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AULACOGENS AND CONTINENTAL BREAKUP

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INTRODUCTION

Shatski and the Recognition of Aulacogens

Aulacogens (Greek *aulax*, a furrow) are long troughs extending into continental cratons from fold belts. They contain accumulations of sediment that are commonly more than three times as thick as neighboring contemporary cratonic sequences. Recognition that sequences in fold belts are generally thicker than those on cratons had been an essential element in the development of geosynclinal theory in the 19th century, and stratigraphic studies accompanying development of the petroleum industry in the 1920s and 30s confirmed this idea and led to further recognition of systematic variations within sedimentary cratonic cover. Thick sedimentary sequences were recognized as characteristic of a group of basins (foreland basins or exogeosynclines) lying parallel to and on the cratonic side of fold belts, and another group of basins, of which the Michigan and Paris basins are typical, was distinguished as being apparently randomly distributed within cratonic areas. By the middle of this century classifications of sedimentary basins, such as those of Kay (1951) and Umbgrove (1947), recognized these kinds of intracratonic basins as well as the geosynclines of folded areas but did not yet distinguish aulacogens.

The Soviet geologist Nicholas Shatski (sometimes transliterated Schatski), in the course of petroleum exploration during the Russo-German war of 1941–45, recognized long sediment-filled troughs in the cratonic Russian platform and later called the troughs aulacogens (Shatski 1946a,b, 1947, 1955; translated into German in Schatski 1961). The type examples were the Pachelma and Dnieper-Donetz aulacogens west of the Urals and north of the Black Sea. Aulacogens were clearly distinct from other areas with thick sediments on cratons, and their properties generally included (*a*) extension from an orogen far into a craton with gradual diminution in size, (*b*) a thick unfolded or gently folded sedimentary sequence, (*c*) location of the junction between the aulacogen and the orogen at a re-entrant, or deflection, in the fold belt, (*d*) long duration of the aulacogen as an active structure normally corresponding to the active period of the related orogen, (*e*) an early history of the aulacogen as a narrow fault-bounded graben and a later history as a broader superimposed basin itself sometimes involved in later faulting, (*f*) the occurrence of horst-like features within the aulacogen that influenced sedimentation, especially in the early history, (*g*) the occurrence of evaporites, (*h*) occurrences of igneous rocks often in a bimodal rhyolitic and basaltic association, the igneous rocks being commonly, but not exclusively, formed at the beginning of the aulacogen's history, (*i*) a tendency to reactivation marked by renewed faulting and thick sedimentation long after the associated orogen completed its cyclical development. Although Shatski (1946b) suggested that structures outside the Soviet Union were aulacogens, citing in North America the Belt terrain of Montana, the Ottawa-Bonnechere graben, and the structure now widely known as the southern Oklahoma aulacogen, and although Soviet and eastern European geologists continued to describe and analyze them, aulacogens received very little attention in other countries for the next 25 years (see references to Soviet literature in Hoffman, Dewey & Burke 1974, Siedlecka 1975).

Aulacogens Related to Plate Structure

In North America the major breakthrough in the recognition of aulacogens came with Hoffman's work in the East Arm of the Great Slave Lake. Hoffman (1973) studied the stratigraphy, sedimentology, and structure of an area of Proterozoic rocks that had been mapped by Stockwell (1936), and contacts with John Rodgers, the Yale stratigrapher, who was familiar with the aulacogen studies of Shatski and other Soviet geologists, helped Hoffman in recognizing that the structure in the East Arm of Great Slave Lake had many of the typical features of an aulacogen. This recognition in about 1970 came at an opportune time. The plate structure of the lithosphere (Wilson 1965) was becoming widely appreciated and geologists were beginning to follow Wilson's lead (1968) in interpreting the record of older earth history in terms of complex interwoven cycles of opening and closing of oceans (Dewey & Bird 1970). Hoffman (1973) showed that relations between the Athapuscow aulacogen (as he named the Great Slave Lake structure), the cratonic Epworth basin to the north, and the Coronation orogen to the west could be related to the Wilson cycle (Dewey & Burke 1974) of opening and closing of oceans. An episode of continental rupture was represented in the development of a well-preserved continental margin or miogeoclinical sequence in the lower part of the Epworth basin and Coronation orogen successions. During this episode sediments were carried from the Canadian shield westward toward the (then) continental margin. Sediments in the narrow, rift-structured lower part of the aulacogen were similarly derived from the east. Later the direction of sediment derivation reversed and clastic sediments were eroded off the mountains of the Coronation orogen and deposited in a foreland trough on the cratonic area of the Epworth basin and in the broad basinal upper part of the aulacogen. The westernmost outcrops of these sediments became involved in the folding and thrusting, calc-alkaline igneous activity, and formation of a foreland trough or exogeosyncline, that are typical of geological development at a convergent plate margin (Dewey & Bird 1970), although there is, as yet, no certainty as to whether the particular plate boundary involved was Andean,

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Himalayan, or an arc-collision boundary. Hoffman had shown that the aulacogens recognized by Soviet scientists, many of whom interpreted world structure without considering major horizontal displacements, could be interpreted in plate-tectonic terms as structures leading away from ruptured continental margins that became involved later in convergent plate margin phenomena.

At the time that Hoffman was unravelling the history of the Athapuscow aulacogen, Burke and Whiteman, working in Africa, were comparing the rifts of the Neogene African rift system with those developed in Africa at the time of the breakup of Gondwana. By considering a fairly large number of rifts they were able to show (Burke & Whiteman 1973) that twice in the last 200 m.y. there had been a common sequence of development in Africa that went from doming, through the development of three-armed rift systems on the crests of domes, to continental rupture by the development of two crestal rifts as a plate margin or margins, with preservation of the third or "failed arm" as a rift striking into the continent (Figure 1).

Burke & Dewey (1973) related this sequence of events to the interpretation of aulacogens. For the first time clearly grasping in plate tectonic terms an idea that Alpine geologists of an earlier generation (Suess 1909, Argand 1924) had groped for. Wilson (1968) had made the observation that orogenic belts generally mark places where oceans have opened and closed. Once this is appreciated, aulacogens, striking at high angles into orogenic belts, can be recognized as "failed" rifts in which the later episodes of the Wilson cycle of opening and closing of oceans are recorded (Figure 1). A similar idea occurred to Siedlecka (1975, especially Figure 7 and p. 341) as a means of interpreting relations between the Timan aulacogen and the oceans whose sites are now marked by the northern Urals and the Caledonides of northern Norway, but publication of her work was delayed.

Rifts, Graben, Failed Rifts, and Aulacogens

Intersecting rift patterns and their developed forms, with a failed rift system striking into a continent from an ocean embayment or an aulacogen striking away from a fold belt at a re-entrant, are distinctive and readily recognized. Burke & Dewey (1973) outlined the characteristics of a number of these and many more have been described in the last three years. A complex and as yet unstabilized nomenclature is emerging, but it seems desirable to limit the use of the word aulacogen to structures meeting Shatsky's definition, that is, to structures with thick sedimentary sequences striking into fold belts. The term *failed rift* (also *failed rift arm* or *failed arm*) is available for rifts or rift complexes striking from oceans into continents, and these terms also seem appropriate for old rift systems that strike into fold belts but have no associated thick sediment sequence (for example, the Great Dike system of Rhodesia). The German word *graben* (both singular and plural) has been applied to a number of rift structures ("Viking graben," "Rhine graben") and, like rift, seems useful as a general descriptive term. It has sometimes been used adjectivally (for example: "graben facies" for the sediments and igneous rocks typical of early rifting).

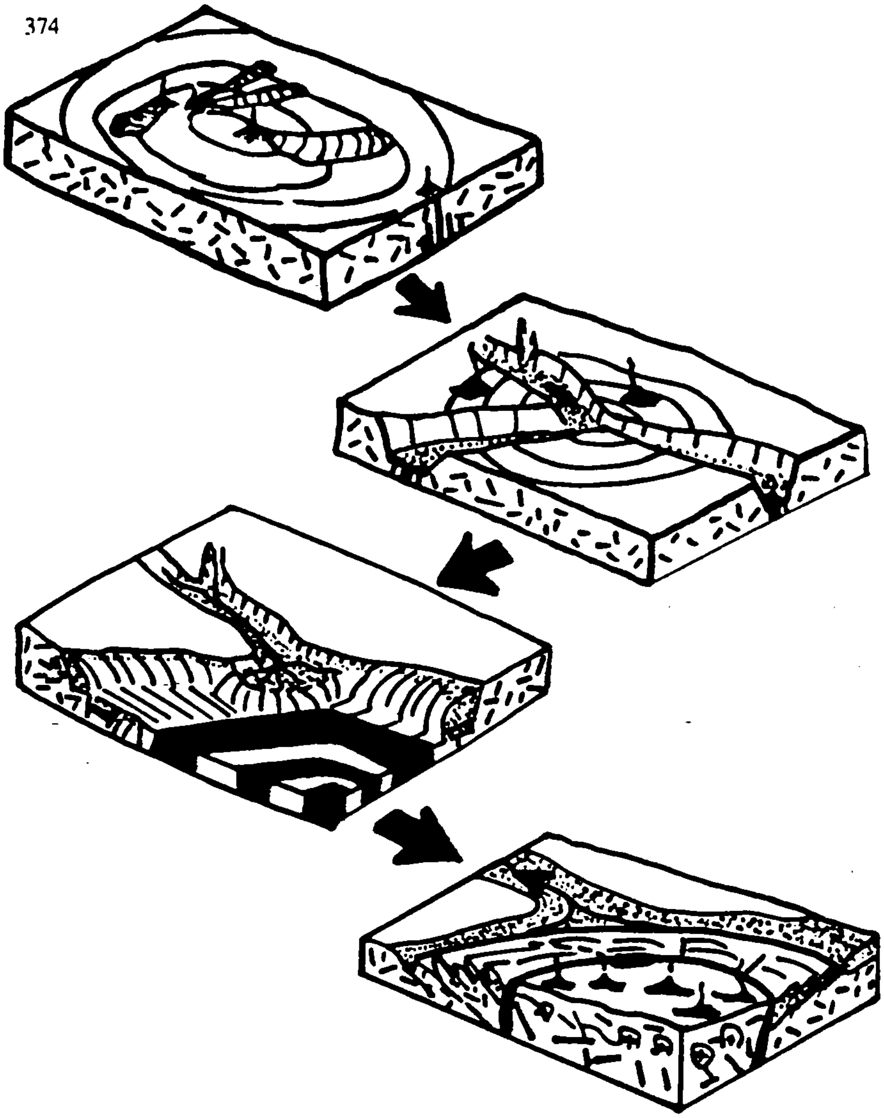
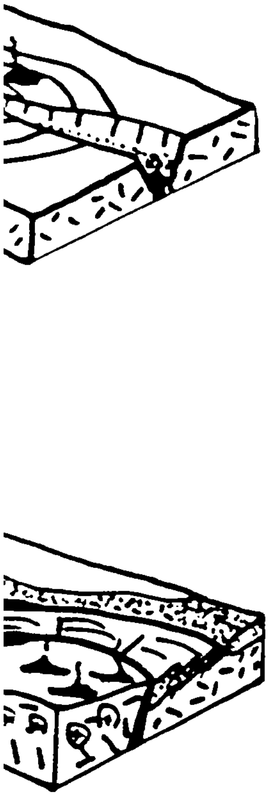


Figure 1 The sequence of swell, rift, continental rupture, and collision in aulacogen formation. A swell within a continent (top left) is crested with volcanoes from which lavas flow and evolves into a three-rift system (upper right) with volcanoes, sediment fill (stippled), and axial dikes. Two of the rifts develop to a continental margin (lower left) and ocean (striped) forms on their sites. A miogeoclinal wedge (stippled) is deposited along the new continental margin and a delta progrades down the failed rift to lie on ocean floor. Later (bottom right) another continent crosses the closing ocean and two continents collide. Rocks of the miogeoclinal wedge are thrust onto the continents and eroded by a river flowing down the aulacogen in the reversed direction. A suture zone (vertical black lines) marks the former site of the ocean and igneous rocks develop in the thickened continent on one side.



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Aim and Scope of Review

Aulacogens are structures that record a great deal of earth history, and because they commonly escape the extreme tectonism experienced in fold belts at ocean closure, this record is often better preserved than in the fold belts themselves. However, emphasis in this review is less on the details of the historical record than on the information that aulacogens yield in their distribution in space and time and in their contained sediments, igneous rocks, and structures about the processes that have operated in their origin and development. For this reason, discussion of the initial rifting process, an evolutionary stage through which all aulacogens have passed, is included, as well as consideration of the later phases of aulacogen development.

RIFT DEVELOPMENT AND CONTINENTAL RUPTURE

The earliest stage in the development of an aulacogen is one of intracontinental rifting, and it is at this stage that the peculiarities of crustal and lithospheric structure are established which govern the later history. East Africa has been suffering this kind of rifting for the last 25 m.y. (since the beginning of the Neogene) and is therefore of special interest.

Neogene Rifts in East Africa

Although many features of the East African Rift System are relevant to the study of aulacogens, one of the most striking is the elaborate areal pattern of the active rifts (Figure 2). If the African continent splits into two in the future by the formation of new ocean along a linked set of rifts, many rifts will be left as failed arms in one or other of the two new continents.

The best developed three-armed rift system is around the Afar, where the Gulf of Aden and Red Sea are oceanic. Ocean floor, or something very like it, lies on the bottom of much of the Afar, and the Ethiopian rift is at present a failed arm. If, at some time in the future, ocean floor develops along this rift, it will lose its failed status and evidence of the earlier rifting event may be preserved along the sides of the new ocean.

The northern and southern Gregory rifts in Kenya form a three-rift system with the Kavirondo rift, which is centered on the town of Nakuru and is at an early evolutionary stage. Studies of the elevation of erosion surfaces on the rift shoulders around the Nakuru rift junction have shown that the topographic dome, centered on Nakuru at the crest of which the rifts meet, developed before the rifts themselves (Baker & Wohlenberg 1971). This is of interest because it has been suggested that intracontinental rifts commonly develop by horizontal propagation of vertical lithospheric cracks with uplift following later as a response to the emplacement of hot rock in the crack. While this process certainly happens (Dewey & Burke 1974), present evidence indicates that intracontinental rift systems have developed more commonly by linking uplifted areas on which individual crestal rift systems have formed [see discussion in Burke (1976a)].

Failed rift systems and aulacogens within continents often contain several kilometers of sediments that accumulated in the early stages of rifting. Familiar examples are the Triassic rifts of eastern North America, which formed during the rifting episode that culminated in the opening of the central Atlantic between the east coast of North America and the bulge of Africa. Lee (1976), for example, has reported an estimate of more than 10 km of Triassic sediments in the Culpeper graben. Comparable sedimentary accumulations are not known in rifts of the East African system, but it seems likely that the African rifts have evolved to a structural state in which such an accumulation could occur, and it is appropriate to consider what evidence there is of the structure underlying the rifts.

UNDERLYING STRUCTURE OF EAST AFRICAN RIFTS It is becoming widely appreciated that the structural peculiarities of the African Plate [its anomalous elevation, basin and swell structure, large amount of intraplate (hot spot) vulcanism, and active rift system] are associated with Africa's position at rest for about the last 25 m.y. with respect to the underlying mantle and the earth's spin-axis (see, for example, Burke & Wilson 1972, Briden & Gass 1974, Burke & Dewey 1974, Richter & Parsons 1975,

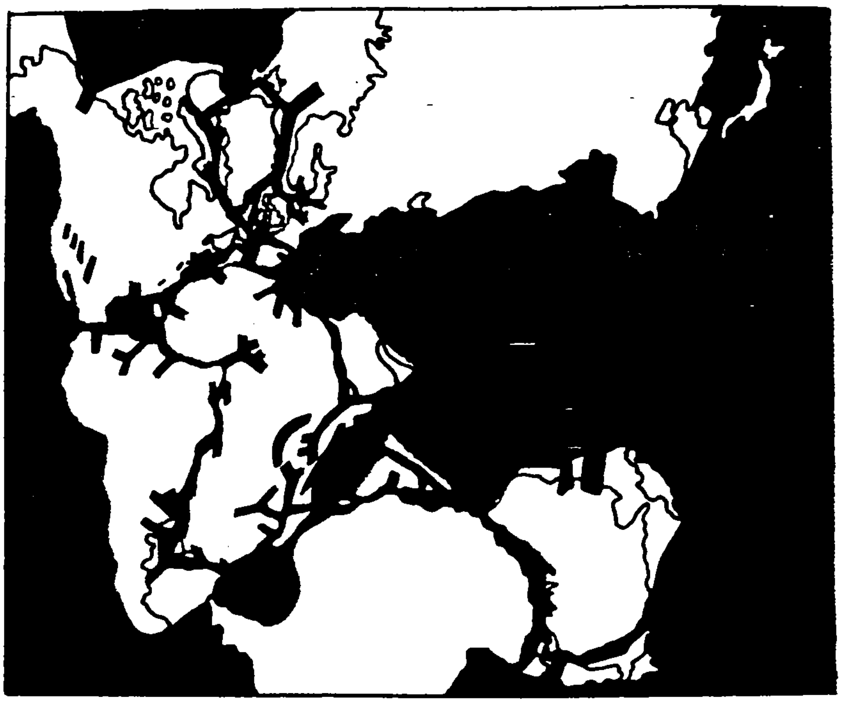


Figure 2 Mesozoic and Cenozoic rift systems and oceans are shown in black on a Triassic earth (based on Smith, Briden & Drewry 1972) to illustrate the abundance of failed rift systems associated with continental breakup. In Africa the rift systems have been active twice, in Mesozoic and Cenozoic times.

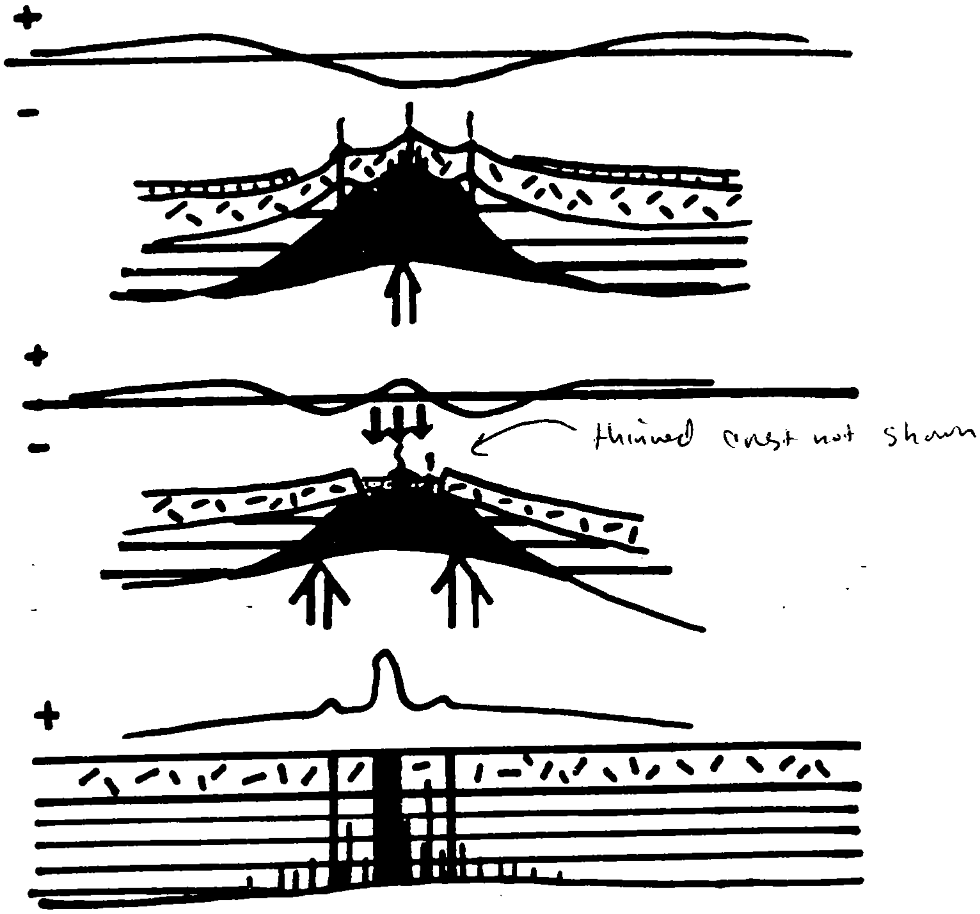
McKenzie & Weiss 1975). Because there is no lateral motion between the lithosphere and the underlying asthenosphere, the present topography of the African Plate seems likely to bear an unusually simple relation to underlying mantle convection. Elevated areas, many of them capped by volcanoes (e.g. the Cape Verde islands and the Ahaggar), are likely to overlie rising convection currents or plumes and depressions (e.g. the Chad basin) to mark the areas between the rising currents. The elevations mark underlying areas of mass deficiency related to partial melting of the mantle, which is produced by the hot rising currents. As long as the rising convection current continues to reach the base of the lithosphere in the same place, elevation is dynamically maintained as a response to underlying mass deficiency. Ages of volcanic rocks that go back to 25 m.y. ago on African uplifts indicate that these areas have been elevated, although perhaps intermittently, throughout the Neogene.

The rift valleys of East Africa occur within a broad uplifted area (the East African swell) and are associated with discrete uplifts, as at Nakuru, within the swell. Geophysical observations on the rift system have suffered from difficulty in distinguishing effects related to the rift valleys from those related to the broad uplifts. The active rift systems of East Africa overlie large volumes of hot, partly melted asthenosphere that have their topographic manifestation in high ground, and most teleseismic effects in the Rift system, for example, the poor transmission of Sn (Gumper & Pomeroy 1970), are no doubt related to this material. Gravity observations are particularly ambiguous and susceptible to assumptions about regional fields as well as the effects of sediment accumulations in the rifts (Figure 3).

Axial dikes Perhaps the most structurally significant geophysical observations made in the East African Rift System were refraction seismic studies in the Kenya Rift reported by Griffiths et al (1971). Although their work was not unambiguous, Griffiths and his colleagues showed that their results could have been caused by an axial dike of basaltic material about 10 kilometers wide lying roughly in the middle of the Gregory rift, reaching nearly to the surface and extending along the rift valley for a distance of over 100 kilometers. Khan & Mansfield (1971) showed that gravity observations in the Kenya rift were compatible with the presence of such an axial dike, and Searle & Gouin (1972) showed that the gravity field in the 150 km wide Ethiopian rift at the latitude of Addis Ababa could be interpreted as related to three similar axial basaltic dikes together about 75 km wide.

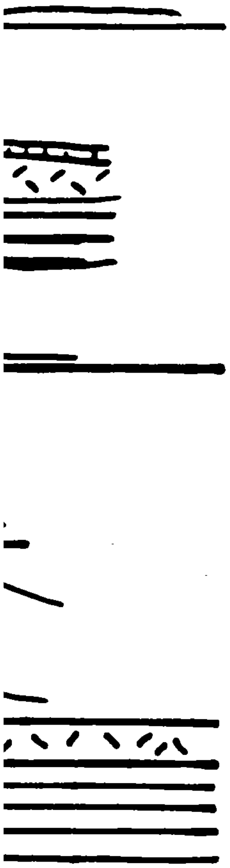
Three other lines of evidence support the idea that axial dikes are an important element in rift valley structure. These are evidence from the igneous rocks of both ancient and modern rifts and the outcrop and gravity pattern of ancient rifts.

A great deal has been learned about the igneous rocks of ancient and modern rift systems. The most structurally significant conclusions from these studies are that rift igneous rocks have been produced by partial melting of the mantle, probably at depths in the range 60–120 km, and that although fractional crystallization and remelting have been important in producing the wide range of alkaline and, to a lesser extent, tholeiitic igneous rocks reported from the rifts, both isotopic and other geochemical evidence show that generally reaction with continental crustal rocks has been unimportant. The implication is that rift igneous rocks are



thinned crust not shown

Figure 3 Structure and Bouguer anomalies at swell, active, and failed rift structures. Bouguer anomaly over a swell (top) is negative and attributable to mass deficient, partly melted asthenosphere (black) rising (open arrow) through the lithospheric mantle (lined) and doming continental crust (dashes). Volcanoes crest the dome and overlying sediments (dots) form a bordering scarp (based on the Ahaggar). A central positive Bouguer anomaly is related to axial dikes in an active rift (middle figure). A broad negative anomaly is attributed to the persistent asthenosphere swell (black, open arrows). The greater mass of the axial dike system due to mafic and ultramafic rocks makes the rift sink (solid arrows) (based on Kenya Rift). In an inactive rift (bottom) with no sediments the axial dikes are exposed cutting the continental crust but are more abundant in the lithospheric mantle. A sharp positive Bouguer anomaly marks the axial dike (based on the Great Dike of Rhodesia).



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discrete bodies with intrusive contacts and without significant reaction zones with their country rocks throughout the thickness of the continental crust. This result is entirely compatible with the axial dike model.

Gravity surveys over inactive rift systems are especially illuminating because the mass deficient part of the asthenosphere that dominates the gravity field over an active rift is not present under an inactive rift, where the gravity field mainly results from the changes effected in the crust and lithosphere at the time of rift formation. Jones (1956), reporting a gravity survey of the Cretaceous Canellones graben in Uruguay, showed an axial positive anomaly. Oil wells drilled over this anomaly and on its flank confirmed that an axial dike model can satisfy the gravity observations. Positive Bouguer anomalies attributable to axial dikes are known over other fossil rift structures (see Burke & Whiteman 1973, Figure 2) and in the *Great Dike* of Rhodesia it appears (Grantham 1957) that the responsible igneous rocks outcrop. The *Great Dike* is about 10 km wide, has vertical sides (Weiss 1940), and is composed of layered mafic and ultramafic rocks of approximately tholeiitic composition.

The floor of a rift valley lies in isobaric equilibrium at a lower elevation than the shoulders because of the greater density of the basaltic and ultramafic rocks of its underlying axial dike system. The Neogene structure of Africa suggests that during active rifting, as sediments are eroded from elevated rift shoulders and deposited on the rift floor loading it and causing subsidence, the shoulders are elevated anew because of the persistent underlying mass deficiency in the asthenosphere. It is very likely that this process has allowed the accumulation of sedimentary sections up to 10 km thick in such graben as the Culpeper basin. When the underlying mass-deficient object is no longer there, general subsidence leaves the rift with its thick sediment section and a thinned underlying continental crust, the latter being an expression of the dike injection within the continent (Figure 3). The widely mapped variations in the thickness of continental crust (from 35–45 km over most continents) indicate that the lithosphere is strong enough to maintain the lateral stresses set up by the irregular mass distribution across the fossil rift.

Other Active Continental Rift Systems

Although the East African rifts are the best developed of active intracontinental rifts, there are both active and Neogene rifts in most other continents. Many of these are small-scale or poorly known features, but the Rhine graben in Europe and the Baikal graben in Asia are major features that have been thoroughly studied. The Baikal and Rhine graben have both been attributed to tension set up within the Eurasian continent as a result of Alpine-Himalayan plate collisions farther south (see, for example, Molnar & Tapponnier 1975; Şengör 1976). It is sometimes possible to determine whether or not old rifts or aulacogens originated in this way by dating the time of their inception. If rift formation coincides with neighboring collisional phenomena, there is a good possibility that the mechanism considered to have produced the Baikal rift may have operated. For example, J. Tuzo Wilson has suggested (personal communication) that the Ottawa-Bonnechere graben was formed in association with Appalachian collisional events of mid-Ordovician or later age, but Rickard's (1973) study of Lower Paleozoic sediment thicknesses in New York State shows that the Ottawa structure was already there in Cambrian times some m.y. earlier and is therefore more likely to be a feature produced by African-type continental rupture than by a continental rupture produced as a result of collisional orogeny.

Rifting events during collisional orogeny are well known in the Alpine System (Dewey, in press), the best documented being those associated with the Miocene rotation of Corsica and Sardinia away from the Mediterranean coasts of France and Spain (Dewey et al 1973). Because the products of this kind of rifting phenomenon are normally soon caught up in mountain belts, they are outside the scope of this review. Tensional processes perhaps associated with lateral plate motion have produced the rift-like features of the Basin and Range province.

Conditions at Rifting

Evidence from active and fossil rifts indicates that although continental rifts can develop in a variety of environments, the largest scale rift systems are associated with continental rupture. The rupturing process leaves inactive rifts within continents underlaid by abnormal lithosphere, which controls the further structural development of the rifts. Although the nature of the abnormality in the lithosphere underlying rifts is not generally established, evidence of the presence of an axial dike system has been recognized under both ancient and active rifts and axial dikes reaching high into the crust may be a general feature of the lithosphere underlying fully developed continental rift valleys. The lithosphere below the axial dikes in ancient rifts is likely to contain pyrolite depleted by the removal of both the axial dike basalt and the alkaline and tholeiitic volcanic rocks of the rift system. This depleted pyrolite is material that would have formed part of the asthenosphere while the rift system was active. Some of the basaltic material in ancient axial dikes and in other structures under rifts is likely to have undergone a transition to eclogite which, because of its great density, will contribute to subsidence of the rift. How much basalt becomes eclogite in this kind of environment depends on thermal history. Experimental work shows that eclogite is a stable form of rocks of basaltic composition over a much wider pressure and temperature range than its scarcity at outcrop suggests (Ringwood & Green 1966). The scarcity is commonly interpreted to indicate that the basalt to eclogite transition is kinetically controlled and normally takes place at too slow a rate to be significant over geological time. A key to some of the variation in behavior of failed rift arms may therefore lie in the basalt-to-eclogite transition. Where the axial dike system is subjected to prolonged elevated temperatures, dike material becomes eclogite and additional subsidence ensues. Where the axial dike material persists as basalt, renewed subsidence, after the initial loading of the active rift, may not occur. Since only part of the dike system material may suffer the phase changes involved in the eclogite transition, varied amounts of subsidence will take place even where the transition to eclogite occurs. If a part of the dike rock persists in basaltic mineralogy, then renewed subsidence may accompany additional later formation of eclogite.

FAILED RIFT SYSTEMS EXTENDING FROM OCEAN MARGINS

The most studied rift systems in the world are those formed at continental rupture and now located within the continents bordering Atlantic-type oceans. Rift complexes are best developed close to the continental margins, but in some cases, for example the North Sea and the Benue trough, they extend far into the continent. The reason these rifts are so well known is that they have been explored for petroleum because they contain great thicknesses of Mesozoic and Cenozoic marine and nonmarine sediments and because major rivers have prograded down them to produce oil-bearing deltas.

Many of the major oil provinces of the world occur within these rift systems and, although their structural and stratigraphic history is well known, underlying deep crustal and lithospheric structure is as yet little known.

Distribution of Rifts Striking into Continents

Since the short-lived continental assembly of Pangea began to break up about 200 m.y. ago, major oceans have formed in the North and South Atlantic, the Indian Ocean, the Arctic, and the Southern Ocean, and many smaller oceans have developed elsewhere. Figure 2 shows a Triassic reconstruction of the world on which both the sites of oceans and major Mesozoic and Cenozoic rift systems associated with continental rupture are shown in black. There are hundreds of rifts in the systems sketched on Figure 2 and it is likely that many more remain to be mapped.

The best known rift systems are those bordering the Atlantic Ocean (Burke 1976a). These fall into three groups: an old population of Triassic age around the site of the central Atlantic between the bulge of Africa and North America, a population associated with the opening of the South Atlantic at the beginning of the Cretaceous, and a very varied and complex group on the flanks of the North Atlantic largely related to the complex Permian and later rifting events of Northwest Europe.

In the Arctic development of a spreading boundary adjacent to the Canadian Arctic islands in the Jurassic was accompanied by transform motion parallel to the north coast of Alaska and development of a failed rift system on the site of the Mackenzie delta (Herron, Dewey & Pitman 1974). This development implies that unrecognized failed rift systems may exist at the continental margin north of Siberia.

Around the Indian Ocean Mesozoic failed rift systems are well developed on the east coast of Africa, the west coast of Madagascar (UNESCO-ASGA 1968), the east coast of India, and the coasts of Sri Lanka. The west and northwestern coasts of Australia have well-developed failed rift systems (Veevers 1974, Veevers & Cotterill 1976). No rift systems have been described from Antarctica or the east coast of Madagascar, and the Khambat rift system of the west coast of India appears of early Cenozoic age. On the south coast of Australia there are well-developed failed rift systems associated with the opening of the ocean between

Australia and Antarctica, but no failed rifts have yet been reported from the Antarctic side. Between Australia and New Zealand the Tasman sea has one well-developed failed rift in the Gippsland basin.

Mesozoic rifts opening into the Tethys are discernible in places, although continuing convergent activity obscures their development. The Sirte and Hun graben of Libya, having so far escaped convergent phenomena, are the most prominent Tethyan rifts.

Late Triassic and Early Jurassic rifts around the Caribbean and Gulf of Mexico help to date the formation of the ocean floor in those areas. The Maracaibo structure has suffered later convergent and strike-slip movement and is partly obscured, but the three rifts of the Boa Vista system (Berrangé & Dearnley 1975) and the Mississippi and Seewannee embayments are well-preserved rifts striking at high angles into the South and North American continents. Failed rift systems have not generally been recognized in association with the numerous marginal basins of the western Pacific, maybe because they originate in a dominantly convergent environment. However, the Seoul-Wonsan graben (Figure 4) striking north-northeast across the Korean peninsula is an apparent exception. This graben is of Miocene to Recent age and contains Quaternary volcanoes. If it formed, as the illustration indicates is possible, in association with the development of the Japan Sea, it suggests a Miocene age for that small ocean basin.

The numerous failed rift systems extending into the Russian Platform from the

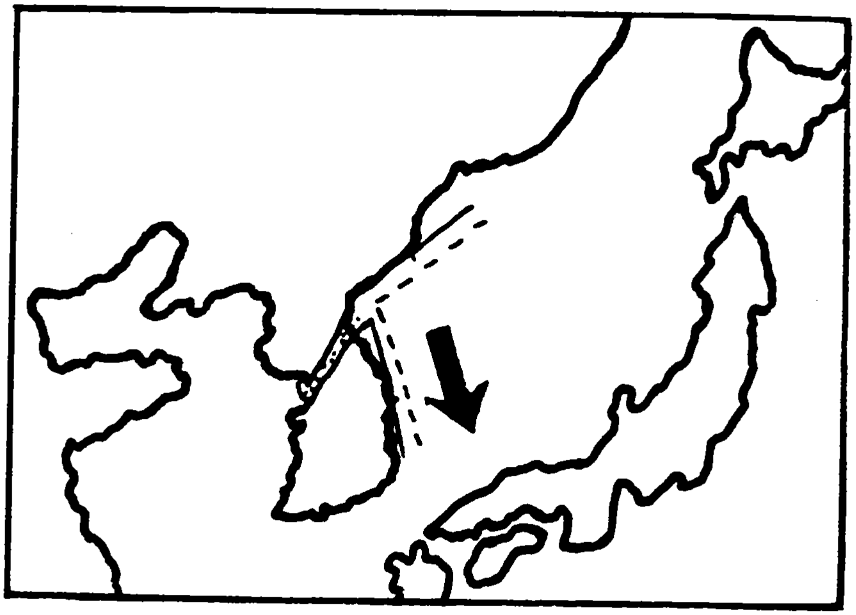

Figure 4 The Neogene and Recent Seoul-Wonsan graben (stippled) may be a failed rift associated with the opening of the Japan Sea.

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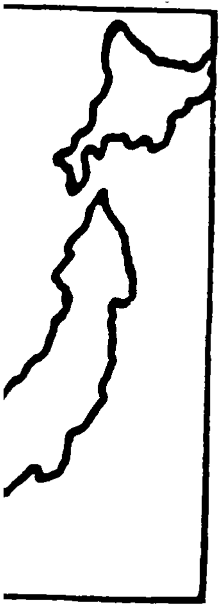

may be a failed rift

North Caspian depression (*Tectonic Map of Europe* 1962) should perhaps be included here. These failed rifts, including the type aulacogen of the Dneiper valley, all strike into the North Caspian depression (Figure 5), an area that is underlaid by about 14 km of sediment including, within the lower half of the succession, a salt sequence probably of Upper Paleozoic age. This salt sequence

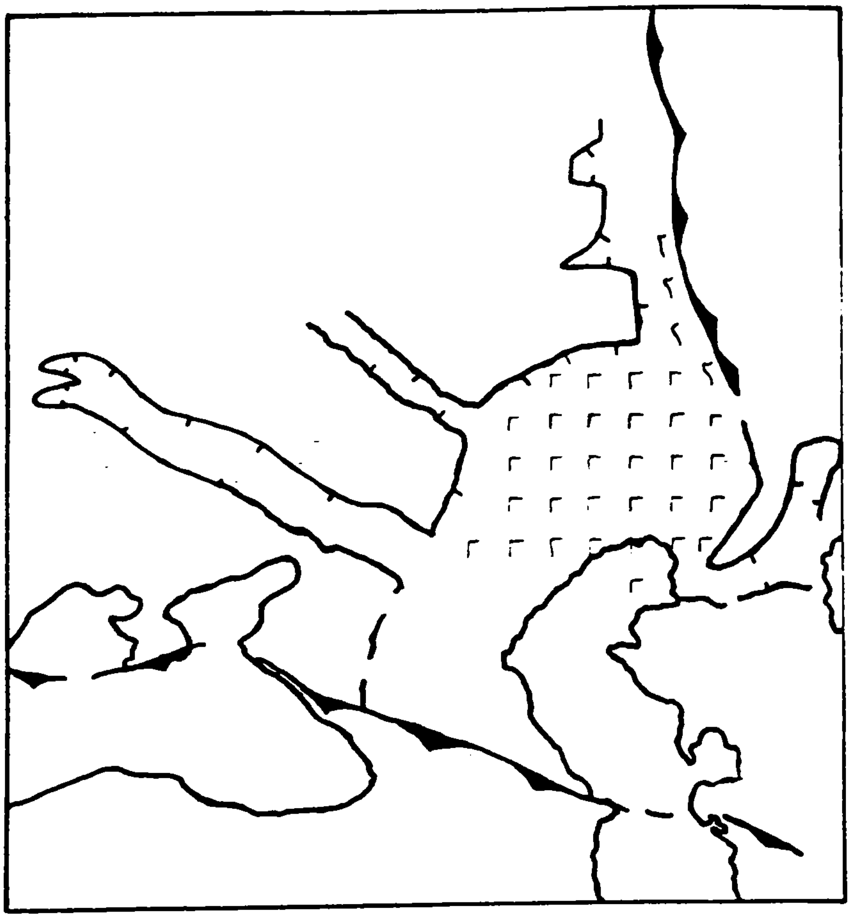

Figure 5 Area north of the Caspian (right) and Black (left) seas. The North Caspian depression is underlain by evaporites (inverted L's) and these salts are tectonized in the southern Urals (distorted inverted L's). Aulacogens including the Dneiper-Donetz aulacogen strike into the Urals and the depression. Analogy with the Gulf of Mexico suggests that the North Caspian depression may be underlain by pre-Permian ocean floor that has escaped obduction in both the Ural continental collision (thrust symbols on right of figure) and the Caucasus active collision (thrust symbols at bottom of map) (based on *Tectonic Map of Europe*, 1962).

has been tectonized on the western side of the Ural mountains by Permian convergent processes (as indicated on Figure 5). What kind of rocks underlie the North Caspian depression is not known. Seismic velocities, reported by Soviet scientists, lie in the ambiguous range between continental and oceanic, and in view of the increasing recognition that major salt deposits, such as those of the Gulf of Mexico (Ladd et al 1976), the Atlantic (Burke 1975a), and the Mediterranean (Ryan & Hsü 1973), have been laid down on oceanic crust, it seems probable that oceanic crust underlies the North Caspian depression. If this is so, it is probably the oldest oceanic crust in the world neither subducted nor caught up in a mountain belt by obduction.

Characteristics of Failed Rifts Extending into Continents

There are too many failed rift systems that extend from the margins of oceans into continents for it to be practicable to catalogue them here. A more useful course seems to be to distinguish categories and outline the features of examples of each. Accordingly, failed rift systems are discussed here roughly in order of increasing complexity.

ETHIOPIAN-TYPE RIFTS The simplest of rifts facing oceans are those like the Ethiopian. In most cases, time has permitted rifts of this type to develop further, and older rifts that have developed no further than the Ethiopian stage are not commonly preserved. Perhaps the Oslo graben (Ramberg 1972) is an example of a fossil rift in this early stage of development. A significant feature of the Ethiopian rift is that sediments derived from erosion of the African continent are being transported along it, mainly by the Awash river, and being deposited on oceanic crust in the Afar. These sediments are close analogues of the clastics that bury ocean floor topography below the salt of the Gulf of Mexico (Ladd et al 1976) (Figure 4) and below the salt in the marginal graben of the South Atlantic. It is at the Ethiopian rift stage that much of the copper mineralization of failed rifts and aulacogens discussed by Sawkins (1976) develops.

SUEZ-TYPE RIFTS The Suez graben has apparently no ocean floor at its base but has subsided about 5 km since the early Miocene (Heybroek 1965). T. Thompson (personal communication) has pointed out that the occurrence of Cretaceous Nubian sandstone at the base of the Suez section makes it unlikely that doming preceded subsidence, inasmuch as the thin Nubian section (< 400 m) would have been stripped off a precursor dome. The Suez graben seems more likely to have developed through tension set up in the African plate when spreading on the Red Sea and transform motion on the Dead Sea rift began and perhaps date these events as early Miocene. The Lower Cretaceous graben of Cape Province in South Africa apparently developed in a similar way when the Malvinas plateau, part of South America, moved along a transform fault past the south coast of Africa (Rigassi & Dixon 1972, Burke 1976a).

NEWARK-TYPE RIFTS The Triassic rifts of the eastern seaboard of North America, although they contain thick nonmarine sequences deposited before continental rupture, had practically no further development once the Central Atlantic began to open. Almost the latest event in their development was a basaltic emplacement episode best known in the Palisades sill, and this may have coincided with the onset of Atlantic sea floor spreading (Cousminer & Manspeizer 1976). This does not seem a very common style of rift behavior and it will be particularly interesting to learn, as petroleum exploration develops on the neighboring continental shelf, whether buried Triassic rifts in that area behaved in the same way.

SERGIPE-TYPE RIFTS Rifts of this class contain several kilometers of nonmarine sequences overlain by an evaporite blanket that commonly drapes older structures. The type examples are in the Lower Cretaceous Sergipe-Alagoa basin of coastal Brazil (Asmus & Ponte 1973), and other examples from the South Atlantic, all developed at continental rupture, include those of the Cuanza, Cabinda, and Gabon basins on the African side. All these produce hydrocarbon from below the evaporite horizon. The rift systems below the salt often show horst and graben structures that invite comparison with those of the active Afar. The unconformable relation of the salt is sometimes ascribed to a specific tectonic event but may generally be explained as a result of spills of saline waters over irregular topography into subaerial subsealevel graben (Burke 1975a).

In the North Atlantic, Sergipe-type graben with probable salt spills into subsealevel structures occur in the Permian of the North Sea (Taylor & Colter 1975), the uppermost Triassic of Portugal (Zbyszewski 1959), and the Aquitaine basin (BRGM et al 1974). Much of the Keuper salt of northwest Europe can be regarded as deposited in Sergipe-type graben. On the North American side of the Atlantic the best described Sergipe-type graben is the Triassic Orpheus graben of offshore Nova Scotia (Jansa & Wade 1975).

The history of the type Sergipe graben throughout the later Cretaceous and Cenozoic (Asmus & Ponte 1973) is one of continued miogeoclinal deposition and subsidence at the continental margin. Renewed tectonic activity of the graben has been apparently restricted to halokinesis.

RIO SALADA-TYPE RIFTS The Sergipe-type graben characterized by salt deposits is a climatically controlled environment because salt is only precipitated in graben where evaporation rates are exceptionally high. Graben formed at continental rupture without a hypersaline phase pass straight from nonmarine to marine environments. The southern part of the South Atlantic was in more temperate latitudes at the time of Cretaceous continental rupture than the area of Sergipe-type graben north of the Walvis ridge and Rio Grande Rise. Graben in the southern area show a simple nonmarine to marine transition. The Rio Salada–graben of Argentina (Urrien & Zambrano 1973) is proposed as the type.

Graben of this type can be the site of major petroleum resources if the first marine shales provide both source rocks and traps and the underlying nonmarine sands provide reservoirs.

BARREIRINHAS-TYPE RIFTS Dewey (1975) showed that rifts associated with intracontinental transforms may be expected to exhibit compressional structures because of the imperfection of strike-slip motion along transforms, which is inevitable on a many-plate earth. The Barreirinhas basin of northern Brazil (Asmus & Ponte 1973) shows folds developed in mid-Cretaceous times as the shoulder of Brazil slid past the Guinea Coast of Africa and is the type example of this kind of rift.

LIMPOPO-TYPE RIFTS All the rift types distinguished so far developed as the result of a single rifting event, but it has long been a recognized feature of rift systems that old rifts are the sites of renewed rifting (McConnell 1974). The simple case in which an Ethiopian-type rift is reactivated later is widely represented in eastern Africa, where rifts formed during the breakup of Gondwana have been rejuvenated in the Neogene. A simple example is the Limpopo rift (Cox 1970), which had an igneous-dominated history in Triassic and Jurassic time and has undergone dominantly topographic rejuvenation in the Neogene. In both Mesozoic and Neogene times delta progradation along the Limpopo rift ensued. The Godavari and Cuttack graben of India, active in the Permo-Triassic and Cretaceous, are examples of the Limpopo-type rift.

LUSITANIAN-TYPE RIFTS A common situation is for an initial intracontinental or Ethiopian type rift to be reactivated so that the intracontinental rift later becomes a site of rifting that leads to ocean development. The Lusitanian basin of Portugal (Wilson 1975, Zbyszewski 1959, Montadert et al 1974) is the proposed type example. Late Triassic rifting along the border between the Grand Banks and Iberia led to the formation of salt-filled Triassic intracontinental graben in the Lusitanian basin. Throughout the Jurassic shelf sediments were deposited over the graben that rifted again in lower Cretaceous time to form part of the North Atlantic ocean. The Early Cretaceous ocean-forming event was preceded by a doming and rifting episode at the end of the Jurassic with faulting, basaltic igneous activity, and accentuated halokinesis.

NORTH SEA-TYPE RIFTS The rift system of the North Sea is highly complex and individual rifts show varied styles of development, but the distinctive feature of the system is that the rifts, after establishment in Permian times, have experienced repeated renewed activity without ever developing ocean floor (Whiteman et al 1975a, b; Ziegler 1975b; Woodland 1975). The Viking graben, for example, was initiated in the Permian and was active in Triassic, Middle and Late Jurassic, and Lower Cretaceous times. The Middle Jurassic (Bathonian) episode was the most important phase of renewed rifting in the North Sea. During this phase a classic dome system centered on the area underlying the Piper oil field with basaltic vulcanism, and three radial rifts were developed (Figure 6).

During the varied Mesozoic rifting episodes more than three kilometers of sediment accumulated in North Sea graben, but continental rupture between Greenland and Norway and the British Isles at the end of the Paleocene was accompanied by a radical change in the style of North Sea structural development. The individual rifts ceased to subside independently and a broad trough coaxial with the present North Sea began to develop, filling with sediment largely eroded from the high ground around the igneous centers of the west of Scotland. This

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change from a narrow subsiding rift system to a later broad basin is like that recognized by Soviet geologists in aulacogens. In the Athapuscow and Southern Oklahoma aulacogens the change to a broader basinal structure correlates with the onset of collisional orogeny (Hoffman, Dewey & Burke 1974). Evidence from the North Sea shows that the change may occur in a failed rift system extending toward a continental margin and is not restricted to the onset of convergent processes.

Other areas in northwest Europe provide the best described examples of North Sea-type rifts. The Mesozoic developments of the More and Voring basins of offshore Norway (Ronnevik et al 1975) and the Aquitaine basin in France (BRGM et al 1974) are comparable. Episodes of repeated rifting without ocean formation

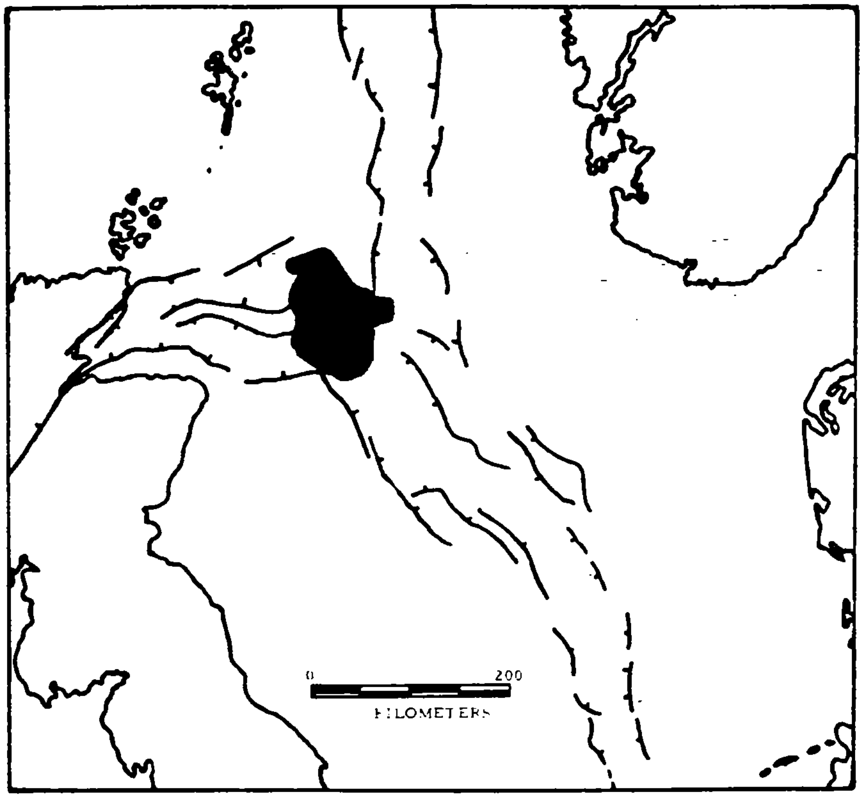

Figure 6 Jurassic volcanics of Piper area (black) in the North Sea lie at the three-rift junction of Central, Viking (top of map), and Moray (left of map) graben. Uplifted structure within the Moray graben is Halibut horst. North Sea graben developed in Permian times and were repeatedly reactivated in the Mesozoic. In the most violent reactivation in mid-Jurassic times, whose effects are depicted here, basaltic volcanism, uplift, erosion, and deposition of thick marine and nonmarine graben facies sediments all occurred (based on papers in Woodland 1975).

similar to those that have struck northwestern Europe since the Permain have not been described from other parts of the world, and they may be very unusual phenomena.

BENUE-TYPE RIFTS There is clearly a gradation from rift to ocean as axial dike emplacement increases. Very narrow oceans that have opened and soon after shut are not different from wide rifts involved in convergence. This generalization is significant in the interpretation of aulacogens as it implies that there is a gradation, in the more tectonized of aulacogens, into fold belts.

The type example of a rift system that has large-scale compressional folds parallel to its axis is the Benue rift system of Cretaceous age striking into Africa from the shoulder of South America (Burke & Dewey 1974; Burke, Dessauvagie & Whiteman 1971). This is a large-scale structure nearly 1000 km long and 100 km wide. At its southeastern end the occurrence of andesitic volcanics and associated intrusions suggests that where widest the Benue ocean contained enough lithosphere to subduct to a depth where partial melting could induce andesite formation, that is, about 100 km.

MISSISSIPPI-TYPE RIFTS The early history of the Mesozoic rift occupying the southern Mississippi embayment is of Sergipe type with continental clastics below Lou Ann salt (Lowest Jurassic?), and this development appears related to the formation of the Gulf of Mexico ocean. After continental-margin, shelf-sea development in the later Mesozoic, with carbonate reefs fringing much of the northern shore of the Gulf of Mexico, Cenozoic history was dominated by deltaic progradation (McGookey 1975). In the Paleogene, deltas formed by the erosion of Laramide mountains developed in the northwestern corner of the Gulf, but by the Neogene, deltaic activity was concentrated in the Mississippi and the river prograded down its embayment until its delta lay on oceanic crust. Progradation of major rivers in this way down failed rift systems is very widespread and many examples were discussed by Burke & Dewey (1973). Different kinds of rifts with variable early histories are likely to develop prograding deltaic systems of Mississippi type. Additional examples include the Gabon and Cuanza basins (Burke 1976a) and the Mackenzie delta. Special cases of deltas that prograde along rifts are those that reach oceanic crust that is young, hot, and still rapidly subsiding. The most obvious example of this kind of delta is that of the Colorado river. In some older cases where sediment supply has been cut off to deltas deposited on rapidly subsiding ocean floor, the entire delta may lie at depths of 1 km or more. The "delta of the Barentz sea" (Briseid & Mascle 1975) is an example of this style of behavior. As Greenland slid past Svalbard by transform motion (Talwani & Eldholm 1972), erosion of the "Alpine" mountains of Spitzbergen (Birkenmaier 1972) provided large volumes of sediment that were carried by river across the Hammerfest Basin (Ronnevik et al 1975) to lie on the young ocean floor of the Norwegian Sea.

Once Greenland was free of the coast of Spitzbergen, the Alpine mountains, no longer dynamically maintained, were eroded away and sediment supply to the Barentz delta was cut off. As the delta lay largely on ocean floor, less than 10 m.y. old, it has sunk in the last 35 m.y. to its present depth

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AULACOGENS AND FAILED RIFT SYSTEMS STRIKING INTO FOLD BELTS

The distinction of 11 different kinds of failed rift systems striking into continents from ocean margins gives an idea of the diversity of development that can be expected in aulacogens since the oceans in which the rift systems end can be expected to close at some time in the future, turning these failed rift systems into aulacogens. Because aulacogens are subject to further tectonic and erosional events, it is unlikely that the rocks in them record the same diversity as rift systems striking into oceans. For this reason, no attempt at subdivision of aulacogens is made here. Instead, after a brief discussion of what happens to a failed rift system at a collision, the properties of some examples are reviewed, roughly in order of increasing age.

The Later History of Aulacogens

Events that happen in aulacogens as a result of continental or island arc collision have been well described from the Athapuscow (Hoffman 1973) and Southern Oklahoma (Ham & Wilson 1967) structures. In both these areas thick, coarse clastic sediments, marine below, nonmarine above, eroded from the rising collisional mountains, have been deposited in a trough about three times as wide as the rift structure active in earlier history. Local sediment derivation is also important within both troughs and indicates the existence of upfaulted blocks. Wickham et al (1975) recognized large-scale left-lateral strike-slip faulting active in the Southern Oklahoma aulacogen during the deformation associated with the Ouachita collisional orogeny at the end of the Paleozoic. This kind of within-plate deformation at collision is becoming widely recognized (e.g. Molnar & Tapponnier 1975). The abnormal lithosphere in the aulacogen provides a locus for displacement and deformation. Similar strike-slip faulting and related deposition may have occurred in the Athapuscow structure, and the great McDonald fault forming the southeastern boundary of the aulacogen could well be an analogue of the strike-slip faults of Asia that Molnar & Tapponnier (1975) associate with the Indo-Asian collision.

Aulacogens and Failed Rift Systems of Phanerozoic Fold Belts

TETHYAN SYSTEMS Because continental collision in the Alpine-Himalayan mountain system is still incomplete, fully developed aulacogens are not common. Rifts developed in association with the opening of Tethys have been widely recognized (see Dewey et al 1973, especially p. 3156) and in the Upper Triassic of western Tethys Sergipe-type rifts were particularly common. Only the Upper Rhine graben, whose site was occupied by the Hessian-Thur depression in the Triassic (Ziegler 1975a, Figure 8; Ziegler 1975b, Figure 11), appears to be completing the aulacogen cycle as the Rhine carries detritus northward from the Alps.

IAPETAN SYSTEMS The ocean that opened and closed in forming the Northern Appalachians and Caledonides has been called Iapetus (after the putative father of Atlantis). Rift systems striking into North America at the same time as the opening of this ocean include the site of the Southern Oklahoma aulacogen and the Ottawa-

Bonnechere graben. Rankin (1975) has identified late Precambrian volcanics at the Sutton mountains (Quebec), South Mountain (Pennsylvania), and Mt. Rogers (Virginia), marking places where rifts that evolved to become Iapetus met the Ottawa-Bonnechere graben and two more southerly failed rifts. Kay (1975) suggested that the Ottawa-Bonnechere graben might be a later feature but the early Paleozoic ages obtained by Doig (1970) on alkaline intrusions along the westward extension of its strike and the Cambrian and Lower Ordovician thick sections near its mouth (Rickard 1973) are good evidence for its origin at the time of the opening of Iapetus.

The Ottawa-Bonnechere graben illustrates how incomplete the record in an old failed rift system may be. Although thick clastics derived from the Taconic arc collision are known in the Appalachians of Quebec and of New York State, to the north and south, there is no preserved thick section representing the later stage of aulacogen development in the graben itself. The reason for this appears to lie in the fact that the Ottawa-Bonnechere graben has been the site of Cretaceous hot-spot (nonplate margin) vulcanism, presumably localized by its abnormal lithosphere. Uplift associated with this vulcanism has led to erosion of the higher sequences from the graben, which seem likely to have contained evidence of derivation from the Appalachians.

Farther east the history of failed rift systems on this side of Iapetus is, as yet, poorly known. Doig (1970) reported early Paleozoic dates on alkaline intrusions at Saguenay, in Labrador, and in West Greenland that may mark the sites of failed rifts, and a pattern of continental margin headlands and embayments northeast of the site of Iapetus that is discernible on the *Tectonic Map of North America* (King 1969) from Marathon and the Mexican border can be extended as far as Newfoundland. Across the Atlantic Kidd (1975) has interpreted the Moine-Dalradian sediment wedge of Scotland as being related to two-stage rifting of Iapetus, but much remains to be done in this area.

In places on other sides of the Iapetus ocean the beginning of the Paleozoic appears to have been mainly marked by convergent phenomena (Burke 1975b). Rifting is indicated by the greatly increased thickness of the Eocambrian Sparagmite formation north of the Oslo graben (Strand & Kulling 1972, p. 18) and the contemporary alkaline intrusions of the Fen area. Aki, Husebye & Christofferson (1975) mapped anomalous lithosphere beneath the Norsar array in this area, but it is not at present possible to distinguish whether this material formed at the opening of Iapetus or in the later Permian rifting on the same site that formed the Oslo graben. Whittington & Hughes (1972) detected major differences between early Ordovician faunas of Scandinavia and southern Britain, and this may imply the existence of a barrier to faunal migration, possibly a rift roughly on the site of the North Sea at this time. The Charnwood Forest late Precambrian of southern Britain in the same area strikes at a high angle to Iapetus and may, like the Benue trough, be the locus of the opening and closing of a narrow ocean.

Aulacogens and Failed Rift Systems of Proterozoic Age

NORTH AMERICA Proterozoic failed rift systems have been widely recognized in North America. Burke & Dewey (1973) concluded that a prominent set of rifts now

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exposed in tectonized condition within the Cordillera, but striking at right angles to its general north-south trend, marked an episode of continental rupture about 1200 m.y. ago and thus dated the origin of the Pacific ocean. But Stewart (1976) interpreted these structures as intracontinental considering that a continental rupture episode was better dated by occurrences of miogeoclinal sediments in the Cordilleran, Innuitian, and Appalachian mountains with ages ranging from 850 to 540 m.y. This difference in interpretation arises, at least in part, from difficulties in dating rocks, especially sediments, in the Precambrian. Dating imprecision is a general constraint on Precambrian aulacogen studies. For example, the Amaragosa aulacogen of Death Valley (Wright et al 1974) contains a sequence of several kilometers of sediment, but it is not yet possible to refine the timing of its distinct depositional episodes to within several hundred million years.

An exceptionally well-dated Precambrian failed sift system is the Keweenawan, which, on zircon dating, appears about 1140 m.y. old (L. T. Silver, cited in Symposium 1972). The Keweenawan rift is mainly filled with volcanics at outcrop in upper Lake Superior (Symposium 1972). It continues southwestward as the midcontinent structure producing the prominent gravity and magnetic anomalies typical of ancient rift systems with axial dikes (Burke & Whiteman 1973). Chase & Gilmer (1973), noting that offsets of the midcontinent gravity high can be described as small circles about a pole in Mexico, have ingeniously suggested that the midcontinent gravity high marks a spreading ridge and that the offsets are transform faults at right angles, but the structure of younger intracontinental rifts shows that concentric transforms develop only when true ocean floor is formed. The Keweenawan appears not to have reached this stage and it seems unlikely that the midcontinent structure, closer to the proposed descriptive pole, could have done so.

In a triple-rift junction at the lower end of Lake Superior, the Keweenawan rift joins the Kapuskasing failed rift of Ontario and a buried structure striking under the Michigan basin that Burke & Dewey (1973) first interpreted as a rift from its gravity and magnetic signature. Deep drilling on this structure has revealed the presence below the oldest Cambrian rocks of 1500 m of what may be Keweenawan graben fill with diabase in a Newark-type rift (Sloss 1976). The development of the broad Paleozoic Michigan basin over this Proterozoic failed rift suggests comparison with the relations between the Cenozoic North Sea broad basin and underlying Mesozoic rifts and also with the Neogene Chad basin and its underlying Cretaceous rifts (Burke 1976b).

The development of the Michigan basin may have had a more direct relationship to Late Proterozoic rifting. Ervin & McGinnis (1975) have shown that a Late Proterozoic rift on the future site of the Mississippi embayment received early Paleozoic sediment and there is evidence that thick accumulations of Cambrian and Early Ordovician sediments extend northward into the Michigan basin (Shell Oil Co. 1975).

EASTERN ASIA AND AUSTRALIA Because of their position on the opposite side of the Pacific from North America, these continents are places to look for Proterozoic rifts that might be complementary to those of western North America. Rifting episodes of about the right age exist in both continents and P. Washington has suggested (personal communication, 1976) that the Proterozoic continental margin of Baikalia with its aulacogens fits very well against that of contemporary Western North America.

In Australia, where Rutland (1973) first identified the Adelaide "geosyncline" as an aulacogen, there are complex rift systems with thick sedimentary sections of Proterozoic age striking into the Tasman fold belt that occupies the whole eastern part of the country. These features thus satisfy the definition of aulacogen used in this review and published descriptions of them (in Brown, Campbell & Crook 1968) present intriguing features. For example, rift-type bimodal volcanics lie at the bottom of 15 km of shallow water sediments in the Adelaide aulacogen. In the latest Precambrian and earliest Paleozoic the Adelaide structure appears to have opened to the south into the Kanmantoo fold belt, which shows a typical re-entrant at the aulacogen mouth, but isopach maps on older lithounits within it indicate that the aulacogen may have opened earlier into the ocean at its northern end. Although the Proterozoic of Australia contains structures, especially the Amadeus basin and Adelaide geosyncline, that are clearly aulacogens, there has been, as yet, no published discussion of their development in relation to Proterozoic Wilson cycles of opening closing of oceans.

Aulacogens and Failed Rift Systems of Archaean Age?

Although the rigidity of the oldest continents is demonstrated by the more than 3 b.y. old Ameralik dike swarm of western Greenland, there are no very old recognized failed rift systems. Burke, Dewey & Kidd (1976, p. 116) considered the southern Huronian, about 2.3 b.y. old, as the earliest candidate for deposition in an aulacogen and the Great Dike of Rhodesia, intruded 2.65 b.y. ago (Allsop 1965), is a likely candidate for a very old rift structure. With its satellite dikes it forms a feature capable of producing the geophysically recognized properties of a rift-system axial dike complex (Figure 3), and it ends both to the north and the south in fold belts.

Coward et al (1976, Figure 5) have suggested that the Tuni ultramafic belt of eastern Botswana (?2.7 b.y. old) may represent a "failed arm," but it seems rather too strongly tectonized to meet the definition. In general, although Archaean greenstone belts show features typical of the Wilson cycle of opening and closing of oceans (Burke, Dewey & Kidd 1976), all rupturing events appear to have been successful in making ocean and no failed systems older than the Great Dike are preserved. The general success of rupture events seems a likely consequence of the then mechanical relations of lithosphere and asthenosphere caused by the need to dissipate more heat from the early earth by making plate boundary and oceanic lithosphere at a faster rate than now (McKenzie & Weiss 1975).

If the absence of old rifts is not just an accident of preservation, the onset of failed rift and aulacogen formation about 2.6 to 2.3 b.y. ago is a secular change brought about as the earth became older. It is one of very few such structural changes recognized to date.

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CONCLUSION

Continental rifting can be the start of a highly complex sequence of events that culminates in the development of aulacogens. The lithospheric peculiarity of the rift environment is established early in its history, but further development can be very diverse and it is not yet possible, for example, to explain why some rifts form oceans while others do not.

It has only been since the recognition of the plate structure of the world and the realization that this kind of structure has existed for at least the latter half of earth history that the behavior of old and new rifts has been seen as broadly similar and relatable to cycles of opening and closing of oceans. Further appreciation of this unity will help in the understanding of rift structure. Although, for instance, the stratigraphy and shallow structure of the southern Oklahoma aulacogen are well known from over 75,000 oil wells, the petrology of the igneous rocks at the base of the rift and its deep structure are virtually unknown. Studies of these phenomena will help to show how close the analogy is between the Oklahoma structure and the rifts of East Africa. With intensified searches for fluid hydrocarbons attention will focus on the thermal histories of rift systems, and this should help in understanding their structural development.

It is clear that many young rift systems are associated with the breakup of Pangea (Figure 2). Study of ancient rift ages and distribution should help to show whether such continental unions are the statistically likely result of random motion at plate speeds of continental objects covering one third of the earth or have some other cause. Sawkins (1976) has identified an episode of widespread continental rifting about 1.1 b.y. ago and suggests there may have been another at about 2 b.y.

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