zones of weakness of the rift system exist. However, the weak seismic activity along the system is not characteristic of plate margins, but rather is an expression of the readjustment of existing structures to the regional stress field.

Reconstructions

Reconstructions of the Canadian Arctic Rift System are shown in figure 7 (from Kerr 1981*a*, fig. 16). The conventional plate reconstruction (figure 7*b*; after Srivastava 1978) involves great displacement along Nares Strait. My own reconstruction (figure 7*c*; from Kerr 1981*b*, fig. 16) used my earlier suggestion (Kerr 1967*a*) that Nares Strait is a rift valley with minor rotational opening and minor strike-slip displacement. The history of the Nares Strait controversy was summarized recently (Kerr 1980*c*). Abundant new evidence (Christie *et al.* 1981) confirms that displacement was minor, less than 25 km.

The plate reconstruction of northeastern North America advocated here (figure 7*c*) is similar to a reconstruction made much earlier (Kerr 1967*b*). This reconstruction is part of an integrated theory of plate tectonics. It integrates two conflicting schools of thought, showing that the conventional plate tectonic theories and the oceanization theories of the fixists can be reconciled with one another. According to this integrated theory there was indeed some plate separation and it occurred by rotation; however, there also was major foundering of continental material to leave a continental remnant beneath Baffin Bay and Labrador Sea (Kerr 1967*b*, 1981*a*). The rotational separation and the related crustal foundering were accomplished by fragmenting, stretching and bending of the North American Plate. These three related processes took place on the Canadian Arctic Rift System and have recently been documented (Kerr 1981*b*). All three processes diminished and died out northwestward on that rift system. The bending occurred as the Greenland Sub-plate was rotated away from the rift system in a relative counterclockwise sense, while the main part of the North American Plate rotated clockwise relatively.

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Discussion

D. P. McKenzie, F.R.S. In the areas discussed by Price and by Kerr is there evidence of reactivation of faults during later stages of the deformation? Presumably in Price's area, if this occurred, thrusts would use the planes of pre-existing normal faults, whereas in the Canadian Arctic Islands the normal faults would follow earlier thrust or normal faults.

R. A. Price. A number of normal faults that were active in early Palaeozoic time within, rather than at the margin of, the Continental Terrace Wedge are now reverse faults, with some right-handed strike-slip motion, within the overthrust belt. Elsewhere in the overthrust belt some of the largest thrust faults juxtapose rocks of the same age, but with very different thicknesses and facies. It is probable that these thrust faults are reactivated normal faults that originally had their downthrown side towards the basin to the west.

J. W. Kerr. The present geometry of the sedimentary basins in the Canadian Arctic has been produced by the reactivation of older Precambrian faults that have moved many times. There are faults that have had as many as four phases of movement, with the sense of movement being different at different times.

J. A. Jackson. Where are the normal faults that Price has described now exposed in the field, and what do they look like in the overthrust belt? Are they to the west of the region where the seismic reflexion profiles suggest that the basement is not involved in the deformation?

R. A. Price. The normal faults are within what was the Continental Terrace Wedge. We know nothing about whether similar faults cut the Precambrian basement, except what we can discover from interpretations of gravity profiles. In the field, Upper Devonian rocks are superimposed on Middle Proterozoic in one place, yet a few kilometres away the same rocks will overlie a sequence of Lower Palaeozoic rocks up to 6 km thick. There is therefore 6 km of stratigraphic elief beneath the Sub-Devonian unconformity. This structural boundary in some places trends northeast, and can therefore be followed within individual thrust sheets. Elsewhere it trends northwest, parallel to the thrusts, and cannot be mapped.

A. W. Bally. I am inclined to agree with what Price has just said; however, it is not at all easy to observe the traces of pre-existing normal faults in the Canadian overthrust belt. They are never exposed as normal faults in an outcrop. Even if one saw a normal fault in an outcrop, it would be difficult to decide whether the fault had been formed within soft sediments and due to gravity gliding, like the growth faults of the Gulf Coast, or whether it was a tectonic feature associated with extension of the basement.

Kerr's interpretation of the Kaltag fault differs from the interpretation of other geologists now working in Alaska, who believe that the fault system that follows the Canadian Arctic slope may be a normal fault system associated with the opening of the Arctic Ocean, and not a transform fault as Kerr believes. I agree with Kerr. The structural geology of the region is

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complicated and there appear to be two fault systems, the Kaltag fault in Alaska and another one, which I will call the Boreal fault, which appears to form the northern boundary of the eastern Canadian Arctic. In my judgement, during the early Mesozoic the Boreal fault ran into the east side of the Richardson Mountains and did not join the Kaltag fault. The leading edge of the Innuitian fold belt subcrops between Prince Patrick and Banks Islands, and then continues into the Arctic Ocean, to be intersected by the Boreal fault. The same leading edge of the Innuitian fold belt reappears in the northern Richardson Mountains. Hence at some time in the early Mesozoic the Boreal fault continued into the east side of the Richardson Mountains and offset the leading edge of the Innuitian fold belt by more than 1000 km. The Richardson Mountains themselves, as P. Ziegler pointed out to me, were formed by a later inversion. The argument then suggests that the Richardson Mountain region had formed as a deep graben system in Cambrian-Precambrian time.

In early Mesozoic times, left-lateral strike-slip movements along the Boreal fault coincided with and reactivated the east Richardson Mountain fault system. Only later, during the Laramide orogeny, the fill of the earlier basin was inverted. Because of these late movements, the geometry is difficult to reconstruct and to argue which particular fault was reactivated.

A. B. Watts. Both Price and Kerr mentioned the existence of a hinge line or hinge zone in their areas. How far can this zone be followed along strike in the Canadian Cordillera?

R. A. Price. The west flank of this zone forms a large monocline in the Southern Canadian Cordillera. Across this monocline there is a stratigraphic displacement of 22 km, from Proterozoic on one side to Jurassic. I believe that this monocline was produced by draping the miogeocline over the ancient rifted margin. When one reconstructs the original geometry of the overthrust belt, the boundary between the platform rocks and the miogeocline rocks lies where this monocline now is. There is evidence of Lower Palaeozoic normal faulting within the continental terrace wedge (miogeocline), with the western sides being downthrown. Hence the boundary between the continental edge and slope was originally west of the present position of the monocline. The major boundaries trend northeast in Southern Canada, changing to north and then northwest as they extend northwards for about 300 km.

R. Stoneley. In view of the fact that Devonian to Jurassic, and even lowermost Cretaceous, sediments on the North Slope of Alaska were derived for the north, from the site of the Canada Basin, could Dr Kerr please give the evidence on which he postulated opening of the Canada Basin as early as the Mississippian?

J. W. Kerr. The main evidence that the Canada Basin began to form in Mississippian time and persisted through much of Late Palaeozoic and Mesozoic times is that the adjacent Sverdrup Basin of the Canadian Arctic Islands developed in this interval. The Sverdrup Basin formed on the outer side of a continent, being bordered by the stable continent on the southeast. It subsided because of extension faults beneath that were propagated there from a more deeply subsiding basin farther northwest. That more deeply subsiding basin farther northwest is ancestral to the Canada Basin.

The clearest facies evidence for the early existence of the Canada Basin is in the Triassic, where thick shallow-water clastic rocks grade northwest toward deeper water sediments in the direction of the Canada Basin. Faunal evidence is also supportive. Upper Palaeozoic faunas of the Sverdrup Basin are of Asiatic origin, and appear to have reached the basin via the Canada Basin.

D. G. Roberts. Recent work in the Nares Strait region to the southeast of the Sverdrup Basin shows that there has only been a limited amount of strike-slip motion between the two sides. This observation implies that Baffin Bay should be underlain by stretched continental crust. Is it possible that the pole of rotation between North America and Greenland lay close to the northern end of Baffin Bay at this time? This could explain why the deformation that Kerr has studied changes from extension in the southeast to compression in the northeast.

J. W. Kerr. The pole of relative motion certainly does lie close to where Roberts has suggested. The deformation is not, however, quite as simple as he proposes, and is complicated by the independent motion of a number of small blocks.

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