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PLUME-GENERATED TRIPLE JUNCTIONS: KEY INDICATORS IN APPLYING PLATE TECTONICS TO OLD ROCKS[1]

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ABSTRACT

Continental lithosphere—especially where stationary with respect to mantle plumes—is marked by plume-generated uplifts typically crested by volcanoes that rupture in three rifts at angles of about 120° to each other, perhaps because this configuration requires the least work. It is proposed that since the plate tectonic regime began, about 2×10^9 years B.P., divergent plate motion has commonly begun at axial dikes emplaced in rifts formed in this way. A normal course of events is that two of the rifts meeting at a junction to open by plate accretion while the third rift becomes inactive as a failed arm. The evolution of 45 selected junctions, with ages ranging back to 2×10^9 years B.P., illustrates a variety of ways in which triple junctions may develop. Bends in rifted Atlantic-type continental margins reflect the distribution of triple junctions at the time continents parted and plume traces on ocean floors lead away from these former triple junctions. Where oceans have closed by continental collision, rifts (failed arms) (aulacogens of Soviet authors), striking at high angles into orogenic belts, mark the location of former triple junctions. Reactivation of old rifts is common and new rifts have frequently developed on the sutures along which oceans have closed. Base metal mineralization, especially in the form of syngenetic copper ores, is a feature of some failed arms (Montana, Zambia, Coppermine) and others, which contain up to 10 km of marine sediment, possess some of the world's major petroleum deposits (Northern North Sea, Niger Delta, Gippsland Basin, Gulf of Suez, and Gulf of Sirte). Many of the world's great rivers flow down failed arms (Mississippi, Amazon, Niger, Zambezi, Limpopo, Rhine).

INTRODUCTION

Wilson (1968*b*) argued that, because plate tectonics operated before 200 m.y. B.P., there have been complex, interwoven cycles of ocean opening and closing. Ocean opening begins with continental rupture; study of the rupture process in Africa (Burke and Whiteman, in press) has demonstrated the existence of an evolutionary sequence from uplift, through rifting and uplift-generated triple-junction formation, to continental breakup (fig. 1). Two young episodes of rupture have been distinguished in Africa: One, the breakup of Gondwana, took place during the interval 200–100 m.y. B.P., and the other started about 25 m.y. B.P. and continues at present. The second episode has developed since the African plate came to rest over the deep mantle and has been attributed to the development of new, or invigorated, plumes (Burke and Wilson 1972). The earlier episode may have been triggered in a similar way as Brock (1970) pointed out that Africa appeared to rest with respect to the main dipole magnetic field (and hence the spin axis) from about 200 to 100 m.y. B.P.

Following Cloos (1939), Burke and Whiteman (in press) showed that in Africa, uplifts over plumes (Fig. 2*A*) develop crestal rifts typically meeting at about 120° in *rrr* (rift-rift-rift) junctions presumably because this is a least work configuration (fig. 2*B*). Less commonly, rifts develop tangentially within a swell (e.g., in East Africa) or form a four-armed (*rrrr*) junction. Rifts that reach the stage of axial dike emplacement (Griffiths et al. 1971; Baker and Wohlenberg 1971; Searle and Gouin 1972, esp. fig. 4) in some cases become accreting, or transform, plate boundaries. A common condition in Africa during the last 200 m.y. has been that one arm of an *rrr* junction ceases to develop before the spreading stage and the other two arms form a divergent plate boundary leading to accretion of new oceanic crust and upper mantle (figs. 1, 2*C*).

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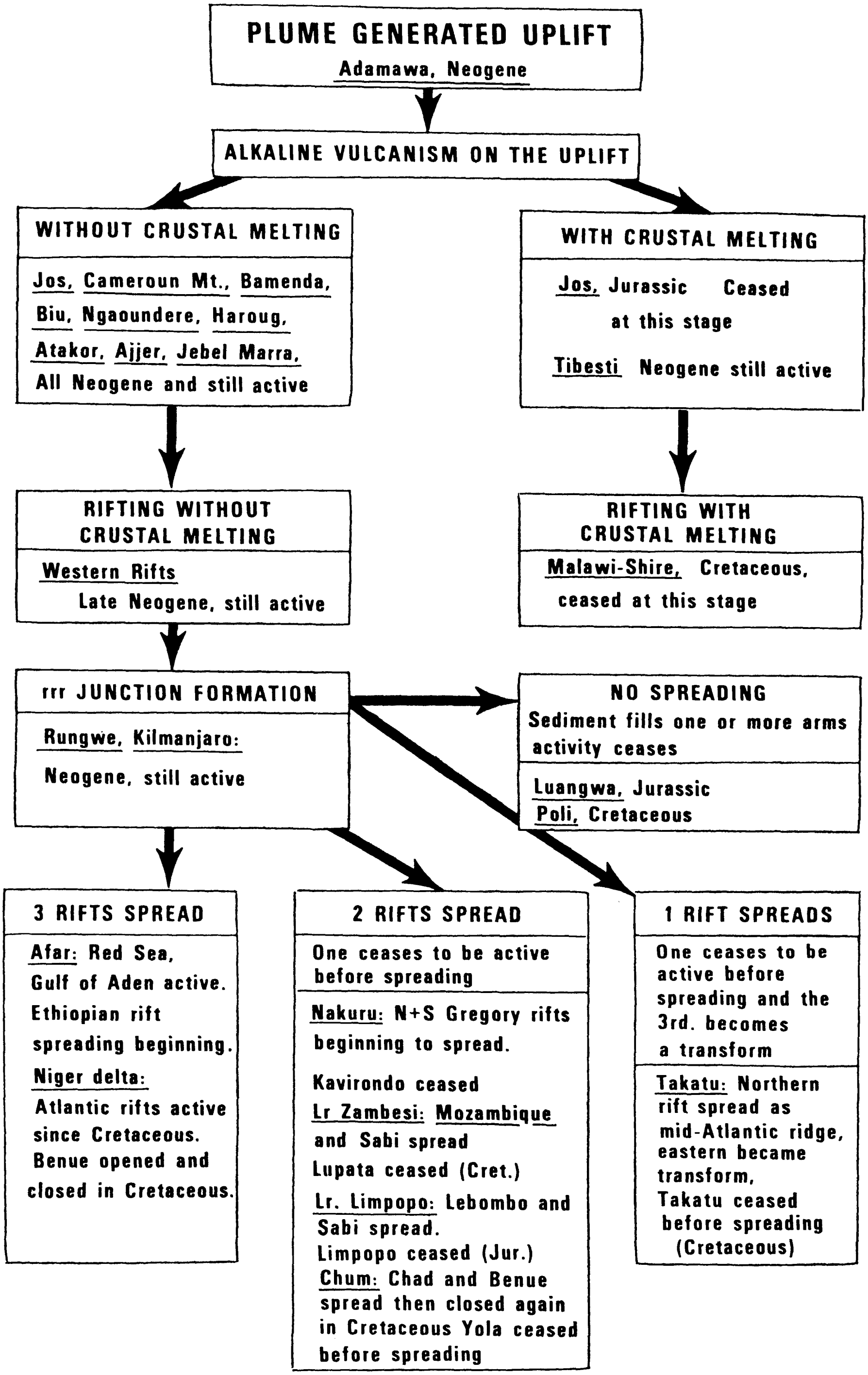

FIG. 1.—Sequences of structural development of African rift systems (from Burke and Whiteman, in press).

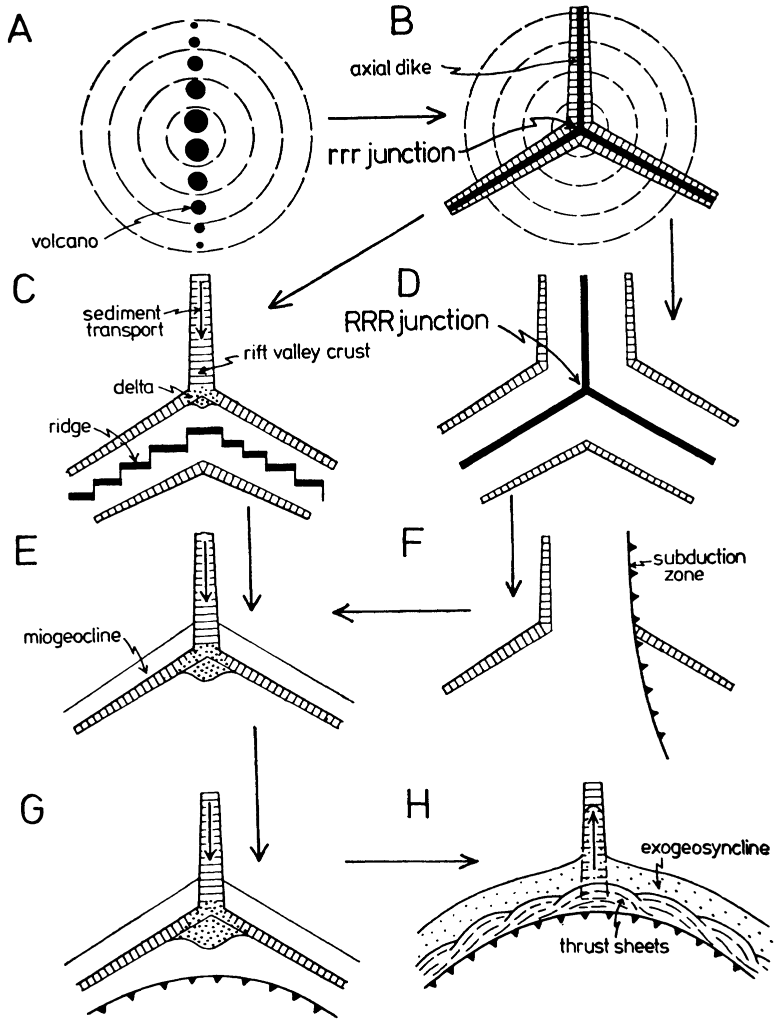

FIG. 2.—Schematic origin and evolution of plume-generated triple junctions: *A*, Uplift develops over plume with crestal alkaline volcanos (e.g., Ahaggar); *B*, three rift valleys develop meeting at an *rrr* junction (e.g., Nakuru); *C*, two rift arms develop into a single accreting plate margin (ridge) and continental separation ensues, leaving the third rift arm (failed arm) as a graben down which a major river may flow and at the mouth of which a major delta may develop (e.g., Limpopo); *D*, three rift arms develop into accreting plate margins meeting at an *RRR* junction (e.g., early Cretaceous history of Atlantic Ocean/Benue Trough relationship); *E*, Atlantic-type continental margin evolves with growth of delta at mouth of a failed arm and miogeoclines (e.g., Mississippi); *F*, one arm of *RRR* system of *D* begins to close by marginal subduction; if ocean is sufficiently wide, a chain of calc-alkaline volcanos will develop along its margin; any sediments in the closing arm will be deformed (e.g., Lower Benue Trough); *G*, Atlantic-type continental margin with miogeoclines and failed rift arms approaches a subduction zone; *H*, continental margin collides with subduction zone, collisional orogeny ensues, sediment transport in the failed arm reverses polarity, and failed arm is preserved as an aulacogen striking at a high angle into an orogenic belt (e.g., Athapuscow).

We suggest that plate motion starts when axial dikes begin to form in crestal rifts on swells overlying mantle plumes. Runcorn (1972) pointed out that, at the stage of continental rupture, forces derived from mantle convection are needed to drive plates, although later moving plates may be largely driven by gravity, either sliding downhill from an oceanic ridge (Hales 1969) or being pulled by a downgoing slab (Jacoby 1970). We believe these forces to be concentrated in mantle plumes because, as we shall show, accreting plate margins (ridges) have commonly developed from rifts, linking plume tops, in continental lithosphere ruptured by uplift. The *rrr* triple-junction pattern formed at this time is a distinctive record of continental rupture recognizable even after rocks near the junction have suffered complex structural development.

We here extend the earlier study of Burke and Whiteman to include examples of plume-generated junctions from outside Africa, covering a range of ages throughout the plate tectonic regime (the last 2×10^9 years). Because old oceans have been closed by continental collision, it is natural to include those rift structures striking at high angles to orogenic belts which have been called aulacogens (Salop and Scheinmann 1969; Hoffman 1972).

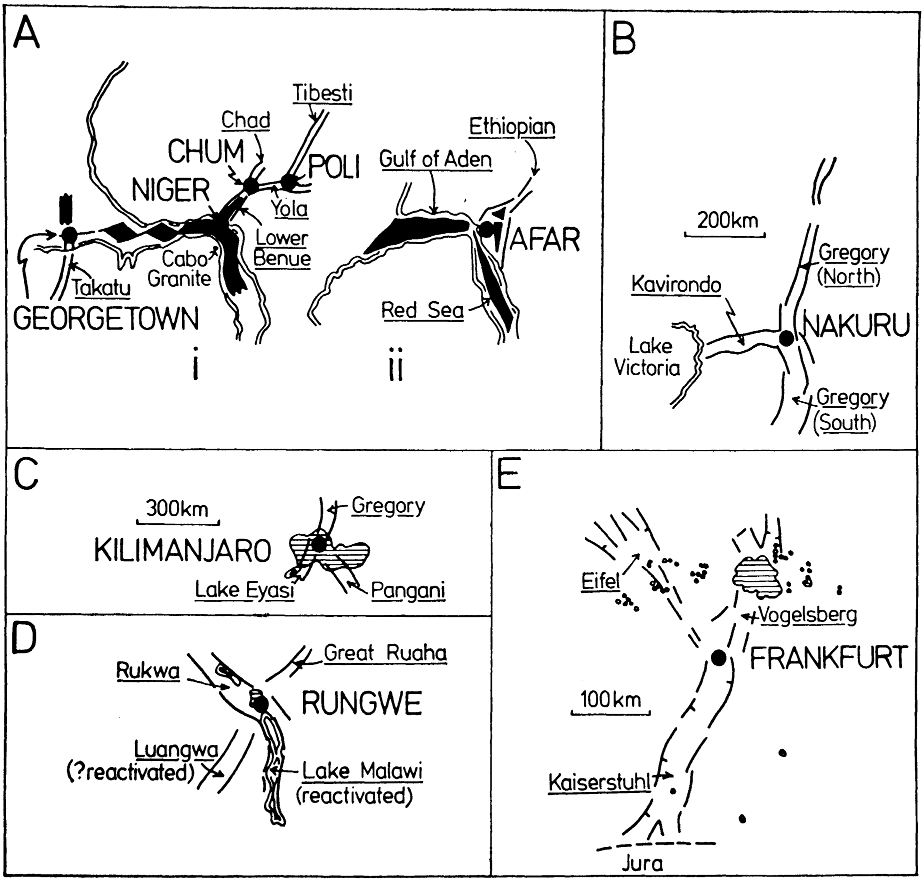

FIG. 3.—The Gulf of Guinea (*i*), 120 m.y. B.P. compared with the Red Sea now (*ii*) showing two triple junctions at the same stage of development: *B*, the Nakuru junction, *C*, the Kilimanjaro junction, *D*, the Rungwe junction, and *E*, the Frankfurt junction.

Plume-generated triple junctions are particularly useful in working out the complex plate histories of the Precambrian because of the common association in them of one rift arm with a relatively simple igneous, sedimentary, and structural history, and two arms that record a history of continental collision (fig. 2*H*).

NOTES ON SELECTED PLUME-GENERATED TRIPLE JUNCTIONS ARRANGED IN ORDER OF INCREASING AGE

Afar.—The Afar (fig. 3*A*, *ii*) is the most intensely studied of active triple junctions. Igneous activity dates back to 60 m.y. B.P. (Megrue et al. 1972). Spreading began on the Red Sea and Gulf of Aden arms 15–25 m.y. B.P. and is perhaps starting on the Ethiopian rift arm (McKenzie et al. 1970). The gravity field over the Ethiopian rift has been interpreted as indicating the presence of three axial dikes at the latitude of Addis Ababa (Searle and Gouin 1972).

South of Addis Ababa, igneous rocks of the rift are mainly alkaline; there is a transition northward and eastward across the Afar to the ridge-forming tholeiites along the axes of the Red Sea and the Gulf of Aden (Gass 1970). Detailed studies in the Afar itself have revealed a complicated pattern of magnetic anomalies and a complex distribution of fragments of continental crust (Baker et al. 1972; Girdler and Hall 1972; Black et al. 1972) which serve to show that the initiation of spreading at a triple junction is a complex process. The prime importance of the Afar is that no other active junction shows the transition from continental rift to spreading ocean so well.

Nakuru.—The East African rift valleys are disposed in a roughly tangential arrangement within the East African swell (Burke and Wilson 1972, fig. 2). We recognize no triple junctions in the western rift, where available K/Ar ages and our own field observations indicate that Neogene rifting and volcanism generally started later than in the eastern rift. Within the eastern rift system, the Nakuru junction (fig. 3*B*), at the intersection of the east-west trending Kavirondo rift and the northern and southern arms of the Gregory rift, is an example of a triple junction that has developed through the stage of uplift, with alkaline volcanism (King et al. 1972; Baker and Wohlenberg 1971, fig. 2), to rifting with further uplift of the rift shoulders and continuing volcanism. The stage of axial dike emplacement (Griffiths et al. 1971; Baker and Wohlenberg 1971) has been reached in the two Gregory arms but not, apparently, in the Kavirondo arm where volcanic activity ceased in the Pliocene. The Kavirondo rift is partly sediment filled and volcanically and tectonically inactive, although two earthquakes occurred near its western end during the period 1950–1969 (Maasha and Molnar 1972). There is some evidence indicating that the two arms of the Gregory rift may be starting to spread (e.g., Searle 1970).

Kilimanjaro.—Cloos (1939) interpreted the rift structure at Kilimanjaro (fig. 3*C*) as produced on the southern border of the Kenya uplift by the splaying of a crestal rift where it reached lower ground. The giant volcano of Kilimanjaro at the intersection of the Gregory, Lake Eyasi, and Pangani rifts may prove to be a center of further uplift, so that even if the structure originated in the way Cloos suggested, it may develop in the future into a crestal triple junction.

Rungwe.—The Rungwe structure consists of the well-developed Lake Rukwa and Lake Malawi rifts with the less obvious Great Ruaha rift that strikes northeastward into Tanzania (fig. 3*D*). The structure lies in a topographically high area and is marked by the Rungwe volcanic rocks of Pliocene to Recent age (Harkin 1959) concentrated near the junction. The Rukwa rift extends northeastward to join the western rifts, initiated much later than the eastern rifts. The active Lake Malawi rift reactivates a

Cretaceous rift and provides a link between the Neogene East African rift system and the Jurassic and Cretaceous structures contemporary with the breakup of Gondwana farther south. There is some evidence (McConnell 1972) of Neogene activity along the Jurassic Luangwa rift. If this is so, the Rungwe is a four-armed junction.

Frankfurt.—The Frankfurt junction (Cloos 1939) consists of three arms with Recent faults and earthquakes (fig. 3*E*). Only the Rhine graben in the middle Rhine valley has classical rift-valley topography. Young volcanism is concentrated close to the junction in the Eifel and the major shield volcano of the Vogelsberg. About 20 m.y. B.P. volcanism was greatest 200 km to the south around the Kaiserstuhl (Burke et al. 1973). No evidence of spreading or axial dike emplacement has been reported from the three arms of the Frankfurt junction, although the Rhine graben is underlain by low velocity mantle (Mueller et al. 1969).

Irkutsk.—The Lake Baikal rift, like the western rift of East Africa, may be too young to have developed triple junctions, but the shape, structure, and rocks of the Angara valley, trending northward away from Lake Baikal (fig. 4*A*) and containing fault-bounded volcanic rocks including trachybasalts (Pavlovsky 1969), suggest that there may be a triple junction south of the city of Irkutsk. Spreading does not appear to have begun on any of the arms of the Irkutsk junction.

Sharm-el-Sheik.—While the Afar junction at the southern end of the Red Sea is

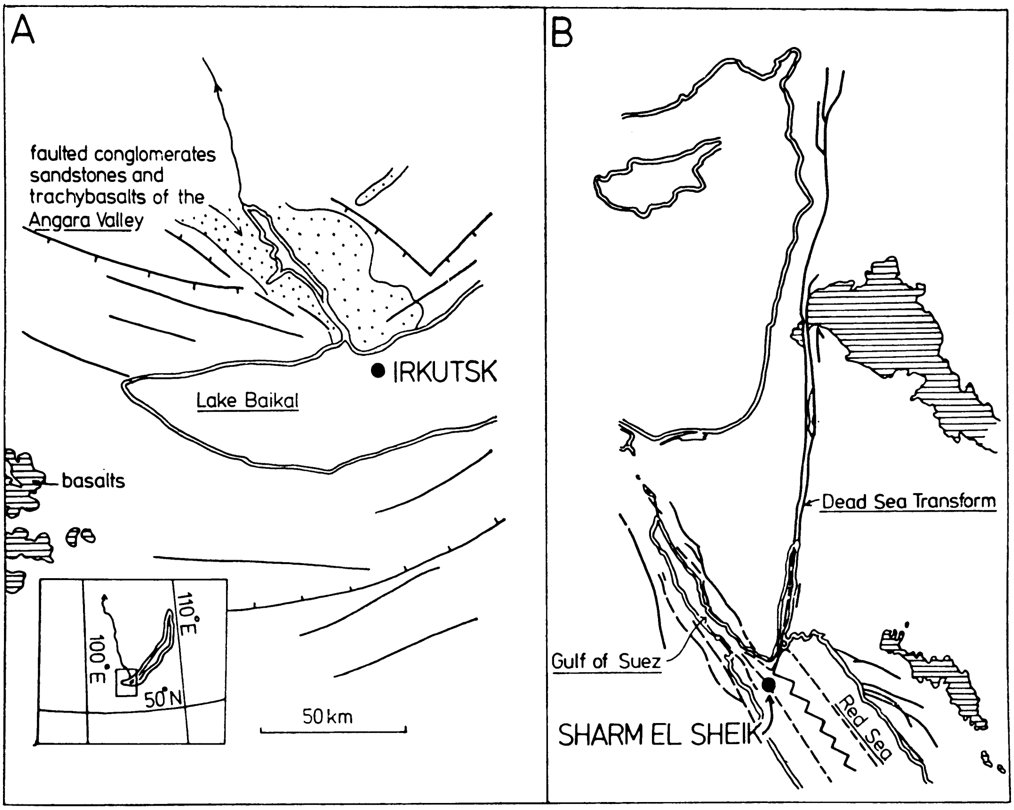

FIG. 4.—*A*, The Irkutsk junction (inset shows position of the area); *B*, the Sharm el Sheik junction.

developing as an *RRR* junction (McKenzie and Morgan 1969) with spreading on three arms, the Sharm-el-Sheik junction at the northern end (fig. 4*B*) is developing by spreading on only one arm, the Red Sea, with transform motion on a second, the Dead Sea. The third arm, the Gulf of Suez, ceased to develop before the spreading stage and resembles many other "failed arms" of triple junctions in containing a thick pile of sediments. About 4 km of Neogene salt, limestone, and clastic sediments were deposited in the Gulf of Suez during the development of the more active arms of the junction (Heybroek 1965). We interpret this and similar thick sediment accumulations within failed arms as a result of modification of the lithosphere initiated during the uplift stage of the development of the triple junction. The Ras Morgan oilfields in the Gulf of Suez are one of many major oil accumulations to be found in the failed arms of triple junctions.

Kangerdlugssuak.—Two arms of this junction (fig. 5*A*) developed to the extent of continental rupture about 60 m.y. ago. Although a large volume of sediment has been eroded off Greenland to build the miogeoclinal continental shelf and rise of the Denmark Strait, the trend of original rifting is indicated by the strike of the coastal dike swarms mapped by Wager and Deer (1938). Cloos (1939) pointed out that the Greenland continental margin flexure, revealed by the gentler dip of the more seaward dikes in the swarm, is very similar to the Lebombo monoclinal flexure (see *below*). Coastal flexures of this kind commonly mark arms of junctions that have developed to the ocean opening stage but they are not normally exposed on land. The Panvel flexure on the Bombay coast of India (Auden 1972) and the flexure affecting the Adigrat sandstone on the eastern flank of the Ethiopian Afar (Dainelli 1943; Black et al. 1972) are examples of exposed continental margin flexures.

The third arm of the Kangerdlugssuak structure trends northwestward and is marked by a depression of the bedrock under the Greenland Icecap (Escher 1970). No sediments are recorded from this arm, which is best known for its tholeiitic (Skaergaard) and alkaline (Kap Edvard Holm) intrusions (Wager and Brown 1968; Deer, in preparation). Plume igneous

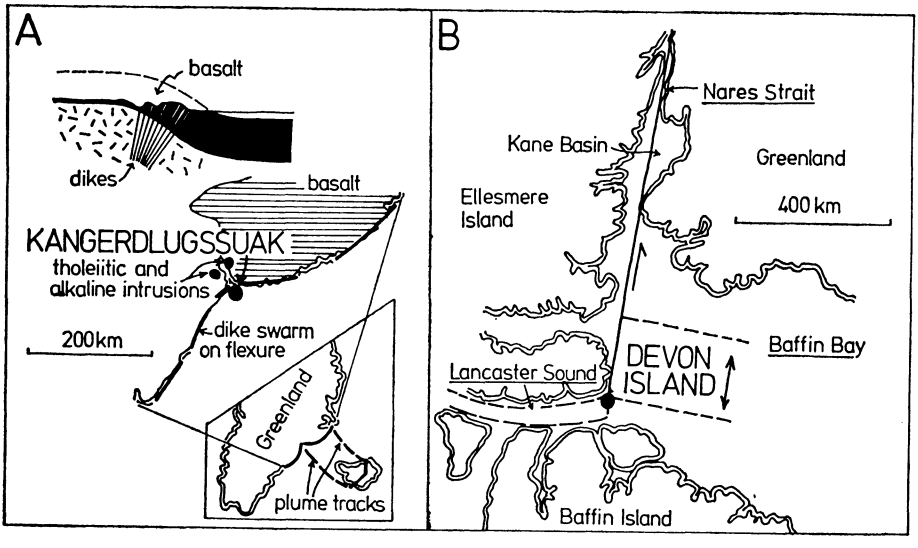

FIG. 5.—*A*, The Kangerdlugssuak junction; *B*, the Devon Island junction.

activity typically includes both tholeiitic and alkaline elements, presumably representing material partially melted and equilibrated at different depths. The Kangerdlugssuak plume trace leads to Iceland (Burke et al. 1973).

Devon Island.—Wegener (1929) recognized this junction (fig. 5*B*) and his interpretation has been elaborated by Wilson (1963), Pitman and Talwani (1972), Keen et al. (1972), and in a comprehensive review of the area by Trettin (1972). Most writers consider that there has been between 150 and 250 km of left lateral transform motion along the Nares strait and that Baffin Bay opened in the late Cretaceous/early Tertiary to form an ocean. We suggest that Lancaster Sound, forming the third arm of the Devon Island junction, became inactive before reaching the spreading stage. Mainly as a result of detailed stratigraphic studies on Ellesmere Island, Kerr (1967), has interpreted the development of this junction without transform motion along the Nares strait and Trettin (1972) suggests that relations between Greenland and Ellesmere remain problematic. There is evidence of older development in Lancaster Sound where little, if any, of a thick sediment sequence appears to have accumulated during the late Mesozoic/early Tertiary junction development. The "relatively low velocity section" in Eastern Lancaster Sound (? later-Palaeozoic) is over 1,500 m thick and magnetic estimates indicate a total sediment thickness of over 6 km in an assymetric graben with prominent faulting on the northern margin (Barrett 1966; Parmenter 1972; Pallister and Bourne 1972).

W. C. Pitman III (personal com-

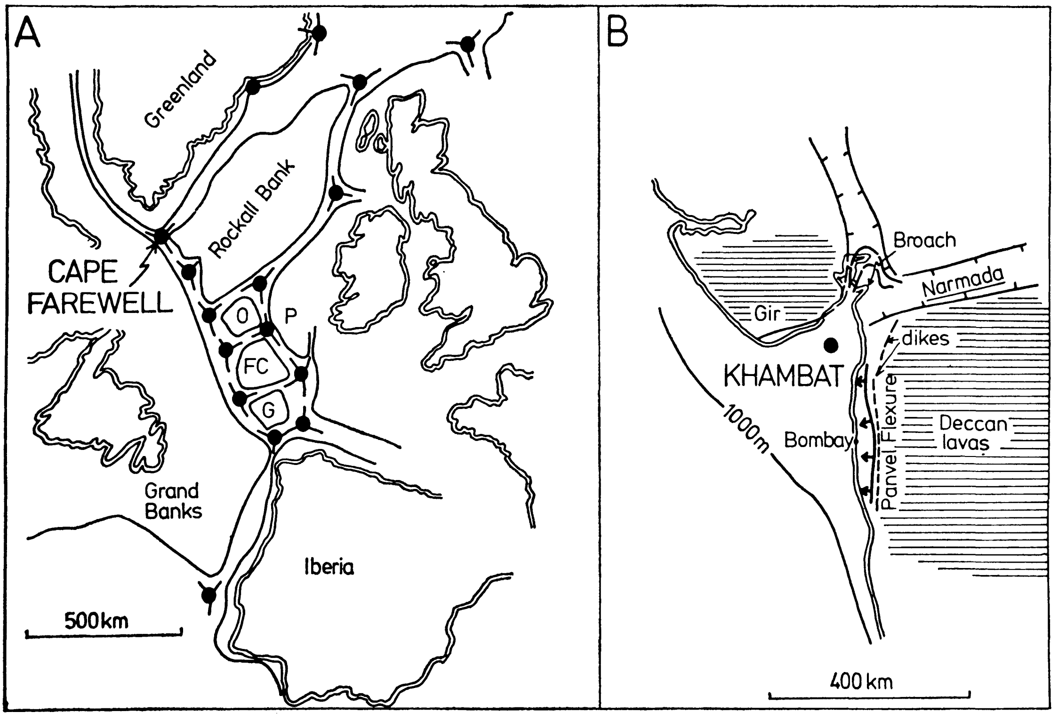

FIG. 6.—*A*, Fifteen *rrr* junctions and one *rrrr* junction in the North Atlantic (based on Laughton 1972, fig. 19, except for the five northern junctions): *FC* = Flemish Cap, *G* = Galicia Bank, *O* = Orphan Knoll, *P* = Porcupine Bank; *B*, The Gulf of Khambat junction.

munication, 1972) has pointed out that Lancaster Sound and its westward continuations (Barrow strait, Viscount Melville Sound, and Maclure strait), describe a small circle about a pole near the North Geographic Pole and therefore that these waterways probably mark a transform fault. The transform fault must be quite old as there is little evidence of Palaeozoic, or later, offset along Lancaster Sound. It is probable that the latest transform motion here was during the Pre-Cambrian.

Cape Farewell.—This junction, named for the southernmost point in Greenland, is one of 15 illustrated in figure 6*A*. It may have been initiated in the Jurassic at a time of minor rifting (Pitman and Talwani 1972; Laughton 1972). However, the first major phase of spreading occurred in the Labrador Sea between late Cretaceous and late Eocene times. Spreading south of the Cape Farewell junction during the late Cretaceous (Laughton 1972, fig. 16) was roughly parallel to that in the Labrador Sea, but there may have been about 50 km of left lateral transform offset along the rift between Greenland and the Rockall Bank by that time.

In Paleocene times, spreading began on the Reykjanes ridge; all three arms of the Cape Farewell junction spread until the Middle Eocene. Since then, there has been no further spreading in the Labrador Sea but spreading has continued on the Reykjanes ridge and in the central North Atlantic. A bend in the Mid-Atlantic Ridge at about 56°N marks the inherited morphology of two arms of the junction. The Cape Farewell junction is a young, well-known feature still in the ocean opening stage. It is worth emphasizing that its complex development with rifting, transform motion, and spreading taking place on different arms at different times has probably been paralleled by older junctions. However, evidence for developing such a history was destroyed in continental collision.

The pattern of triple junctions that we have sketched on one of Laughton's (1972, fig. 19) alternative Jurassic reconstructions of North Atlantic paleogeography is striking. The area over which rifts originally developed was about the same as that of the modern East African swell (about 1,000 km by 1,500 km). Each of the six junctions down the west side of the Atlantic consists of two straight arms striking NNW and a third at right angle trending arms have the better spreading record and some of the ENE structures have spread very little.

The failed arm in the northern North Sea between Norway and Scotland resembles the Gulf of Suez and Gippsland failed arms in containing a thick section (6 km) of oil-bearing marine sediments. Other, as yet unexplored, failed arms around the North Atlantic and elsewhere may also prove to contain major hydrocarbon deposits.

Khambat.—This four-armed junction is related to the opening of the Arabian Sea (fig. 6*B*), in this area perhaps a Paleocene or Eocene event (McKenzie and Sclater 1971; Auden 1972). The Bombay arm is parallel to the Panvel continental margin flexure (Auden 1972) and we suggest that a similar flexure parallels the Gir coast. Alkaline igneous activity is concentrated close to the junction itself in the plutonic centers of Broach and Baroda, although the tholeiitic Deccan lavas spread over a huge area around the structure. It seems probable that the miogeoclinal continental shelf of the Gulf of Khambat overlies oceanic crust. The angular piece of continent that has been removed from the gulf perhaps now lies at the Seychelles (Davies 1968). The plume responsible for the junction may be the Mauritius-Reunion plume, with the Chagos-Laccadive islands forming the older part of the plume trace (Burke and Wilson 1972). The Narmada arm of the Khambat junctions extends eastward to join the Gondwana Asondamodar graben (Tectonic Map of India 1968 and fig. 9*A*) and it may be that the Khambat structure, like the

Rungwe, owes its four-armed character to rejuvenation of an old rift.

Bass Strait.—The Bass strait triple junction formed in relation to the opening of the Tasman Sea, which took place between 80 and 60 m.y. ago (Hayes and Ringis 1972). The Gippsland basin, forming the third arm of the junction, shows no sign of opening but contains 4 km of Cretaceous and Tertiary hydrocarbon-rich sediment (fig. 7*A*). The Mount Gambier and Otway basins on the west side of the Bass strait (fig. 7*D*) are related to the somewhat later opening of the Southern Ocean that continues to spread.

Although Tasmania forms part of the Australian continent, it could have been split off if the Otway and Gippsland arms had reached the stage of axial dike emplacement and had then spread. There is a clear resemblance to Ceylon that forms part of the Indian continent but is separated from it by failed arms of the Trivandrum and Palk junctions (see *below* and fig. 6*C*). There appears to be a gradation from structures like these through those like Flemish Cap to isolated bodies of continental crust like the Galicia Bank and Orphan knoll (fig. 6*A*).

Niger delta.—The best-known fact of continental drift is that the right-angle bend of the shoulder of Brazil fits into the

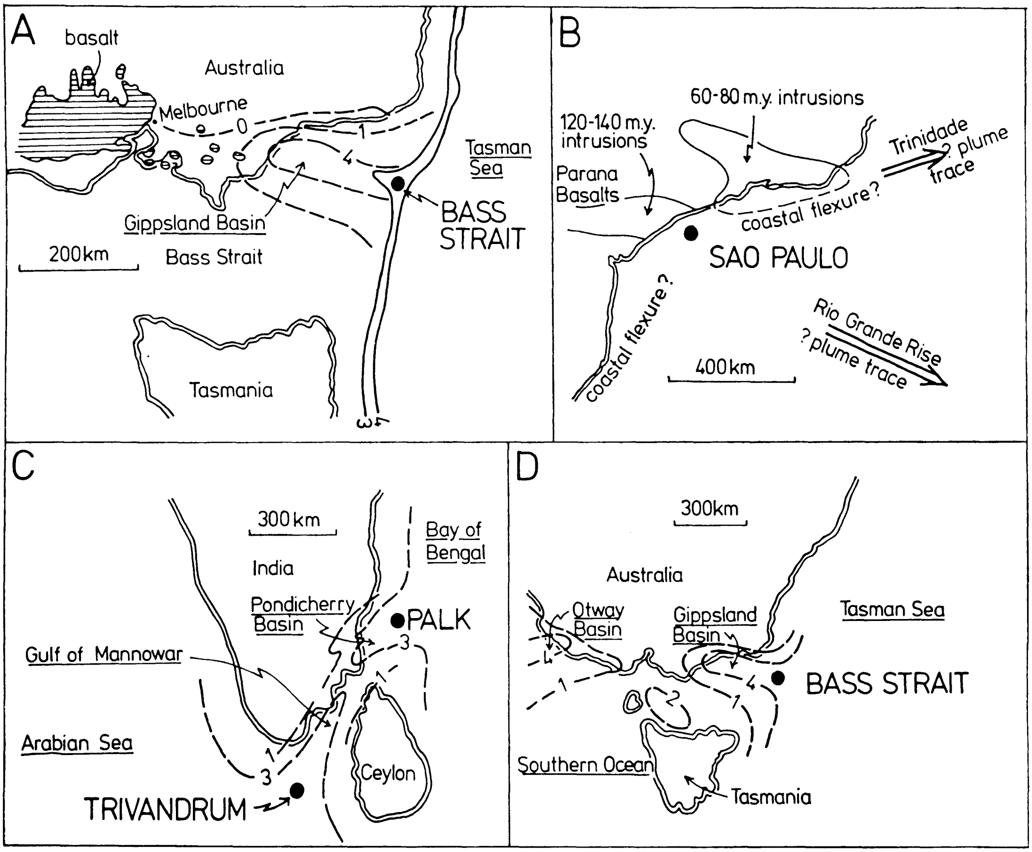

FIG. 7.—*A*, The Bass Strait junction (contours in kilometers on base of Cretaceous/Tertiary sequence of Gippsland Basin; bathymetric contours in kilometers at margin of Tasman Sea); *B*, the São Paulo junction; *C*, the Trivandrum and Palk junctions; *D*, the Otway and Gippsland Basins (contours in kilometers on base of Cretaceous/Tertiary sequence).

Gulf of Guinea at the Niger delta (Snider 1859; Bullard et al. 1965). Many triple junctions (see, e.g., figs. 3, 5*A*, 6*A*, 7*B*) lie at less conspicuous bends along the margins of continents and it seems likely that the distribution of triple junctions controls the shape of continental margins.

The Niger delta triple junction spread from 120–80 m.y. (fig. 3*A*, *i*) on three arms. The Benue trough arm then closed, with a short-lived subduction episode, and the South Atlantic and Gulf of Guinea arms have continued to spread—the latter through development of the giant equatorial transforms (Burke and Whiteman in press; Burke et al. 1971, 1972. We regard the Cabo granite (Almeida and Black 1972) of Lower Cretaceous age in Brazil as a product of the Niger delta plume. There is no clear plume trace from the Cabo granite, but this may be related to a weakening of the plume following partial melting of continental crust (Burke and Whiteman, in press). However, any plume trace would be hard to see through the area of the giant transforms of the equatorial Atlantic.

Georgetown.—West of the giant transforms, and determining another bend in the African coast, lies the Georgetown junction (fig. 3*A*, *i*) due north of the Takutu rift (McConnell et al. 1969; McConnell 1969). In Guyana, this rift is filled about 2 km deep with Cretaceous sandstones and underlying volcanics. It does not appear to have reached the axial dike or spreading stages. The Gulf of Guinea arm developed through transform motion and the Atlantic arm, opposite the bulge of Africa, by spreading.

Chum.—About 600 km up the Benue trough from the Niger delta, the rift structure splits close to Chum (Burke and Whiteman, in press). Eastward from the junction, only about 300 m of gently folded Cretaceous sediments occupy the Yola rift (fig. 3*A*, *i*). Trending north from the junction, the Chad arm contains a thicker, more strongly-folded section. Bouguer anomaly maps (Cratchley and Jones 1965; Louis 1970; Ajakaiye and Burke 1973) show that the Benue structure extends along the north-trending rift to die out under the Chad basin. The Chad and Benue arms spread and later closed in the Cretaceous but the Yola arm became inactive without spreading.

Poli.—The Poli junction is poorly defined at outcrop. The Yola arm extends eastward for 500 km from Chum as a series of shallow Cretaceous sediment-filled troughs (Burke and Whiteman, in press). Its continuation farther east is not known at outcrop but a 100-km wide belt of 50 mgal negative Bouguer anomalies (Louis 1970) that extends for another 800 km through Fort Archambault is believed to mark a rift continuation filled with Cretaceous sediments. Louis also mapped a remarkable 1,500 km-long line of positive Bouguer anomalies from Poli northward to the Tibesti; we suggest this marks a rift forming a third arm of the Poli structure. This feature lies almost entirely under the thin Neogene sediments of the Chad basin. Typically, profiles 50 km long across the feature show 50 mgal positive anomalies. Louis used a density contrast of 0.3 in model studies of the anomaly and we suggest that it is caused by axial dikes emplaced in a rift that did not spread. The similarity of the Bouguer anomalies in the Kenya and Ethiopian rifts to those in this feature is striking (Burke and Whiteman, in press). Older features with gravity fields similar to those of axial dikes are the mid-continent anomaly in the United States and the Great Dike of Rhodesia.

São Paolo.—The São Paolo junction is marked by two continental margin flexures on the east coast of South America and by a line of alkaline igneous rocks leading from the Brazilian coast toward the Paraná basalts (fig. 7*B*). This arm contains alkaline intrusives about 140–120 m.y. old (Amiral et al. 1967). The trace of the plume responsible extends southeastward along the Rio Grande rise. We interpret a group of alkaline rocks clustering around

Rio de Janeiro, about 200 km east of São Paolo, as one end of a younger plume trace that first made its presence felt 60–80 m.y. B.P. after a radical change in the direction of motion of the Americas plate with respect to the plume population. This plume now underlies Trinidade and Martin Vaz about 1,500 km to the east.

Trivandrum.—The Trivandrum junction lies about 1,000 km south of the Khambat junction on the west coast of India (fig. 7*C*). Continental margin flexures form the Malabar coast and the southwest coast of Ceylon. The third arm is a 350-km-long, NNE-trending depression, the Gulf of Mannowar, separating Ceylon from India and containing more than 3 km of Mesozoic and younger sediment. The relationship of the Gulf of Mannowar to the Pondicherry basin (fig. 6*C*) resembles that between the Otway and Gippsland basins (fig. 7*D*). Undersea topography indicates that there may have been left lateral transform motion through the Gulf of Mannowar.

Luangwa (*mid-Zambesi*).—A 30° bend in the course of the Zambesi River marks the junction of two rift arms and from this point the Luangwa rift strikes northeast (fig. 8*A*). Karroo sediment is found in all three arms that meet at this junction where igneous activity has taken the form

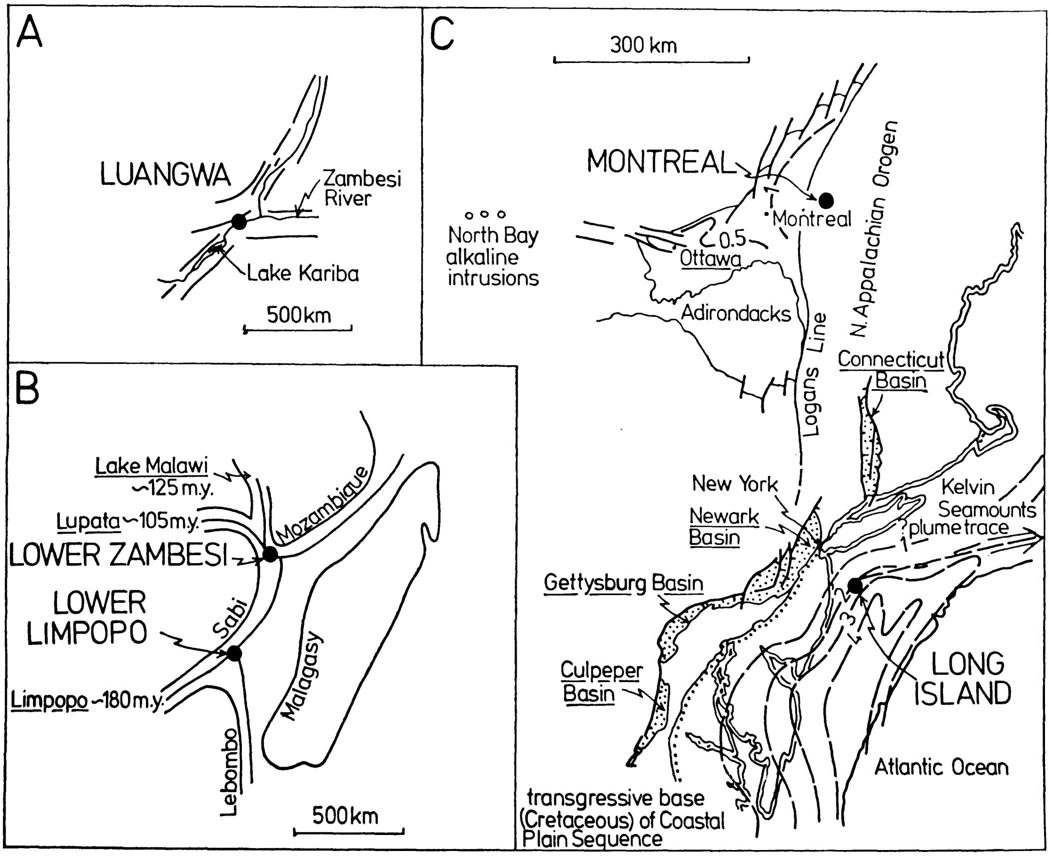

FIG. 8.—*A*, The Luangwa junction; *B*, the Lower Zambesi and Lower Limpopo junctions; *C*, the Montreal and Long Island junctions (contours in kilometers on base of lower Paleozoic sequence in the St. Lawrence Valley; contours in kilometers on base of Mesozoic through Recent continental margin sequence).

of carbonatite intrusion (Bailey 1961) and flood basalts. The junction ceased to be active and all three arms were filled with sediment without spreading. Development appears to have been completed by the end of the Jurassic.

Lower Zambesi.—The Lower Zambesi (Woolley and Garson 1970) structure has four arms (fig. 8*B*). The eastward-directed arm cuts steeply across the trend of the Mozambique belt (Holmes 1951) to the Mozambique channel. Because the basement falls steeply to a depth of 2,000 m across this arm (ASGA/UNESCO 1968), we suggest that it is a continental margin flexure and designate it the Mozambique monocline. The south-trending arm of the structure is the northern part of the Sabi monocline. Between these two monoclinal features lie the Shire-Malawi and Lupata rifts. The Malawi rift is an area of abundant, immediately subvolcanic igneous activity from which Woolley and Garson (1970) reported 10 ages averaging about 125 m.y. The Lupata arm is a less deeply eroded structure containing Karroo and Cretaceous sediments and volcanic rocks. Four ages from the Lupara Cretaceous average 115 m.y. The very large volumes of Cretaceous alkaline syenite in the Malawi rift may indicate an element of crustal melting, a process that has been argued elsewhere (Burke and Whiteman, in press) to impede, or halt, the structural evolution of a junction.

Figure 8*B* illustrates the suggested relationships (after Burke and Whiteman, in press) between the Lower Zambesi and Limpopo structures and Madagascar. Most Indian Ocean reconstructions restore Madagascar to a position considerably north of its present latitude. This is hard to justify because transform motion in this part of the Indian Ocean was in an NNE direction prior to the generation of anomaly 13 (35 m.y. B.P.; McKenzie and Sclater 1971). No trace of a structural framework within which Madagascar can be moved first south and then north can be detected. The Mozambique, Sabi, and Lebombo monoclines mark the northwestern sides of three rift arms that spread to move the microcontinent toward the southeast. Because the Limpopo structure started to develop before the Zambesi structure, the southeasterly spreading also involved some anticlockwise rotation. Later transform motion brought Madagascar north-northeastward to its present position.

Lower Limpopo.—The Limpopo structure (fig. 8*B*) consists of the Sabi and the Lebombo monoclines (Cloos 1939) and the Limpopo rift, which contains alkaline volcanic rocks in the Tuli syncline and immediately subvolcanic rocks in the Nuanetsi and Marangudzi complexes (Cox 1970, 1972; Woolley and Garson 1970). The Limpopo igneous rocks yield Karroo ages. Like the Lower Zambesi arm, the Limpopo rift ceased to function without spreading.

Long Island.—The Long Island four-armed junction (fig. 8*C*) consists of the Connecticut and Newark graben with thick fluviatile and lacustrine sediments, alkaline and tholeiitic intrusives, and two continent margin flexures. The plume trace forms the Kelvin seamount chain. Rifting in the arms that did not spread began about 200 m.y. ago; spreading in the Central Atlantic started about 180 m.y. ago (Pitman and Talwani 1972).

Cuttack.—The Cuttack junction lies on the east coast of India where the Mahanadi graben (fig. 9*A*), of Gondwana age, joins two continental margin flexures of the Bay of Bengal. A maximum of 3 km of sediment has accumulated at the junction (Tectonic Map of India 1968). The opening of the Bay of Bengal has not proved easy to date and may have occurred at any time between the Permian and the lowest Cretaceous (Veevers et al. 1971).

Guntur.—About 500 km southeast of Cuttack, where the Godavari graben reaches the Bay of Bengal, over 4 km of Mesozoic and Tertiary sediments have accumulated at the edge of the continent (fig. 9*A*). On either side of the junction,

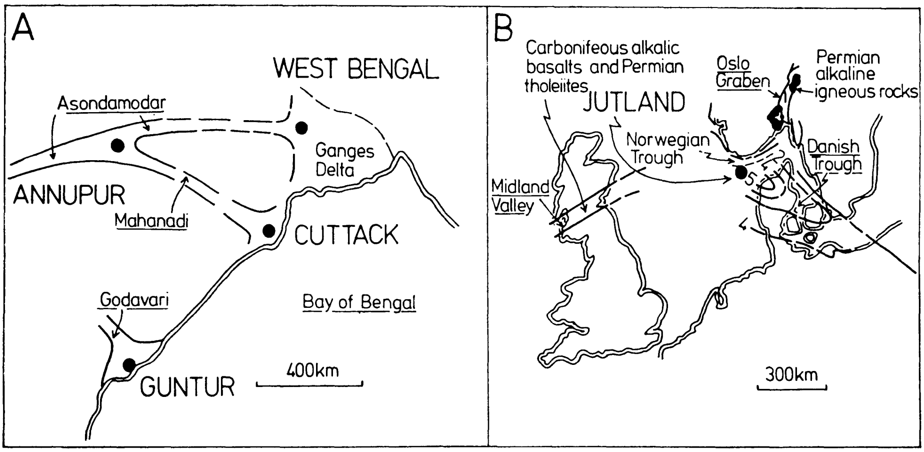

FIG. 9.—*A*, Junctions of eastern India and Bangla Desh; *B*, the Jutland junction (contours in kilometers on base of Mesozoic/Tertiary sequence of Danish Trough).

miogeoclinal accumulations along the continental margin flexure are thinner and confined to offshore areas. Along the continental margins of opening oceans, it is common for the coastline to change direction at triple junctions (see, e.g., fig. 3*A*, *i*). Here (fig. 9*A*) there is a 45° change from a northwesterly to a north-south trend.

Palk.—The Palk junction (fig. 7*C*) lies opposite the Trivandrum junction. The Pondicherry failed arm, which contains a maximum of 4 km of sediment, extends toward the Mannowar basin. The continental margin flexures again change trend slightly across the junction.

West Bengal (*buried junction*).—The eastern end of the Asondamodar graben lies under Ganges delta alluvium (fig. 9*A*). Subsurface indications (Tectonic Map of India 1968) show that the graben extends into an area around Calcutta where basement is warped down to 8 km below sea level. This structure appears to mark an extension of the continental margin northward from the Cuttack junction. The Ganges delta in Bangla Desh thus overlies oceanic crust. The occurrence of growth faults in the delta is consistent with the suggestion that it is underlain by oceanic crust since these structures are restricted to deltas with about 4 km of freeboard (Burke 1972).

Annupur.—The Asondamodar and Mahanadi graben (fig. 9*A*) join within the Indian continent near Annupur. Gondwana rocks overlie crystalline basement in all three arms and there is no indication that any of the rifts reached the stage of axial dike emplacement.

Jutland.—Permian faulting, tholeiitic igneous activity and nonmarine sediment deposition are well known in the Midland Valley of Scotland (Dunning 1966) and, similarly, Permian faulting and alkaline igneous activity in the Oslo graben. Neither rift reached the spreading stage, but Ramberg's (1972) gravity and magnetic study indicates the presence of an axial dike some kilometers deep in the crust below the Oslo graben. Both rifts trend toward a junction off Jutland (fig. 9*B*) from which a third structure, the Danish Trough trends southeast. This feature is marked by the maximum accumulation of Zechstein salt (Sanneman 1968).

Jackson.—The opening of the Gulf of Mexico has left its mark in the prominent basement dislocation downthrowing toward the gulf at a depth of about 6 km in Texas, Arkansas, and Mississippi (fig. 10).

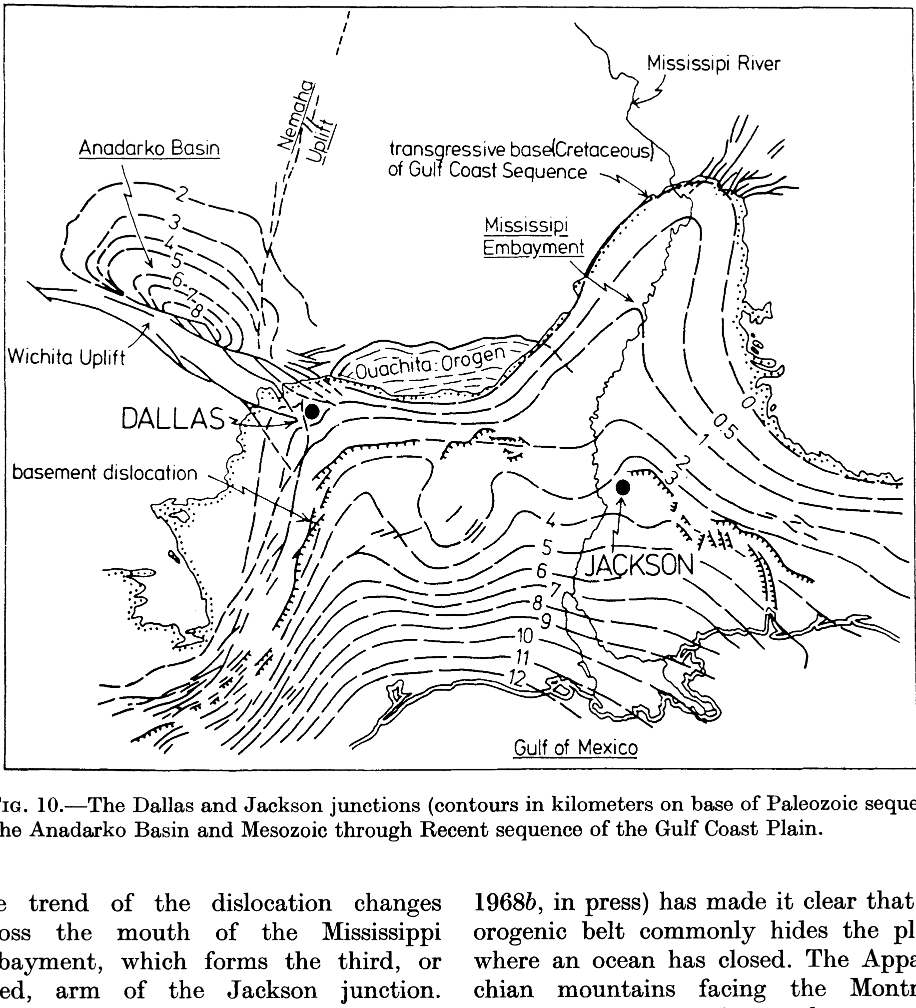

FIG. 10.—The Dallas and Jackson junctions (contours in kilometers on base of Paleozoic sequence of the Anadarko Basin and Mesozoic through Recent sequence of the Gulf Coast Plain.

The trend of the dislocation changes across the mouth of the Mississippi embayment, which forms the third, or failed, arm of the Jackson junction. Marine rocks in the embayment may be as old as Permian; a thick, almost continuous, succession of sediment has been deposited in the embayment throughout Mesozoic and Tertiary time. Although the embayment has steep flanks, there is no evidence of rifting along its length or of dike emplacement. At the head of the structure lead/zinc mineralization is associated with faults parallel to its length.

Montreal.—Thus far, all junctions discussed in this paper that have reached the spreading stage, lie at the edge of oceans. Montreal (fig. 8*C*) is the first junction discussed that lies at the edge of an orogenic belt. Wilson (1963, 1966, 1968*a*, 1968*b*, in press) has made it clear that an orogenic belt commonly hides the place where an ocean has closed. The Appalachian mountains facing the Montreal junction contain evidence of a complex sequence of events, including island arc development (Bird and Dewey 1970) and small ocean basin opening and closing (Dewey and Bird 1971) after the "Proto-Atlantic" had opened (Wilson 1963) and before it shut (Dewey and Burke 1973). Because of this complex series of events, the record of development of the Montreal junction is less distinct than that of many younger junctions but, like other old junctions, it records a complete cycle of events from continental rupture to ocean closure.

The Ottawa-Bonnachere graben (fig. 8*C*; Kay 1942) is the failed arm of the Montreal junction. The arms that opened to the scale of an ocean have been completely destroyed in later events. Sediments of the Appalacian shelf and miogeocline were formed during the opening and record in some detail how it happened, but exactly where the opening rifts lay is now impossible to deduce. About 1 km of Cambrian and Ordovician sediments, mainly limestones with some basal sandstones, have been deposited in the graben near Montreal and about 0.5 km near Ottawa (fig. 8*C*). The line of the graben is marked by faults and alkaline intrusions, including carbonatites, as far as North Bay, about 300 km to the west (Doig 1970).

Some idea of the North American coastline of the "Proto-Atlantic" can be gained from the distribution of alkaline rocks and carbonatites with ages that cluster around 550 m.y. (Doig 1970, fig. 4). There appear to have been triple junctions west of Saguenay and around Cape Farewell, the latter related to a failed arm that extended roughly up the axis of what would become the Labrador Sea. nearly 500 m.y. later. The Loch Borolan intrusions in northwest Scotland (Dunning 1966) perhaps indicate the position of another failed arm farther east. On the other side of the early Paleozoic ocean, alkaline intrusives mark the positions of contemporary junctions near the Oslo graben and Gulf of Bothnia.

Dallas.—The Dallas junction (fig. 10) is an example of a junction that has evolved to the stage of collision and has later been partly destroyed through the opening of a younger ocean. The Anadarko basin (King 1969) formed as the rift arm of a junction at the margin of the opening "Proto-Atlantic" in the early Paleozoic, roughly at the same time as the Ottawa-Bonnechere graben. The basin now contains a maximum of 10 km of relatively undisturbed sediment; in the lower part limestone predominates. After the Variscan Ocean closure (Dewey and Burke 1973), coarse clastics derived from the Amarillo-Wichita uplift and the Ouachita collisional orogen flooded the basin. The opening of the Gulf of Mexico through the development of the Jackson junction has removed a part of the collision orogen to an as yet unidentified location. The Nemaha ridge (fig. 10) is a pronounced, structurally positive feature; it may overlie a rift that attained the stage of axial dike emplacement but failed to spread. If so, the Dallas structure is a four-armed (*rrrr*) structure.

Michipicoten.—Within the 200-m.y. interval between 1,300 and 1,100 m.y. B.P., widespread rifting affected a large continental mass, part of which now forms the North American Shield. The North American continent, including Greenland, was blocked out by these rifts in a form not very different from that of today (fig. 11*A*). Spreading on western rifts opened the "Proto-Pacific" and spreading on eastern rifts (now completely destroyed) opened a Grenville ocean, which was closed by continental collision with a Tibetan-type reactivation event about 950 m.y. ago (Dewey and Burke 1973).

The Michipicoten junction was formed about 1,100 m.y. B.P., but none of its arms reached the spreading stage. The Keweenawan arm (Symposium 1972) and its extension southwestward into the area of the mid-continent gravity high are well known. Many writers have likened the Keweenawan to a rift; we have argued elsewhere (Burke and Dewey, in press) that structures like the Keweenawan may be the result of short-lived spreading at a rift axial dike leading to ocean opening of a few tens of kilometers. Basalt and sediment filling the young ocean produce a crust of continental thickness that is nonsubductable and can therefore be preserved within a continent.

The second arm of the Michipicoten junction is marked by reactivation of the Kapuskasing structure in Ontario. This feature is a structural high marked by gravity and magnetic anomalies that brings granulitic rocks to the surface. Carbonatites and alkaline intrusions were

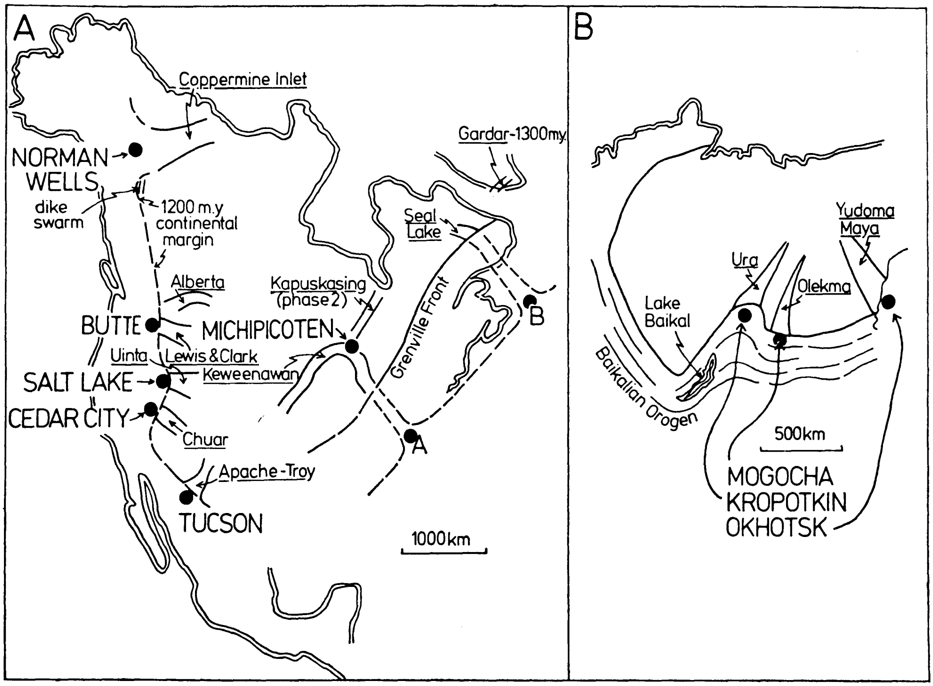

FIG. 11.—*A*, Proterozoic junctions (~ 1,200 m.y. B.P.) of North America; *B*, Proterozoic junctions of the Siberian Platform.

emplaced along the Kapuskasing line, first around 1,700 m.y. B.P. and then about 1,100 m.y. B.P. This second phase of intrusion we relate to the development of the Michipicoten junction. The third arm, known only from gravity and magnetic observations, lies under the lower peninsula of Michigan extending southeastward toward the Grenville boundary.

Grenville junctions A and B.—These junctions (fig. 11*A*) have been completely destroyed; they are discussed here as examples of structures whose former existence can be inferred although their precise position cannot be determined. This class of junction we call phantom junctions. The geophysical anomalies attributed to the southeast-trending arm of the Michipicoten junction become more diffuse across the boundary of the Grenville province. We have shown that the Grenville rocks have many features of continental crust which has been thickened, like the Tibetan plateau, as a result of continued plate convergence after continental collision (Dewey and Burke 1973). The date of crustal thickening is indicated by the latest Grenville reactivation ages of about 950 m.y.; collision occurred shortly before this time. The suture marking the collision lies buried under the Appalachians, in Africa, or under the continental shelves of the African or North American continents. We suggest that the opening of the Grenville ocean is roughly dated by the age of development of the Michipicoten triple junction because the southeastern arm of that junction trends at right angles to the Grenville Front, a feature marking the edge of the reactivated area beyond which continental crust was not thickened and corresponding to the northern edge of the Tibetan plateau today. The Grenville Front is expected to trend roughly parallel to the coastline along which the Grenville ocean opened.

The very thick sediments and volcanics

of Seal Lake (Wynne-Edwards 1972), with their southeastern structural trend (Fahrig 1952), which were formed about 1,200 m.y. B.P., may have been deposited in a rift related to a second Grenville junction (fig. 11*A*, *B*).

1,200-*m.y.-old junctions of the western margin of North America.*—Stewart (1972) drew attention to the great thicknesses of Belt age rocks deposited in troughs roughly perpendicular to the trend of the western margin of North America. He argued from this that Belt deposition took place before the western margin of the continent had ruptured. Our interpretation (fig. 11*A*) is slightly different; we see these transverse troughs, some of which contain more than 10 km of sediment, as failed arms related to a line of five or six triple junctions. The rifts that spread were generally those now trending approximately north-south and they joined along their length to form the eastern margin of the "Proto-Pacific." Precambrian sediments less than 800 m.y. old were piled up along the young continental margin in miogeoclinal wedges. Although arc and Andean types of orogeny have repeatedly modified the 1,200-m.y. continental margin and helped to accrete an average width of 500 km of crust to the North American continent, this margin has been open ocean throughout the last 1,200 m.y.

The northernmost transverse basin containing a thick sequence of Belt-age sediments and volcanics is exposed in Arctic Canada between Great Bear Lake and Coronation Gulf. Rocks forming the Coppermine Group consist of more than 3 km of basalt flows with copper mineralization, overlain by more than 4 km of sediments, including red and gray sandstones, silts, and shales with stromatolitic dolomites, and locally, near the top, gypsum (Douglas et al. 1970). The north-south-trending Muskox layered complex was intruded at about the same time as the Coppermine lavas were erupted. The Mackenzie dike swarm (Fahrig et al. 1965) in this area trends parallel to the suggested trend of the initial Pacific coast. These igneous rocks are of the type associated with continental rupture. The abnormal thickness of the later Precambrian (Purcell and Windermere) rocks in the Mackenzie Mountains southwest of Norman Wells (fig. 11*A*) indicates that the Coppermine arm may have reached its triple junction in this area. The projection of the Mackenzie Mountains eastward from the Cordillera is similar to the reentrants mapped by Soviet geologists where aulacogens enter orogenic belts (see *below*).

Farther south, Kanasewich et al. (1968) described a 300 km-long east-west-trending buried rift in southern Alberta. The rift is filled with about 11 km of late Precambrian sediment. Basaltic sills are locally developed (at Moyie in the Purcell Mountains, yielding 1,100 m.y. ages; Douglas et al. 1970) and the strata-bound orebodies of Sullivan, at Kimberly, B.C., and Coeur d'Alene appear to lie within the rift zone.

The axis of a major transverse Belt basin extends east-west through central Montana (Stewart 1972, fig. 4). The basin, containing up to 7 km of sediment, joins a northwest-trending basin at its western end. Until 1,100 m.y. B.P. sediments from the northeast (perhaps from the Alberta buried rift) and the southwest fed the northwest-trending basin, which contains a maximum of more than 10 km of sandstones, shales, and carbonates with some anomalously high copper values. The distribution of overlying late Precambrian and early Cambrian rocks indicates either that the spreading opening the "Proto-Pacific" took place across a rift axis displaced about 200 km southwest of the axis of the Lower to Middle Belt basin or that there was left lateral transform motion along a northwest-trending fault parallel to the Hope Fault (Harrison 1972, fig. 2) which suffered late Precambrian left lateral motion, and may be a Precambrian transform.

The trends of the Uinta, Chuar, and

Apache depositional areas (all Belt Supergroup equivalents) in failed arms farther south (fig. 11*A*) have been used in extending the sketched position of the 1,200 m.y. continental margin on the assumption that the failed arms trend roughly perpendicular to that margin.

Proterozoic junctions of Eastern Siberia.—The existence of triple junctions in an advanced state of development was implicit in Shatsky's (1955) recognition that aulacogens strike into geosynclines. He proposed the term, "aulacogen," for radially disposed rifts within the Russian platform. The aulacogens deepen toward their junctions with the geocynslines bordering the platform and typically contain miogeoclinal wedges at their distal ends. Shatsky noted that triple junctions generally occur at the apices of reentrants in platform margins (see, e.g., fig. 11*B*). Russian platform aulacogens are largely subsurface features and, although their distribution implies the existence of at least six triple junctions (Khain 1964), for this reason they are not discussed here.

Salop (1960, 1964, 1966, 1967) has described the aulacogens of the Siberian platform; figure 11*B* is based on an illustration of Salop and Scheinmann (1969, fig. 2). These authors remark that "an aulacogen can, it seems, open not only into a geosyncline, but also into the ocean. Admittedly, we do not know of such a fossil aulacogen, especially as we do not know any fossil oceans. And yet, the present Red Sea is much more like an aulacogen than an ordinary rift. The only difference is the ocean and not a geosyncline at its mouth and a rift along the axis of the depression." The unifying concept of cycles of ocean opening and closing introduced by Wilson (1968*a*) resolves this problem. Once orogenic belts are seen as closed oceans, the nature of features like the Red Sea becomes clear.

Salop and Scheinmann (1969) describe the Stanovaya-Baikalian rocks as eugeosynclinal. In their discussion they do not describe the Baikalian as a collision orogen as we have shown it in figure 11*B*, but this is not surprising as it is only recently that Soviet scientists have analyzed orogeny in terms of ocean closure (e.g., Peive et al. 1972). Proterozoic rocks of the Baikal region include associations of rocks of ophiolite lithology and calc-alkaline volcanic rocks (Pavlovsky 1969) indicating that collision orogeny has occurred in this area.

In addition to the Okhotsk, Mogocha, and Kropotkin junctions illustrated in figure 11*B*, it seems likely that there was another Proterozoic triple junction close to the southern end of Lake Baikal. The southward protrusion of the shield margin indicates where the junction lay. The failed arm (or aulacogen) of this junction would have extended roughly southward in continental crust that was removed from the Lake Baikal area during the opening phase of the Baikalian oceanic cycle.

One arm of the Okhotsk junction has been removed in the opening of the Okhotsk small ocean basin although preservation of the Yudoma Maya aulacogen and the Baikalian collision orogen is good enough to enable the position of the junction to be indicated. There is a clear resemblance here to the condition of the Dallas junction soon after the opening of the Gulf of Mexico.

Coronation triple junctions.—The east arm of Great Slave Lake in Canada (fig. 12*A*) has been described by Hoffman (1972) as an aulacogen. It joins the Coronation orogenic belt that records a 1,700-m.y.-old Andean and/or collision event in the Great Slave triple junction. Hoffman's (in press) detailed studies record the differences in sedimentary, structural, and igneous history that exist between the east arm rocks forming the Athapuscow aulacogen; the shelf and exogeosynclinal (foreland basin) sediments of the Epworth basin; and the orogenic associations of the Coronation belt. During the ocean-opening phase, sediments of the aulacogen were largely derived from the

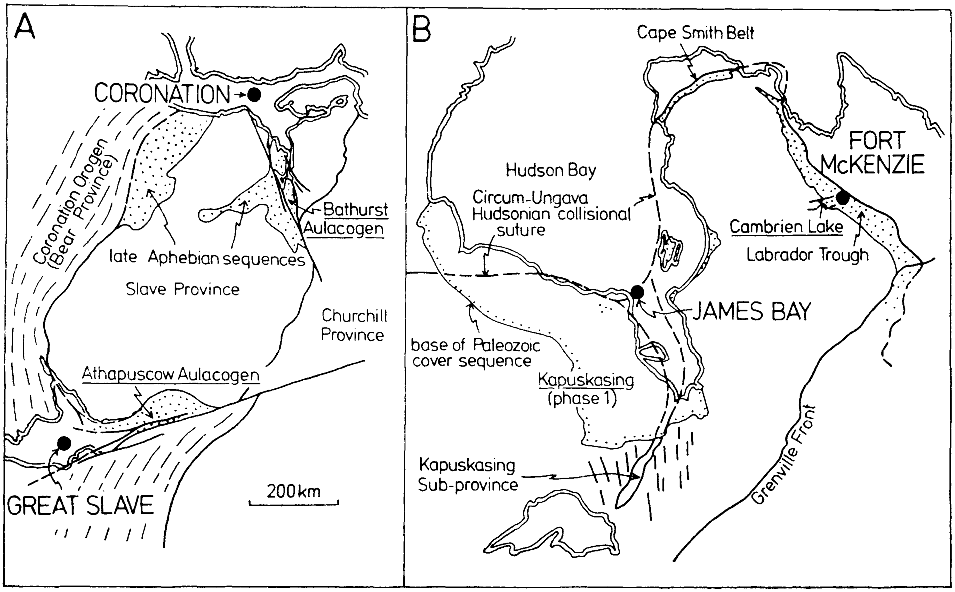

FIG. 12.—*A*, Aphebian junctions of the Coronation orogen, and *B*, Aphebian junctions of the circum-Ungava orogen.

northeast and were carried along the axis of the structure much as sediments derived from the Awash valley flow along the axis of the Ethiopian rift into the Afar today. After development of the Coronation Orogen, sediments were derived from erosion of the young mountains to the southwest and flowed up the aulacogen in the reverse direction (schematically shown in fig. 2*C*). Similar reversals in the direction of sediment derivation are to be expected in every aulacogen (or failed arm) associated with a closed ocean. The occurrence of 25 km-long laccoliths of andesitic composition, cutting sediments high in the Athapuscow aulacogen sequence, and of associated volcanics (Hoffman, in press) indicates to us that this structure may resemble the Benue trough (Burke et al. 1971, 1972) in having closed in a short-lived subduction episode as illustrated in figure 2*D* and 2*E*.

The Bathurst aulacogen (fig. 11*A*) 500 km to the north joins the Coronation orogenic belt in another triple junction under the waters of Coronation Gulf. This structure has not yet been investigated in the same detail as the Athapuscow aulacogen (Hoffman 1972).

Junctions of the circum-Ungava orogen.— Gibb and Walcott (1971) showed that various kinds of evidence support Wilson's (1968*b*) suggestion that an ocean had closed around the Ungava about 1,700 m.y. B.P.; we have interpreted the Hudsonian reactivation of the Churchill province rocks as a Tibetan event following the continental collision that closed the Ungava ocean (Dewey and Burke 1973), a conclusion not currently accepted by all workers (e.g., Dimroth 1972).

The opening of the Ungava ocean is roughly dated at 2,100 m.y. B.P. by the Ungava dikes that we suggest are an ocean-opening dike swarm. Their change in trend from about east-west near the Cape Smith-Wakeham Bay belt to roughly north-south parallel to the Labrador trough (fig. 12*B*) indicates that the opening ocean had a sharp bend, like the modern shoulder of South America, close to Wakeham Bay. This implies the existence of a triple junction whose failed arm was on the continent that drifted away from Ungava. Farther south, the Cambrien Lake graben (Dimroth et al. 1970) contains about 3 km of sediments and strikes into the Labrador trough. The Cambrien Lake sequence shows a reversal in sediment derivation from lower to upper beds like that recognized in the Athapuscow aulacogen by Hoffman. We call this the Ft. Mackenzie junction, but its precise position is not determinable. It is perhaps significant that Dimroth (1965) has mapped carbonatites in the Labrador trough opposite the Cambrien Lake graben.

Gibb and Walcott (1971) extended the circum-Ungava suture into James Bay and thence westward to join the Thompson Lake belt. The Kapuskasing structure projected northward forms a triple junction with the suture in the James Bay area. We suggest that the earlier phase of Kapuskasing alkaline intrusion (ca. 1,700 m.y.) was related to ocean opening that appears to have been rather later than farther east.

DISCUSSION

The purpose of the foregoing notes is less to attempt an analysis of the geological development of a number of triple junctions than to illustrate some of the varied ways in which triple junctions have developed during the plate tectonic regime. Similarities and differences in development have been noted and we now attempt some tentative generalizations about junction development in the hope that they will prove useful in further tectonic analyses. The tectonic map of Australia (Geological Society of Australia 1971), for example, appears to be a treasure house of triple junctions for anyone who can master the complexities of its legend.

Of the 45 junctions that we have recognized, five are at a young stage of development and may yet spread on two or more arms. Five of the older junctions failed to develop on any arms beyond the rifting stage and three developed by spreading on three arms. The remaining 32 junctions have all developed by spreading or transform motion on two arms, the third arm failing to develop beyond the rifting stage. Burke and Whiteman (in press), in their study of African junctions, concluded that this was the commonest style of development and their conclusion is borne out by our work. It is not yet possible to test, over a longer time range, their suggestion that failed arms are more likely to have equatorial trends, and spreading arms polar trends, with respect to the current spin axis of the earth. This is because old, especially Precambrian, pole positions known mainly from paleomagnetic studies are inadequately dated at present. Although poles have been determined with precision, it is hard to be certain that the remnant magnetism of the rock was acquired at the same time as the radiometric date determined.

Five of the 45 junctions possibly have four arms, although in two cases there is evidence that the fourth arm is the product of reactivation of an older rift. Where spreading has occurred at four-armed junctions, it has taken place on two arms, leaving two failed arms. We have not recognized any five-armed junctions and significantly we list no single rifts. A single rift would develop from a straight crestal rift across a periclinal uplift. Most pre-rift topographic uplifts appear highly periclinal (Burke and Whiteman cite a length to breadth ratio of about 2:1 in Africa) and are capped by straight lines of volcanoes parallel to the longer axis of the uplift. Spreading across straight rift boundaries formed on such an uplift would lead to straight continental margins from which plume traces would extend into oceans. Our observations (figs. 3, 5, 6, 7) show that initial plume sites are normally located at bends in—rather than in the middle of straight stretches of—continental margins, indicating that three-armed junctions rather than a single crestal rift are the rule. We suggest, therefore, that bends in continental margins commonly mark the sites of triple junctions and, further, that these bends may be recognized even after collision orogeny so that some prominent bends (syntaxes or oroclines) in mountain chains, as for example the right-angle bend between the Labrador and Cape Smith-Wakeham Bay fold belts (fig. 12*B*) are inherited from irregularities in the continental margin formed at opening which, in that particular case, happened more than 2,100 m.y. B.P.

Reactivation of old rifts has occurred very commonly. Wilson (1966) cited what has become a classic example when he showed that the Atlantic opened in the Mezozoic roughly on the same line along which its predecessor had opened in the earliest Paleozoic and had closed during the late Paleozoic. Moreover, the hidden, probably buried, suture marking the site of the closed Grenville ocean lies in the same general area. Successive oceans have opened three times, and closed twice, along the same zone. We interpret this tendency for renewed rifting along old sutures to be a result of surfaces of weakness at sutures extending through the entire thickness of the lithosphere. Suture zones are, therefore, more vulnerable to continental rupture than normal continental lithosphere and are likely to be picked out by the probing action of underlying mantle plumes. Exactly what happens where depends on such variables as size of plumes, patterns of plume distribution, and velocity of lithosphere over plumes (Kidd et al., in press).

Failed arms also show evidence of reactivation. The Kapuskasing structure (fig. 11*A*) was twice marked by alkaline igneous activity during the Precambrian but has not yet been involved in a spreading event. The Labrador Sea was marked by a line of alkaline intrusions about 550 m.y. B.P. (Doig 1970, fig. 4) and by renewed alkaline volcanism in the Jurassic (Laughton 1972), but did not spread until it was involved in a short-lived episode from 80 to 60 m.y. B.P. The early Tertiary failed arm of Lancaster Sound (fig. 5*B*) is probably underlain by a thick Paleozoic sequence and lies along what appears to be an old Precambrian transform. The Lake Baikal rift (figs. 4*A*, 11*B*) lies along a suture formed in the Proterozoic Baikalian collision orogeny. The more southerly rifts of East Africa were involved in Mesozoic rifting during the breakup of Gondwana as well as in Neogene events. There has been a tendency (see, e.g., McConnell 1972) to infer because an area suffered rifting say 100 m.y. B.P. and is being rifted now, that the area has remained in an environment favorable to rifting throughout the intervening period. According to our interpretation, in which rifting is a product of plume-generated uplift, this is improbable because plates are generally in motion over the world plume population and rifting is a response to the episodic probing of passing plumes under slowly moving, or stationary, plates.

Asymmetry in rift development with, for example, major normal faulting confined to one side is very common and we make no attempt to analyze its incidence here. The Kenya rift was highly asymetric when formed in Early Neogene times and became more symmetric later (Baker 1965), but some failed arms (e.g., the Anadarko and the Athapuscow) were more symmetric initially than they are now. The scale of the asymmetry appears nowhere very great when compared with the initial doming of 100-km-thick lithosphere.

Mineralization in rifts and failed arms (e.g., the Keweenawan, Coppermine, Belt of Montana, Southern Alberta buried rift, Danish arm of the Jutland structure, Copperbelt of Zambia and Katanga) commonly consists of copper and other base metals normally deposited syngenetically as sulfides in volcanic deposits or sediments. The mineralization in the Benue trough (Farrington 1952; Cratchley and Jones 1965; Grant 1971), now in the form of lead, zinc, and copper sulfides in the cross-joints of anticlines formed in relation to the Benue ocean closure, is perhaps similar in origin although it has suffered redistribution. Red Sea and Salton Sea brines have often been compared to rift, or failed-arm, mineralization (see, e.g., Kanasiewich et al. 1968).

Major fluid hydrocarbon accumulations in failed arms are very widespread. The northern North Sea, Gippsland Basin, Gulf of Suez, Niger delta, Maracaibo Basin, and Sirte Basin open into oceans but the older Anadarko basin is linked to a collision orogen. Many young failed arms have not yet been fully explored for hydrocarbons.

Some of the world's great rivers flow along failed arms, especially where nearing the ocean (Hoffman, in press). In Africa, the Benue-Niger, Zambesi, and Limpopo are examples. In Europe, the Rhine flows along two arms of the Frankfurt junction, and in times of low sea level reached the ocean along the northern North Sea failed arm. In India, the Godavari, Mahanadi, and Narmada all flow along failed arms, as does the Ganges, which runs along the axis of the Himalayan exogeosyncline, but enters its delta along the Asondamodar failed arm. In the Americas, the Mississippi flows down its embayment across the Jackson junction. The Amazon reaches the Atlantic along the failed arm of what appears to have been a late Paleozoic junction that did not spread at all (Burke et al. 1971).

Since big rivers tend to reach oceans along failed arms, exceptional accumulations of sediments, formed at the mouth of these structures, may remain discernible even after orogenic events. The Mackenzie Mountains in the Canadian cordillera contain greater thicknesses of 1,200–600-m.y.-old clastics than occur along strike on either side of them (Wheeler et al. 1972). We suggest that this may mark the mouth of a great river which flowed down the Coppermine arm (fig. 11*A*). The thick local sediment accumulation may help to explain why the Mackenzie Mountains extend farther east than most of the Cordillera. There is a similar, though smaller-scale, local thickening of sediment in the Labrador trough opposite the mouth of the Cambrien Lake failed arm and the Moine sediment wedge in the Scottish Caledonides shows some similarity (Kidd, Burke, and Dewey, in preparation).

It has been suggested (Burke and Wilson 1972) that the Neogene basin, swell, and rift event in Africa was related to the African plate coming to rest with respect to the plumes beneath it 25–30 m.y. ago and, further (Wilson and Burke 1972), that Andean orogenic events are confined to one side of a continent on a moving plate while island-arc orogenic events may occur simultaneously on more than one side of a continent lying on a stationary plate. An episode of formation of triple junctions leading to continental rupture may, by analogy with Neogene conditions in Africa, be an indication that the plate on which it occurs was temporarily at rest over its plumes. Most contemporary plates would therefore have been in motion over their plumes, and Andean and collision orogens might be forming contemporaneously on one margin of each moving plate though continental margin island-arc orogenies would be confined to the borders of other stationary plates. If it proves feasible to make analyses of this type, qualitative pictures of very old worldwide plate structure may eventually emerge. Unfortunately, radiometric ages are not yet good enough to make this feasible. For example, figure 11*A* illustrates a situation in which a number of rifts related to perhaps as many as a dozen triple junctions developed to break up a vast continental mass and block out a body similar in shape to modern North America. However, accuracy of available dates is not good enough to establish whether the rifts and triple junctions were contemporary. Episodes of plate standstill may prove to be inherently short-lived, since development of rifts to oceans after the stage of axial dike emplacement, requires new plate motion.

CONCLUSIONS

1. Plumes under continental lithosphere—especially where that lithosphere is at rest over the underlying asthenosphere—typically cause uplifts that rupture along three rifts meeting at *rrr* junctions. Commonly, two of these rifts become a plate boundary (either a ridge or a ridge/transform) while the third does not spread and becomes a failed arm.

2. The margins of continents, around opening oceans, are dominated by continental margin flexures linking triple junctions usually located at prominent bends in the coastline.

3. Although formed at the continental rupture stage in the ocean opening and closing cycle, triple junctions remain recognizable (in spite of varied and complex histories of the kinds outlined in this paper) throughout the cycle even to the stage of continental collision so that study of triple junctions is especially useful in working out orogenic history. For example, prominent bends (syntaxes) in mountain belts can in some cases be clearly related to earlier triple junctions.

4. Although some failed arms are marked only by a line of alkaline intrusions, others have complex sedimentary, igneous, and structural histories. These include the aulacogens of Soviet authors, arms with economically important sulfide deposits, and arms containing some of the world's larger oil provinces.

5. Triple junctions are recognizable as far back as the beginning of the plate tectonic regime, indicating that plumes played a part in driving plates then as they do now. We have recognized no triple junctions in rocks older than about 2,200 m.y., which is further evidence that the world was a different place during the permobile phase (Burke and Dewey, in press).

6. Many great rivers flow down failed arms to the ocean and their deltas augment normal miogeoclinal wedges. Local large increases in old miogeoclinal volumes may indicate where old great rivers and failed arms reached the ocean.

7. Young rifts commonly reactivate old rifts or develop along sutures where old oceans have closed. This may be because rifts and sutures extending through the thickness of continental lithosphere present zones of weakness to probing plumes.

8. If it can be shown that rifts and triple junctions develop preferentially in continental lithosphere stationary over plumes—andean orogenies characterize one side of a plate moving over the plume population and island-arc orogens occur on more than one side of a continent on a stationary plate—it may be possible, when radiometric and paleomagnetic data are better, to make qualitative reconstructions of the old plate structure of the world.

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