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WORLD DISTRIBUTION OF SUTURES — THE SITES OF FORMER OCEANS

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ABSTRACT

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Continental collision is an inevitable consequence of plate motion. We show that many mountain belts within continents are products of continental collision and suggest that this process produced all fold mountain belts that now lie within continents although the destructive effects of suturing have in some cases eliminated from preservation much of the evidence of operation of the Wilson cycle of ocean opening and closing.

We review the distribution of sutures of Proterozoic and Phanerozoic age in all continents except Antarctica and conclude, from consideration of 57 major suture zones, that plate-tectonic processes have operated on the earth throughout the last 2.5 b.y. and that it is unnecessary to invoke the operation of non-uniformitarian ensialic mountain building processes to explain any ancient fold belts.

INTRODUCTION

Plate structure of the lithosphere and its consequences for historical geology

In 1965, Tuzo Wilson showed that the lithosphere was broken into large plates in horizontal motion with respect to each other along transform, convergent, and divergent boundaries. Within three years, publications, mainly by seismologists and marine geologists, reported confirmation of Wilson's idea and application of it to the spherical earth showed how plate tectonics could be used to describe the evolution of lithospheric structure over the last 200 m.y. (see, for example, McKenzie and Parker, 1967; Morgan, 1968; Le Pichon, 1968). In 1968, Wilson followed his recognition of plate structure by pointing out that the existence of plate motion made it appropriate to analyze earth history in terms of complex interwoven cycles of ocean opening and closing. Plates in motion over the earth's surface carrying continental material that extends over one-third of that surface are bound to produce continental collisions and, unless the continents become welded into one piece that remains intact, there will also be continental ruptures. Wilson (1968a) distinguished rocks and structures characterizing stages in the evolution of ocean basins from rifting to collision elaborating his ideas in the second edition of his textbook (Jacobs et al., 1972).

The idea that mountain belts mark former sites of oceans can be seen in the writings of an earlier generation of Alpine geologists (for example, Argand, 1924). Wilson's contribution was to show that this conclusion followed directly from appreciation of the plate structure of the lithosphere. Dewey (1969) and Hamilton (1970) were first to interpret mountain belts (the Caledonides and the Urals) as products of continental collision in plate-tectonic terms, and the idea that mountain belts represent places where oceans have opened and closed was further developed by Dewey and Bird (1970) and applied to analyses of the Appalachians (Bird and Dewey, 1970; Dewey and Bird, 1971) and the Alps (Dewey et al., 1973). Dewey and Burke (1974) used the name Wilson cycle for the cyclical process of ocean opening and closing because Wilson had been the first to appreciate the importance of this process on a plate-structured earth.

Because rigorous plate-tectonic analysis is only possible where ocean floor structure permits accurate location of sequential finite-difference poles and because all pre-Jurassic ocean has been subducted or obducted (except possibly in the North Caspian depression, Burke, in press), evidence of older plate motion is only preserved in the rocks and structures that indicate operation of the Wilson cycle. Opinions differ somewhat among geologists on how long ago the Wilson cycle began to operate on the earth. Some are content with the idea that the Wilson cycle can be used to describe mountain building processes from the Mesozoic on, but refined analyses of Palaeozoic mountain structure in terms of the Wilson cycle have been made, especially for the Tasman, Appalachian, Hercynian, and Caledonide belts. A major increase in the plausibility of these analyses accompanied the realization that much of the material preserved in mountain belts is associated with the closing of marginal basins rather than major oceans (Dewey and Bird, 1971).

Precambrian Wilson cycles?

Opinions are very sharply divided about whether ocean opening and closing processes operated in the Precambrian and about whether other processes, peculiar to those times, replaced Wilson cycles or operated simultaneously with them. The doctrine of uniformitarianism would suggest that the processes operating today operated in the past, but it is clear that in the remotest past the doctrine breaks down. There was no plate tectonics during inhomogeneous accretion. In its extreme form of application in the Precambrian, uniformitarianism states that the oldest preserved rocks, predominantly basalts and granodiorites, are like those being formed by plate-tectonic processes today and, therefore, plate-tectonic processes operated at that time. Some papers in Windley's (1976b) symposium and Mackenzie and Weiss (1975) adopt an attitude approaching this but in the view of some other authors contributing to the symposium and of Hargraves (1976) the processes operating on the earth in the Precambrian were very different.

Many writers who reject the idea of Wilson cycles in the Precambrian do so because they see no signs of large-scale horizontal motion, but this is not unexpected because the processes of subduction and obduction destroy geological evidence of large-scale horizontal motion leaving only suture zones whose size is independent of the size of the ocean whose closure they mark (Dewey, this volume).

Geophysical arguments

Geophysical arguments have figured on both sides of the controversy about horizontal displacements in the Precambrian. In the nineteen-fifties, palaeomagnetists, using what, in restrospect, look like rather poor data, had played an important role in convincing sceptical geologists about the reality of the large-scale displacements of continental drift. In contrast, in the nineteen-seventies, some palaeomagnetists have interpreted Precambrian data as showing that much continental material was in one piece for long intervals (Piper et al., 1973), or even (Piper, 1976) that nearly all was in one continent for nearly half of earth history. We have shown elsewhere (Burke et al., 1976b) by plotting apparent polar wander paths for areas between sutures that Precambrian paleomagnetic results, given their general imprecision, are just as compatible with operation of the Wilson cycle as with other less uniformitarian tectonic hypotheses.

The other geophysical consideration that has been widely used in discussing Precambrian tectonic regimes is the secular variation in terrestrial heat generation. Because of the relatively short half-lives of potassium and uranium, heat is now being generated in the earth at about half the rate that it was at the end of Archean times. Lambert (1976), Hargraves (1976), Fyfe (1976) and many others have suggested that this greater heat was mainly lost by conduction through the lithosphere and that unusually steep thermal gradients characterized the Precambrian, but others (for example: Mackenzie and Weiss, 1975; Burke et al., 1976a) have pointed out that this approach overlooks one of the most significant consequences of the recognition of plate structure. Sclater and Francheteau (1970) showed that the main way heat escapes from the earth is by the making of lithospheric plates at mid-ocean ridges ($\sim$10% of earth heat loss) and by cooling it as it ages ($>$50% of earth heat loss). Double the quantity of heat could have been dissipated from the earth in the Archean by generating twice as much sea floor in unit time. This could have been achieved by having twice the length of ridge that we have now or the same length and spreading twice as fast. This condition would not have required exceptionally steep thermal gradients and the idea of steep thermal gradients seems improbable because pyrolite will always partly melt to make basalt at similar pressures and temperatures, and the process of plate tectonics involving the production of a cooling boundary conduction layer of basalt and depleted pyrolite is such an efficient way of cooling the earth that it seems unlikely that any other process operated from the time there was free water on the earth's surface.

Alternatives to operation of the Wilson cycle in the Precambrian

Hargraves (1976) is an example of the high thermal gradient and lithospheric conduction Precambrian model. He envisages an early earth with a continuous sialic continental cover about 8 km thick overlain by 2 km of water, the mantle below convects and basalt, produced by partly melting mantle, is erupted through the sial to build greenstone belts as submarine piles on top of submerged continent. Perhaps the most implausible feature of this model is that the eruption of the huge volume of basalt is achieved without development of any dike or rift system in the continent such as forms today. It might be argued that the boat shape of greenstone belts justifies this idea, but we have recently reviewed the evidence (Burke et al., 1976a) and concluded, following Ramsay (1963), that greenstone belts are sites of extreme horizontal compression and that the typical greenstone belt boat shapes are the results of horizontal tectonics rather than primary deposition.

We have also shown (Dewey and Burke, 1973) that the reactivated terrains common in the Precambrian are closely analogous to the Tibetan plateau and have interpreted them as products of continental collision, but Hepworth (1972) and later other authors have suggested that reactivated terrains may be related to rifting associated with aborted continental rupture rather than to continental collision. Fortunately, the geology of failed rift systems is well known (Burke and Whiteman, 1973; Burke and Dewey, 1973a; Burke, in press) and in structure and geochemistry it is quite unlike that of reactivated terrains. Igneous activity in rifts is predominantly alkaline with abundant basalt and seldom involves partial melting of continental crust. Where it does, the products are very local as in the southern Malawi in the Cretaceous and northern Nigeria in the Jurassic. Rift structures are everywhere predominantly tensional. By contrast, reactivated terrains contain: abundant granite and granodiorite, enormous amounts of partially melted continental crust and structures that are overwhelmingly compressional, the only tensional features being of the type commonly formed on fold limbs in compressional environments. A further important difference is that reactivated terrains extend over large areas while rift systems are long, narrow and branching. There is thus no analogue at all between the well documented properties of failed rift systems and those of reactivated terrains. Engel et al. (1974) produced the striking idea that plate tectonics had operated in the Archean but not again till after the Permian, but Mitchell (1975) suggested that this conclusion, largely based on alkali oxide ratios, resulted from inadequate recognition of the effects of collision. The difference between Proterozoic and Archaean rocks that led Engel and his colleagues to their conclusion has long been familiar to Precambrian geologists. Ocean floor and island-arc rocks are widespread in the Archean but restricted to suture zones in Proterozoic and Paleozoic rocks. Mackenzie and Weiss (1975) attributed this difference to the greater role played by small-scale convection in the Archean and Burke et al. (1976a) attributed it to the not very different idea of a greater length of plate boundary required to dissipate more heat in the Archean.

Planetologists (for example: Lowman, 1976; Kaula, 1975) have compared the Precambrian earth to other terrestrial planets. All recognize either explicitly or implicitly, the dominance of water in controlling the earth's plate-tectonic behavior.

Episodicity in orogeny?

When numerous radiometric ages first became available on Precambrian rocks, histograms of numbers of ages against time were plotted (for example: Gastil, 1960) and episodicity of orogeny was in some cases inferred from irregularities in the patterns. As the varied significance of radiometric ages was realized and influences rendering plots of all the data a poor record of episodicity, if it occurred at all, the practice of making such histograms died away. Sawkins (1976) has made a more sophisticated approach to the question of episodicity. He pointed out that there is evidence in most continents of rifting events at about 1.1 b.y. ago just as there is evidence of rifting in the last 200 m.y. associated with the rupture of Pangea. Sawkins sees less distinct evidence for an earlier episode of continental rupture at about 2.0 b.y. If there is episodicity in rifting, it is an important question whether or not it merely reflects the statistical likelihood of occasional continental assemblies and disruptions or whether there is a more fundamental episodicity in earth behavior.

Ocean closure sites within continents?

If the Wilson cycle operates, it must produce continental collisions, the sites of which are preserved as orogenic belts within continents. In this paper we review the evidence on which we believe such sites can be identified in all continents except Antarctica. A companion paper (Dewey, this volume), using the Alpine—Himalayan mountain belt as an example, outlines the complexity and diversity of suture zones and in an earlier paper (Burke et al., 1976b) we demonstrated the compatibility of the paleomagnetic evidence with Precambrian operation of the Wilson cycle.

Ophiolites, megasutures, minisutures

The best evidence of the closure of an ocean is the occurrence of a fully developed ophiolite sequence (a piece of ocean floor) in a fold belt between two cratonic areas. As Dewey (this volume) shows, the chances of preservation of this kind of evidence are small and only one fully developed ophiolite sequence of Precambrian age (Leblanc, 1976) has as yet been recognized.

If the Pacific is a good example of a mature ocean, then numerous arc events can be expected between opening and closing of fossil oceans. Marginal basins will generally be associated with the arc events and the floor of these basins is likely to be obducted in arc collision events and preserved as sutures. It is paradoxical that study of Paleozoic mountain belts has shown that the preservation of marginal basin floor in what might be called minisutures is more common than preservation of main ocean floor in what might be called megasutures (Kidd, in press). Dewey (this volume) discusses this point. A likely reason for the greater probability of subduction of main ocean floor and obduction of marginal basin ocean floor is that the latter is young and hot, while the former is old and cold.

Dewey's review (this volume) indicates that there are very good chances that no ocean floor material at all is preserved where an ocean has closed and and in these cases less direct evidence has to be sought and can often be found. If the Wilson cycle is the only process that operates, then any fold belt within a continent marks a place where an ocean has closed. In following sections we consider a number of fold belts and explain why we think they mark sutures, places where oceans have closed.

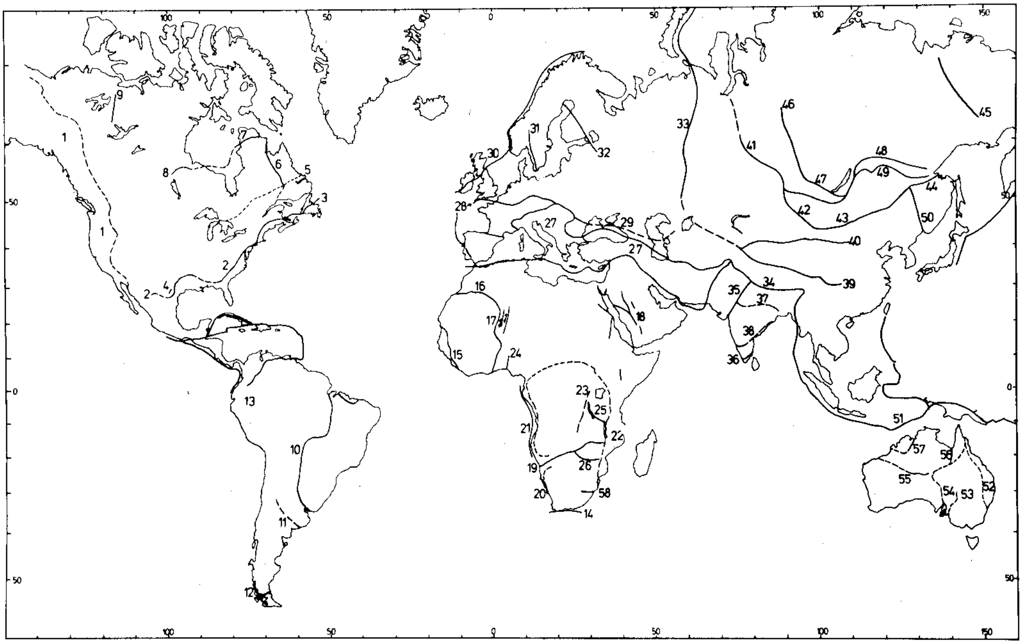

Fig. 1. World map showing distribution of major Phanerozoic and Proterozoic suture zones.

NORTH AMERICA

Cordillera (Fig. 1:1)

The Cordillera of western North America records a Proterozoic continental rupture marked by aulacogens and failed rifts striking into the continent. Burke and Dewey (1973b) suggested that this event took place about 1200 m.y. ago and that it dated the opening of the Pacific Ocean although Stewart (1976) favored a younger age because massive development of the Cordilleran miogeoclinal wedge took place only in the later Precambrian. The Phanerozoic history of the Cordillera starts with a well developed Atlantic-type margin and records convergent and strike-slip phenonema from the Devonian on. Several episodes of marginal basin development occurred and closure of these basins led to the formation of minisutures (Burchfiel and Davis, 1972; Monger et al., 1972; Schweikert and Cowan, 1975) some of them strikingly like greenstone belts in appearance (Burke et al., 1976a, fig. 4).

The North American Cordillera is a wide structure up to 1500 km wide at the most, and resembles the Tasman belt of Australia in this respect. The unusual width of these two orogens may be related to the fact that their history does not yet include a major continental collision as both have faced ocean since a rupture episode in the Proterozoic.

Southern Appalachians (Fig. 1:2)

Six aulacogens strike into North America from re-entrants in the Appalachians in west Texas, south Oklahoma, Virginia, Pennsylvania, and Quebec (Burke, in press). Rankin (1975) considered that dated volcanic rocks at the mouths of three aulacogens showed that continental rupture leading to the formation of the Iapetus Ocean started about 820 m.y. ago. The development of an Atlantic-type continental margin throughout the length of the Appalachians in Cambrian and Ordovician times is well documented (Bird and Dewey, 1970; Rodgers, 1970) and although the history of later Paleozoic arc and continental collision is known in some detail in the northern Appalachians, no such detailed analysis is yet available for the southern part of the chain. Williams (1976) has traced the Humber, Dunnage, Gander and Avalon zones of Newfoundland into the southern Appalachians. Since Paleozoic sutures lie within the Dunnage zone in the north ocean closure must be represented in the equivalent to the south although its location and character have not yet been defined. The southern Appalachians also contain an end Paleozoic continental collision orogeny whose suture zone lies under the continental shelf. This event is not important north of New York except in a small area around Boston. Dewey and Burke (1973) accounted for this by dominantly transform motion in the area of the Atlas Mountains and Arthaud and Matte (in press) have refined this interpretation.

The Ouachita Mountains, a westward extension of the southern Appalachians, have been interpreted as the site of continental or arc collision by Wickham et al. (1976) and Graham et al. (1975) interpreted the Carboniferous flysch of the Ouachitas as deposited on ocean floor, like the Bengal fan, and thrust onto continent in later convergence. The occurrence of tectonic slivers of serpentinite in the flysch (Sterling and Stone, 1961) seems strong evidence in support of the idea that it was deposited on ocean floor.

Northern Appalachians (Fig. 1:3)

McKerrow and Ziegler (1972) offered an ingenious solution in terms of the Wilson cycle to the distribution of the Erian, Acadian, Hercynian and Alleghenian deformations in the Appalachians and Caledonides. They related the Erian phase to the collision of North America—Greenland with the Baltic Shield closing the Iapetan Ocean. Acadian deformation they considered a product of collision of the Acadian continental (or inactive arc) prong with the northern Appalachian area already deformed in the Erian event. At the same time, South America (from Peru to Venezuela) collided with the Prong and the more southerly Appalachians closing part of the Rheic Ocean and southern Iapetus. After the Acadian collision renewed rupture followed by counterclockwise rotation of Africa and South America with respect to North America led to final closing of the Rheic Ocean and formation of the Hercynian mountains. Rast et al. (1976) have modified this scheme to accommodate successive arc or microcontinental collisions.

Dewey and Kidd (1974) considered the varying intensity of collision along strike in the northern Appalachians as related to the irregularity of the continental margins (Dewey and Burke, 1974) emphasizing the abundance of granite and granodiorite in the zones of intense collision, where sutures are cryptic, and the relatively well preserved ophiolites of the zones of less intense collision.

Innuitian Orogen

The Arctic Islands of Canada (not shown on Fig. 1) contain a well developed Lower Palaeozoic collisional orogenic belt (Trettin et al., 1972) that has been ruptured by the opening of the Arctic Ocean (Herron et al., 1974) so that the mobile core and the suture zone are divided between the continental shelf of the Arctic Islands and that of northern Siberia. In both areas they are overlain by Later Mesozoic and Cenozoic miogeoclinal accumulations and are unknown at outcrop. As Trettin et al. (1972, p. 167) point out, the orogen may have involved collisions with island arcs and, in Mid- to Late Devonian time, must have involved a collision with Siberia but critical evidence has been removed and buried. Ultramafic rocks at M'Clintock Inlet may represent dismembered ophiolite involved in arc or continental collision.

Llano (Fig. 1:4)

North America is almost surrounded by three Paleozoic orogenic belts, the orogens of the eastern and northern coasts were involved in Paleozoic continental collisions and Mesozoic ocean opening events while that on the west coast has experienced no continental collision, only arc, microcontinental, marginal basin and strike-slip events since the mid-Proterozoic. Older mountain belts within the continent, if produced by the Wilson cycle must represent continental collisions. Analysis of the major area of Precambrian outcrop in the Canadian shield in terms of the Wilson cycle is progressing, but interpretation of the inliers of Precambrian rock farther south in the same terms is likely to make slow progress. Although individual environments can be distinguished (the serpentinite sliver of the Llano may well mark a suture and the volcanics of the St. Francois Mountains, a high-level Tibetan environment), the relations between isolated areas are too poorly known as yet to permit coherent analyses of regional structure.

Grenville (Fig. 1:5)

Baer (1976) has analyzed the Grenville Province as a product of continental collision. He envisages three major events in the reactivation history of the Province of which the earliest is the Elsonian emplacement of the anorthosite suite (1450—1500 m.y. ago). In the second stage, rifting associated with the opening of an ocean on the site of the Atlantic formed graben in Seal Lake and southeastern Ontario. Burke and Dewey (1973) located a third graben under the site of the Michigan basin. The Grenville Group was mainly deposited in the Ontario graben. The third event, the Grenville orogeny (about 1,100 m.y. ago) resulted from a continental collision along a suture zone that 'has now disappeared under or in the Appalachians' (1976, p. 500). In the case of the Grenville, as in the case of the Innuitian orogeny, there is sufficient evidence to permit recognition of the operation of the Wilson cycle although the suture zone itself is inaccessible.

Grenville rocks have been the subject of numerous paleomagnetic studies but, as Buchan and Dunlop (1976) point out, these are of limited value in tectonic interpretations as it is unlikely that any of three distinct components of magnetization sees through the high-grade Grenville regional metamorphism.

Labrador Trough (Fig. 1:6)

Wilson (1968b), Gibb and Walcott (1972), and Burke and Dewey (1973a, b) have all suggested that a suture lies to the east of this Proterozoic structure in the Canadian Shield and Sutton and Watson (1974, p. 434) interpret the structure as a 'tear' along which an ocean may have been formed and subsequently destroyed. Dimroth (1972) has summarized the geological evidence on which most authors base their interpretations. Shelf sediments, including the Labrador iron ores extend for a distance of more than 500 km from north to south along strike and across strike to the east thrust masses include typical graben facies sediments and volcanics overlain by the rocks of a miogeoclinal wedge. This association is characteristic of Atlantic-type continental margins involved in later arc or continental collisions and is an association quite unknown in any environment other than a continental margin. Farther east, slivers of serpentinite lie close to the boundary between the greenschist and amphibolite facies rocks of the orogen, and farther east still there is reactivated basement with granite and granodiorite which we take to mark the other continent involved in the collision. Well developed dismembered ophiolites have not been described anywhere along the 500 km of the Labrador trough orogen and for this reason the suture here may be considered somewhat cryptic. Cryptic sutures often become less cryptic along strike and that of the Labrador trough is no exception. The trough can be mapped southward across the Grenville Front where its strike changes from NNW to SW and the site of the suture, although involved in Grenville metamorphism, can be followed through the same strike change as a line of mafic and ultramafic rocks extending at least as far as the Ontario border (Dorr and Laurin, 1971).

Cape Smith (Fig. 1:7)

Along strike in the opposite direction the rocks of the Labrador trough take another right-angled bend into the Cape Smith—Wakeham Bay belt. In this zone the shelf and graben facies, so well developed in the Labrador trough, are poorly represented but tholeiitic pillow lavas and mafic and ultramafic rocks, doubtless representing ocean floor, are so abundant that Baragar (1974, p. 156) reported 90,000 feet of section, presumably including thrust zones. At Wakeham Bay between Labrador and Cape Smith suture zones (6 and 7 on Fig. 1) it is possible to pass from reactivated basement onto Superior province gneisses without crossing any rocks of the Wilson cycle. At places where sutures are completely cryptic, such as this, little can be learned about the history of ocean opening and closing, the study of which must be pursued at other localities along strike. The suture zone passes westward from Cape Smith under the waters and Paleozoic sediments of Hudson Bay. It lies west of the Belcher islands and an aulacogen trends into Ungava from the fold belt at Richmond Gulf.

Thompson Front (Fig. 1:8)

West of Hudson Bay the suture zone is best known around Thompson in Manitoba (Coats et al., 1972) where the extreme compressional and strike-slip movements affecting mineralized ultramafic and mafic rocks (including pillow lavas) have been mapped in detail. West of Thompson near Manibridge spectacular agmatites mark the place where high potash granites of the reactivated Churchill province have invaded ultramafic rocks of the suture zone. The possibly ophiolitic nature of the Bird River sill, east of the Thompson front, was discussed by Burke et al. (1976a, p. 123).

Sutton and Watson (1974) rejecting the idea that the Wilson cycle was involved in the circum-Ungava or Labrador—Cape Smith—Thompson system suggested that strike-slip movements of non-rigid continent and internal deformation were responsible for much of the Proterozoic development of the Churchill province. They plot as lineaments a variety of structures including: the MacDonald fault (a strike-slip fault); the Thompson front (a suture) and the Grenville front (a complex structure but not a strike-slip fault) covering an age range in excess of 600 m.y. and find that these structures are concentric about a pole in the Aleutians. Because of the concentricity the lineaments are suggested to be some kind of intra-continental transforms. Of the plotted structures only the MacDonald fault bears much resemblance to an intra-continental transform. These features are normally associated with continental collision (Molnar and Tapponnier, 1975; Arthaud and Matte, in press) and are not normally concentric because they form boundaries to microplates. The intra-continental deformation model fails completely to account for the distribution of ocean-floor material in the circum-Ungava sutures and as the concentric structures have little in common with each other and the concentricity is not well established or likely to be significant, we conclude that the circum-Ungava orogeny is better interpreted as a product of the Wilson cycle. Gibb (1975) reached the same conclusion and it is noteworthy that although like Sutton and Watson, he considered fault systems, his orientations were quite different.

Coronation orogen (Fig. 1:9)

Hoffman (1973) showed that the Coronation orogen between Great Slave and Great Bear lakes recorded the development of an Atlantic-type continental margin and a failed rift system that were succeeded by convergence and the maturation of the failed rift into an aulacogen (Hoffman et al., 1974). This appears the oldest (~2.0—1.7 b.y.) Wilson cycle that is very well preserved, mapped and described. Uncertainty exists, mainly because of the limited area exposed, as to whether the convergent phenomena involve the collision of an arc or a continent or whether they represent an Andean margin. We interpret the relations as most resembling a continental collision. The Andean margin analogue is unsatisfactory because in allochthonous slices of the Coronation orogen there is material deposited seaward of the shelf break of the Atlantic-type margin and Andean margins develop farther into the continent. Both arc and continental collisions permit thrusting of material from over the shelf break onto the continent. Because the structure and geochemistry of the volcanics and high-level intrusives of the Bear province (Hoffman and Cecile, 1974; Hoffman and Bell, 1975; Badham,

1973) resemble those of Tibet, more than other environments, and in particular the buttress unconformity of Hoffman and Bell (1975, p. 63) with repeated movement of the Wopmay fault, seems closely analogous to the relations of the Kailas conglomerates of Tibet to the Himalayan back thrust (Gansser, 1964), we favor a continental-collision interpretation. Hoffman and Bell (1975, p. 64) see analogies to the Basin and Range and to Andean environments although calc-alkaline compositions do not occur in the Basin and Range tensional environment.

Penokean orogeny

Van Schmus (1976) interprets the Penokean of Wisconsin and Minnesota (not shown on Fig. 1) as representing an Andean margin developed about 1900 m.y. ago. It is not yet clear whether continental North America south of the Penokean area was sutured to the Superior province at this time or later.

SOUTH AMERICA

Cordillera

The age of continental rupture first forming a Pacific coastline to South America is not well established. A miogeocline of lowest Cambrian age, with *Olenellus*, is described from the PreCordillera of Argentina by Borello (1972) but the Paleozoic development of the Cordillera is relatively poorly known for reasons of inaccessibility, complexity, and obscuration by Mesozoic and Cenozoic rocks and tectonics. As DuToit (1937) showed, in Paleozoic times the Cordilleran continental margin swung southeastward in Argentina to join the Cape and Tasman fold belts. Although poorly exposed, the Paleozoic orogenic belt of Argentina in the PreCordillera and in such isolated areas as the Sierra de la Ventana (Fig. 1:11) shows resemblances to the Tasman belt with dismembered ophiolites (Borello, 1972, p. 296) and like the Tasman, may have been the scene of numerous arc and microcontinental collisions throughout the Paleozoic.

Mesozoic marginal basins (Fig. 1:12 and 13)

The Mesozoic development of the South American Cordillera has lately been shown to include episodes of marginal basin opening and closing at both its northern and southern ends. In the north the Caribbean had opened in the Early Jurassic (Ladd, 1976) and by the end of the Jurassic contained an island arc separated from Venezuela by a marginal basin. Closure of this basin by mid-Cretaceous times has left a minisuture locally preserved in the Caribbean Mountains and offshore islands of Venezuela (Maresch, 1974).

At the other end of the Andes a marginal basin opened behind an active andesitic island arc in the earliest Cretaceous and had closed again by the middle Cretaceous leaving a minisuture in the Rocas Verdes of southern Chile (Dalziel et al., 1974).

Marginal basins of Mesozoic age have not been identified between Venezuela and southern Chile, and it is interesting to speculate whether the plate structure maintained an Andean margin between these areas or whether more cryptic minisutures remain to be discovered.

Precambrian of South America (Fig. 1:10)

Most of the Precambrian of South America lies within the Brazilian and Guyana shields. The Late Proterozoic rocks of the Sierras Pampeanas of Argentina (Cordani et al., 1972) form an exception. They show a relationship to the pre-Cordilleran Lower Paleozoic rocks to the west similar to that between Late Proterozoic rocks and Tasman belt Paleozoics. Like their Australian analogues they may have been formed after the opening of the Pacific Ocean.

No coherent sutures have been recognized north of the Amazon younger than those in the greenstone belts of Venezuela, Guyana, Surinam and French Guiana that predate 2.0 b.y. South of the Amazon a huge area, constituting half of the Brazilian shield has been involved in mountain building in the Braziliane events (900—550 m.y. ago, Ferreira, 1972). This material includes both reactivated older basement and rocks which we regard as formed in ocean opening and closing events during the Late Proterozoic. We have plotted the western boundary of the area involved in Braziliane folding as Fig. 1:10. The Sao Francisco craton is a large isolated fragment of unreactivated basement within the area involved in Braziliane folding (Cordani et al., 1972, fig. 1) and Jordan (1972, figs. 6 and 7) shows what may be a sutured boundary on its northeastern margin with a correlation between the Bambui and Lavras rocks of the undeformed cratonal cover and the deformed and ultramafic rocks of the Serra de Jacobina. Perhaps this structural relationship may be extended to involve the Sergipe 'geosyncline' and the Caririan reactivated belt.

The strongest evidence for the existence of a suture zone within the Braziliane terrain comes from the line of dismembered ophiolites of the Brasilia trough that extends north—south for 600 km roughly along the 49th meridian. Quade and Stache (1972) considered that the ultramafics and associated rocks in the center of the trough lay in a 'eugeosynclinal' environment and that miogeoclines could be distinguished both to the east and the west. From their descriptions this area appears to have been the site of a cycle of ocean opening and closing in the Later Proterozoic. Brazilian geologists have not, as yet, made comprehensive attempts to apply the Wilson cycle concept to their Precambrian terrains. Information on the geological and tectonic maps of Brazil (1971) and the advanced state of radiometric age studies in the country suggest that when they do, very interesting analyses will emerge.

AFRICA

Phanerozoic sutures

Apart from PanAfrican events that extend up from the Late Proterozoic into the Cambrian mountain building activity in Africa during the Phanerozoic has been almost entirely around the edges of the continent. The most conspicuous exception is the highly folded 1000 km long, 150 km wide Benue trough of Cretaceous age. The trough (not shown on Fig. 1) is a fine example of the fact that fold belts within continents mark sites of ocean opening and closing. When the South Atlantic began to open at the beginning of the Cretaceous, the African continental mass formed two plates as an ocean began to open along the Benue trough. By 80 m.y. ago this ocean had sutured shut and Africa has since behaved as a single plate (Burke and Dewey, 1974).

Alpine events (Fig. 1:27) are beginning to mark Africa only in the Atlas Mountains but no Cenozoic suturing has yet occurred. At the southern tip of the continent in the Cape fold belt (Fig. 1:14) a Lower Paleozoic miogeocline went into the convergent mode in the Upper Paleozoic and evidence indicating a continental collision to the south is well preserved in the Permo-Trias of the Karroo foreland trough or exogeosyncline.

The Cape folds resemble the Innuitian because in both the suture zone has been removed in the opening of a later ocean. In both cases operation of the Wilson cycle can be clearly inferred from the rocks that remain. Development of the Cape Province graben in the Lowest Cretaceous marked the opening of an ocean south of the Cape fold belt as the Malvinas (Falkland) plateau slid past Africa in transform motion (Burke, in press). The Cape suture zone may have been wide, resembling those of the Tasman belt and the South America Cordillera along strike. If it was wide, parts of it may underlie not only the Falkland (Malvinas) plateau but also the concave side of the Antarctic peninsula.

Pan African suture around the West African craton (Fig. 1:15, 16, 17)

In 1970, Burke and Whiteman sketched the outline of PanAfrican suture zones around the West African craton (Burke and Dewey, 1973b, fig. 3; see also Burke and Dewey, 1972). Leblanc (1976) has identified rocks lying in the suture zone at Bou Azzer in Morocco as ophiolite and this occurrence is of special interest as the oldest ophiolite so far identified and the only described complete (that is, not dismembered) Precambrian ophiolite. Similar, but dismembered, ophiolitic rocks occur in tectonic association with calc-alkaline volcanics in the residual hills (boutonnieres) of the Wadi Saoura 500 km farther east and we extend the Bou Azzer suture zone along a curving strike through these isolated outcrops. The Tindouf and Ougarta basins, lying on the West African craton of the south of the suture zone, are excellent examples of foreland troughs (or exogeosynclines) formed during collision and overlying miogeoclines formed at the continental margin when the West African craton was ruptured. The strike of the axis of deposition in the two basins curves round parallel to the trend of the suture. An interpretation of the Tindouf basin as a marginal basin (Hurley et al., 1974) is not consistent with structural and stratigraphic evidence. Farther southeast, in the Ahaggar, there are rocks described as dismembered ophiolites by Leblanc (1976, p. 34) and Caby (1972). Studies in this general area by Caby (1970) and others over the last decade have revealed a sequence of events readily explained in terms of the Wilson cycle. A continental shelf with a miogeoclinal wedge is represented by the 'Stromatolite series' of Proterozoic age. Ophiolite obduction at the margin of this continent was associated with tectonism of island arc and marginal basin basalts, andesites and greywackes in an end Proterozoic (PanAfrican) continental collision. The later stages of this collision involved enormous strike-slip faults (>400 km long in Ouzzal) like those reported from Asia today by Molnar and Tapponnier (1975). The youngest products of the collision are potassic ignimbrites and glacial continental sandstones (of the 'Purple series') which are analogous to those forming on the Tibetan Plateau as a result of continental collision today. Similar isolated occurrences of potassic calc-alkaline late, or post, tectonic volcanic rocks with high-level granites have been reported from many areas of PanAfrican reactivation (for example: Barbeau and Geze, 1957; McCurry, 1975) and we suggest that, like those in the Purple series, they are surface expressions of the potassic acid magmas produced by widespread PanAfrican partial melting of the continent resulting from thickening in post-collisional convergence. The lavas of the Tibetan Plateau (Hennig, 1915) are the modern analogue.

Burke and Dewey (1972) described the PanAfrican suture farther south in Benin (Dahomey), Togo and Ghana emphasizing the character of the reactivated terrain in Nigeria to the east and the way in which the suture became progressively cryptic southward so that although greywackes, serpentinites, basalts, and calc-alkaline volcanic rocks outcrop in Togoland and easternmost Ghana, shelf and miogeoclinal sediments from either side of the closed ocean are in contact south of the Volta river. In Brazil, around Sao Luis, the suture zone is completely cryptic with reactivated basement in thrust contact with unreactivated.

The suture returns to Africa from South America in Liberia where Thorman (1976) has recently described the PanAfrican—Liberian age province boundary as a thrust junction with klippen at Gibi Mountain. Thorman (1976, p. 856) rejects the idea that a suture zone passes through the coastal area of Liberia because he has mapped lithounits for tens of kilometers obliquely across the age boundary (Thorman, 1974) and because there is no mineral facies break at the Todi shear zone marking the age province boundary (granulites occur on both sides). He suggests (personal communication) that some type of event other than continental collision may have occurred, but we would point out that the evidence for continental collision is very strong provided enough strike length of the suture is considered. There are no rocks of obviously oceanic origin for about 1500 km along strike from the Buem Group of Ghana through Brazil and Liberia to the outcrop of the Rokel River Group in Sierra Leone although the suture zone is everywhere mappable as an age province boundary. As Dewey's review (this volume) shows, continental collision is sufficiently complex a process that a cryptic suture 1500 km long may readily be produced. The more unlikely phenomenon would be the closing of an ocean at two places 1500 km apart along strike and production of a mountain belt by a process unrelated to the Wilson cycle in between.

The geology of the PanAfrican boundary in Sierra Leone, Senegal, and Mauretania has been reviewed by Grant (1973) and Sougy and Dillon (1974). The latter authors concluded, as had Burke and Dewey (1972, p. 330), that the Rokelides, at the suture in Sierra Leone, might be related to operation of the Wilson cycle and it is clear from Grant's descriptions and figures (especially Grant, 1973, fig. 6) that an interpretation of the Mauretanides in terms of operation of the Wilson cycle as Burke and Whiteman had suggested (in Burke and Dewey, 1973) is appropriate.

The PanAfrican suture around the West African craton joins the suture system related to the closing of Iapetus in Morocco. Although the details of the latter relationship have not been worked out, it is clear that the ocean closing processes produce a complex reticulate network of mountain belts. Grant (1973, p. 484) suggested that the reticulate pattern of PanAfrican belts contrasted with the curvilinear shape of the Ural and Appalachian Phanerozoic collision zones. The contrast disappears once the nature of the Appalachians and Urals as parts of more extensive diachronous collision zones is appreciated. Again, the complex structure of the Alpine—Himalayan zone (Dewey, this volume) is a good guide.

PanAfrican of northeast Africa and Arabia (Fig. 1:18)

Reactivated PanAfrican terrain stretches eastward for nearly 4,000 km from the Ahaggar (Fig. 1:17) to Arabia. Within this huge area mineral ages are generally reset and there was intense end Proterozoic to early Phanerozoic granitic activity. There is, however, strong evidence that much of the material in the area had been continental crust for a long time. Nigerian basement at Ibadan yields whole rock Rb—Sr ages of 2,200 m.y. (Grant, 1970) and lead isotope data suggest primary ages of about 2,750 m.y. (Oversby, 1975). Ages indicating events about 1.0 b.y. ago are also reported (Grant et al., 1972) from this area of PanAfrican reaction and a Kibaran suture (Fig. 1:24) may lie near Ile-Ife.

It seems unlikely that reactivation over the whole northeast of Africa can be related solely to collision at the edge of the West African craton and there is a likelihood that PanAfrican cryptic sutures remain to be discovered in

Tchad, Libya, the Central African Republic and Sudan Republic. The existence of such sutures in the Arabian shield (Fig. 1:18) was reported by Brown and Coleman (1972) and has been elaborated on by Bakor et al. (1976). The authors describe a dismembered ophiolite from Jebel al Wask, between Medina and the Red Sea and conclude that it is likely to represent the floor of a marginal basin. By closing the Red Sea they are able to link (Bakor et al., 1976, fig. 5) Jebel al Wask and some tens of other ultramafic occurrences into belts in Arabia, Egypt and northern Sudan. They interpret the whole area with its association of oceanic and island-arc volcanic type rocks as a site of PanAfrican arc aggregation. Al Shanti and Mitchell (1976) interpreted the easternmost ultramafic belt in Arabia as a site of continental collision and it may be that continental collision and reactivation followed episodes of arc and microcontinental collision.

An, as yet, unanswered question is how far to the west and south of Arabia this PanAfrican area of arc collisions can be extended. Descriptions of rocks in the Precambrian of Sudan Republic (Whiteman, 1971) and Southern Ethiopia indicate that the Arabian arc-collision zone may extend that far, but the PanAfrican farther south in East Africa appears to lack young island arcs and ocean floor rocks.

Mozambique belt (Fig. 1:22)

The reactivated PanAfrican terrain of East Africa, known as Mozambique belt, contains no well described sutures south of those in Sudan (Bakor et al., 1976). Its western border resembles the Grenville Front in being strongly sheared in some areas though not in others and in having structures mapped across it for many tens of kilometers. We interpret the western boundary of the Mozambique belt as likely to be an analogue of the Grenville Front that is a zone within a continent that marks the limit of convergence, thickening and reactivation. Comparison with the margins of the Tibetan Plateau (Molnar and Tapponnier, 1975) suggests that these boundaries will be loci of strike-slip motion (like the A-Er-Chin fault) in some places and thrusting (as in the Nan Shan) in others.

PanAfrican of Namibia, West Congo, Damarides and Zambesi (Fig. 1:19,20,21)

Kröner (1974, 1975a) has described the development of the Gariep area (Fig. 1:20) in terms of the Wilson cycle. Continental rupture and formation of graben facies 900—800 m.y. ago was followed by ocean and arc development with suturing at about the beginning of the Phanerozoic. Kröner (1974, p. 101) has reported one of the rare Precambrian occurrences of blueschist metamorphism in association with the convergent phase of this cycle in the Bogenfels area to the north.

The PanAfrican rocks of Namibia and western South Africa marking a site of ocean closing lie close to the Atlantic coast illustrating the familiar idea

(Wilson, 1966) that oceans open in places where other oceans have previously closed. Followed northward along the coast PanAfrican fold belts diverge as operation of the Wilson cycle requires they must (Fig. 1:19). One structure persists along the coast through Angola, Zaire and Congo to Gabon and is best marked by an exogeosynclinal or foreland trough development (Schermerhorn and Stanton, 1960), the suture zone and mobile core being unexposed but lying to the west under the continental shelves of Africa and Brazil. The other structure turns inland to form the Damarides.

The Damarides (Clifford, 1967) are among the most interesting of Pan-African fold belts. Shelf carbonate facies (Otavi and Naukluft) occur on both sides of the 400 km wide belt and give way to more clastic tectonized and metamorphosed rocks closer to the center. This relationship alone is strongly suggestive of two miogeoclines facing an area that was once ocean and has now become a fold belt. The area within the fold belt is currently being studied by various methods (Anon, 1975). It contains few mafic rocks but much granite. The best described mafic rocks are the Matchless amphibolites (Anon, 1975) with which minor ultramafics are associated and which lie somewhat to the south of the axis of the fold belt extending for 300 km along strike (Martin, 1965). Kröner (1975b) rejects the idea that this mafic and ultramafic material might represent dismembered ophiolite because it occurs now in a 'flysch-type schist'. Presumably if it reached its present position as a result of operation of the Wilson cycle, it has been tectonically emplaced so this argument is irrelevant. What is impressive about the Matchless amphibolite is its persistence along strike (Anon, 1975, fig. 10) and its location within an intra-continental fold belt between two miogeoclines. The strongest argument for ocean closure in the Damarides is that along strike in both directions in Gariep and the Zambesi Valley there is good evidence of suturing.

To the northeast the Damarides disappear under the sands of the Kalahari and reappear as the Zambesi belt. The Zambesi belt is unique among Pan-African fold belts in that a sketch-map has been published showing continuity of older structures across it (Shackleton, 1973, fig. 1). This is a condition which is impossible if the belt marks the site of a Wilson cycle but feasible if the belt was formed by some in-situ reactivation process. Our conclusion is that the Shackleton's sketch is not convincing in showing that structures are aligned across the Zambesi belt. The sketch, admittedly an interpretation, is misleading partly because all later cover, especially Karroo cover, that extends over more than 50% of the critical area, is omitted. This makes correlation of the southeastern margin of the Irumide belt 'the most significant lineament' look more established on the sketch than it really is. In Zambia this boundary is 'not well defined' (Drysdall et al., 1971). Shackleton shows it as a firm line. In Rhodesia the boundary "must be between the Lomagundi fold belt . . . and Kamativi where Irumide ages occur" (Shackleton, 1973, p. 1092). Kamativi is a small (80 × 30 km) heavily faulted inlier of grey gneisses with tin-bearing pegmatites in Karroo rocks and it shows no evidence of structural continuity with anything let alone the boundary of the Irumides across the Zambesi belt and separated by many kilometers of Karroo. The second lineament is the eastern boundary of the Lomagundi against Archaean basement, a well mapped feature in Rhodesia but there is no Archaean basement mapped north of the Zambesi belt in Zambia (Drysdall et al., 1971) so it is hard to see what can be correlated. The other lineaments, a piece of mafic rock within the Zambesi belt that has been suggested to be part of the Great Dike and the boundary of granulite facies rocks in the Mozambique belt, are irrelevant to an argument about structures crossing the fold belt.

Our conclusion that the Zambesi belt may mark a site of operation of the Wilson cycle is supported by evidence from the Urungwe Klippe (not depicted on Shackleton, 1973, fig. 1). This is an area of metasediments in Rhodesia thrust southward from the Zambesi belt (Stagman, 1962; Shackleton et al., 1966). At the base of the main thrust slice there are local occurrences of banded ironstone, serpentinite and greenstone. We suggest that these might be material obducted from the Zambian suture during continental collision.

The Zambian suture extends eastward into the reactivated Mozambique belt (Fig. 1:22) but its exact location is unmapped as it passes through country overlain by younger rocks.

Older Proterozoic sutures in Africa (Fig. 1:23—26)

Much of the tectonic history of Africa was established in the Archaean which is outside the scope of this review (but see Burke et al., 1976a) and in the PanAfrican at the end of the Proterozoic. Earlier Proterozoic suturing has not been widely recognized.

In southern Africa Matthews (1972) has reported a suture zone of one b.y. age with obducted dismembered ophiolite (not shown on Fig. 1) at the southern border of the Kaapvaal craton close to the Natal coast. When this boundary is pursued westward, it becomes cryptic but the Namaqualand—Natal fold belt to the south is a reactivated zone like those of the Grenville and the PanAfrican and we suggest represents, like them, a Tibetized collision zone. Watters (1976) has described a calc-alkaline magmatic arc from the northwestern corner of the Namaqua fold belt. The development of this feature, the Rehoboth magmatic arc, at a convergent margin requires operation of a Wilson cycle in the interval 1.3—0.9 b.y. roughly on the site of the later cycle represented in the Gariep—Damaride suture zone.

The Kibaride fold belt of mid Proterozoic age (Fig. 1:23; Cahen, 1970, p. 100) contains an immense thickness of clastic sediments and minor volcanics over more than 300 km of strike length in Zaire. Graben facies rock associations are common but no well developed suture zone has yet been identified. A large proportion of highly potassic granites suggests that collision played a major part in development of the Kibarides.

The Ubendian (Fig. 1:25; Pallister, 1971, p. 515) is an Early Proterozoic fold belt (>1800 m.y. old) about 1000 km long by 200 km wide with a considerable amount of metavolcanic, metabasic and ultrabasic material. Calcic anorthosites invite comparison with those of the Archaean of Greenland and the Limpopo which we have suggested may mark old ocean-floor material (Burke et al., 1976a, p. 123) although others (for example, Windley, 1976a) see them as related to convergent plate margin calc-alkaline igneous activity.

The oldest collision zone in Africa, apart from the very numerous sutures of the Archaean and Proterozoic (Birrimian) greenstone belts that we have discussed elsewhere (Burke et al., 1976a), is the Limpopo belt. Coward et al. (1976) have suggested that the Limpopo belt sediments can be traced northwestward into the Matsitama greenstone belt of northern Botswana and we have plotted this curvature of strike (Fig. 1:26). Their figure 5 (p. 329) summarizes the development of this area in terms of the Wilson cycle. Coward and his colleagues have analyzed in detail the polyphase deformation in a large area of southern Rhodesia in relation to the convergent plate margin processes of the Limpopo Valley.

Opening and closing of the ocean on the site of the Limpopo may have been a very rapid process as the emplacement of the Great Dike, apparently the site of the world's oldest failed rift system (Burke, in press), postdated the events analyzed by Coward and others. The cutting off of the Great Dike in the Limpopo belt is associated with a 2.0 b.y. old orogenic event that reactivated much of the older Limpopo material and presumably represents a second Wilson cycle on a site close to that of the one described by Coward et al. (1976).

EUROPE (Fig. 1:27—33)

Hercynian (Fig. 1:28—29)

The Alpine zone (27) is discussed by Dewey (this volume) and we review here only older sutures. The Hercynian of Europe relates closely to that of North America. North of the zone of strike-slip motion in the Atlas (see above p. 75) a suture zone in Portugal can be followed (across the closed Bay of Biscay) into the Lizard complex of southwestern England. Eastward the suture has been detected in the sub-surface of Belgium and in the isolated Late Paleozoic regions of Germany (Anderson, 1975). Farther east we draw the suture zone through the northern Carpathians and on, south of the Crimea, to the Caucausus. Burke (in press) has suggested that Late Paleozoic ocean floor, as yet unsubducted or obducted, underlies the northern Caspian Sea and the north Caspian depression and for this reason we draw the suture (Fig. 1:29) as a dashed line as far as the Aral Sea where a triple-suture knot (like that at Walvis Bay in South Africa) links it to the Urals and Asian systems.

Some orogenic belts have not yet been analyzed in terms of the Wilson cycle but this statement could not be made about the Hercynian of Europe which has been the subject of numerous confusing and conflicting analyses claiming to be 'plate-tectonic interpretations' (Badham and Halls, 1975, cite most of these). Two main reasons for this are that much of the critically important area around the suture zone is buried under later rocks and that, as Zwart (1967) noted, the Hercynian of Europe is a very different kind of orogeny from the Alpine orogeny of Europe. Dewey and Burke (1973) drew attention to the analogy between the present Tibetan situation and that in the Late Carboniferous of Europe. This kind of orogenesis destroys so much of the record of earlier happenings that it is not surprising that opinions as to early Hercynian history vary. In fact, complete analysis of the history of a collisional orogeny is probably impossible. A recent significant advance in Hercynian studies is that of Arthaud and Matte (in press) who relate the complex strike-slip faulting of the Hercynian to major transform motion in Morocco.

Caledonides (Fig. 1:30)

After the Appalachians (Wilson, 1966) the Caledonides (Dewey, 1969) were among the first of fold belts to be interpreted in modern times as products of the Wilson cycle. More sophisticated analyses recognizing marginal basins, variations in collisional intensity and detailed analogues with modern environments (e.g., Dewey and Kidd, 1974; Mitchell and McKerrow, 1975) continue to appear. The Late Proterozoic history of the British Isles, was characterized by convergent events (Thorpe, 1974), and its relation to the opening of Iapetus (Harland and Gayer, 1972) continues to be problematic.

In Norway an Eocambrian aulacogen lay on the future site of the Oslo graben and was marked by an exceptional thickness of 'Sparagmite' and by alkaline igneous rocks at Fen (Strand and Kulling, 1972). We have placed the Caledonide suture offshore of Norway (although obducted fragments probably occur in the Bergen arcs and in Soroy, Nicholson, 1974) because the Devonian igneous activity of East Greenland seems typically Tibetan and collisional in structure and geochemistry (Haller, 1971).

Precambrian sutures in Europe (Fig. 1:31—32)

Only the Baltic shield exposes a large enough area of Precambrian rocks to permit ready suture recognition. The 1.1 b.y. old Sveco-Norwegian suture (Magnusson, 1965) has been described by Zeck and Malling (1976). It runs close to the Norwegian—Swedish border south of the Caledonides and is marked by tectonized ultramafic and mafic volcanic rocks. Reactivation is to the west and it appears to have been a site of continental collision.

We have drawn a suture symbol (32) along the Svecofennian—Karelian boundary. The two areas show strong but contrasting reactivation histories and rock types outcropping close to the suture are suggestive of island-arc, continental and ocean-floor associations (Magnusson, 1965).

ASIA (Fig. 1:34—51)

Asia is the home of Phanerozoic and Proterozoic sutures. The largest piece of continent not cut by a suture is Angara (between 46—48 and 45 on Fig. 1) and it is an interesting but difficult question whether the contrast between say North America, which has virtually been one piece for the last 1.7 b.y., and Asia, which has been the scene of repeated Wilson cycles, is a stochastic product of plate motion on a radially symetrical earth or reflects some fundamental asymmetry. Here we work back from the Cenozoic Himalayan collision (Dewey, this volume) generally northward into the Proterozoic.

Jurassic and Cretaceous sutures (Fig. 1:45)

The Chersky collision (Herron et al., 1974) resulted from the impingement of the Kolyma block, a piece of continent that had occupied the site of the Arctic Ocean during the Late Paleozoic and Early Mesozoic (Churkin, 1972) on Siberia. The Verhoyansk Range, on the Siberian side of the Chersky suture, is the widest (~600 km) area of thrusting of miogeoclinal and shelf sediments toward the foreland we have recognized anywhere although the Lufilian arcs of the Katangan Late Proterozoic north of the Zambesi are almost as wide.

In China, the Yenshanian movements (not plotted on Fig. 1) are of Late Mesozoic age and although this is one of the youngest suturing events in the world, the site of the Yenshanian suture zone has not so far been convincingly delineated throughout its strike length. End Cretaceous collisional events in western Yunnan may be extended southward to join the Red River suture and northward as Dickinson (1973) boldly suggested on one or both sides of the Ordos to join the Chersky suture. This would make the huge Cretaceous Hsing-An batholith (Terman, 1973) a collisional product. Other authors, for example, Burrett (1974, p. 187) and Chang and Zeng (1973), trace the Yenshanian suturing events with a more east—west strike.

Paleozoic collisions of Asia

Because so many Asian collisions took place in the Phanerozoic faunal evidence clarifies the collisional picture. Burrett's (1974) analysis taken in conjunction with Terman's (1973) and Yanshin's (1972) tectonic maps provides a valuable introduction to the complicated series of events.

The general picture following a rifting event of Baikalian age (~1.4 b.y. ago) is of Asian accretion through successive suturing of microcontinents and arcs. Chinese geologists record this relationship in some detail (for example, Chang and Zeng, 1973, fig. 3). In the Upper Paleozoic the Ural collision (Fig. 1:33), suturing Europe to Asia and following Lower Paleozoic arc events has been well documented (Hamilton, 1970; Burrett, 1974). The relation of the Altai to the Urals is unresolved and we plot (Fig. 1:41) one of several alternatives. On the southern side of the Kazakhstan block we trace a Permian suture (Fig. 1:39) past the Pamir and along the Kun Lun as far as areas involved in Yenshanian events. Our main reason for this is that we locate the suture in blueschists and serpentinite inliers below the Tibetan Mesozoic shelf sequence (Hennig, 1915) forming the southern margin of the Upper Paleozoic (? Lower Permian) folded rocks of the Arkin Tagh. The Tarim and Tibetan blocks were sutured in Permian times and the northern side of the Tarim block had been sutured to the Kazakhstan block in Devonian and Carboniferous times. Burrett (1974) sites several references and Norin (1937, 1941) describes ophiolites, colored melange and blueschists from the eastern Tien Shan.

Relations between the Altai (Fig. 1:42—42) and Mongolian—Amur (Fig. 1:43—44) belts suturing Kazakhstan and North China to Siberia, respectively, are not well worked out. Burrett (1974) suggests that the western boundaries involve Lower and Upper Paleozoic collisions while those in the east are Mesozoic. Links with the Yenshan structures, as Dickinson (1973) suggested, may be the cause of confusion. However, Peive et al. (1972, fig. 2) indicate that almost the whole belt is the product of Upper Paleozoic suturing.

Peive et al. (1972) interpret a change from oceanic crust (that is, suture development) as effecting a large area between Kazakhstan and Siberia (Fig. 1:41) in a process that took place in stages between Cambrian and Devonian time. We have not attempted to depict this on Fig. 1.

Proterozoic of Asia

The Proterozoic of Asia south of the Siberian shield and north of the Himalayas is in fragments that are too small to yield much information. We have plotted (Fig. 1:50) a 1 b.y. old suture zone in Amur largely on the basis of ultramafic distribution (Geologic Map of Eurasia, 1972).

In Siberia the main Proterozoic feature is the Baikalian suture (Fig. 1:49) about 850 m.y. old. This suture (P.A. Washington, personal communication, 1976) follows the irregular outline of a continental margin ruptured 1.4 b.y. ago (Burke and Dewey, 1973) and contains abundant ophiolite and calc-alkaline igneous rocks and related sediments. Evidence of both opening and closing of an ocean is abundant. The site of the Baikalian ocean was close to that of an earlier Proterozoic (1.8 b.y.) Wilson cycle recorded in the Sayan—Baikal region (Fig. 1:47, Kosygin and Parfenov, 1975). This structure may be related to the mid Proterozoic history of the Yenisei ridge (Fig. 1:46) where ultramafic rocks were emplaced at about this time.

The oldest evidence of operation of the Wilson cycle in Siberia comes from the southern edge of the Aldan shield where collision at about 1.8 b.y. ago followed rupturing at the end of the Archaean (Rudnik and Sobotovch, 1971).

INDIA

Apart from the Himalayan collision zone (Fig. 1:34) there are no Phanerozoic sutures in the Indian sub-continent. The northern boundary of the peninsula shows signs of a continental rupture at the beginning of the Phanerozoic in the development of typical ocean opening type salts of the Salt Range Cambrian (Gansser, 1964, p. 23) and this boundary appears to have faced ocean until the mid-Cenozoic continental collision.

Proterozoic sutures in India (Fig. 1:35—38?)

We have shown age province boundaries on Fig. 1. Latest Precambrian reactivation occurs in the south and in Sri Lanka and in the northwest. The Aravallis forms a possible suture zone (Fig. 1:35). The boundaries of the Archaean area of Central and Southern India (Fig. 1:37—38) cannot be characterized as sutures and appear in some areas more like intra-continental reactivation limits like the Grenville and Mozambique fronts.

AUSTRALIA

Phanerozoic sutures

Since the beginning of the Mesozoic Australian geology has been dominated by continental rupture. Convergent plate margin phenomena have been restricted to outlying parts of Australasia, such as New Guinea (51), the Timor shelf, New Zealand, and New Caledonia.

A late Proterozoic continental rupture event left a record in the development of the southward opening Adelaide 'geosyncline' (recognized as an aulacogen by Rutland, 1973) and this was followed throughout the Paleozoic by a complex sequence of convergent phenomena that includes arc and microcontinental collisions. These events developed sutures in the Tasman zone of Eastern Australia (between lines 53 and 54 on Fig. 1). Evidence of arc collisions of Permian age is preserved farther east in New Zealand (Landis and Bishop, 1972) and the presence of Precambrian detrital zircons in New Caledonia (Aronson and Tilton, 1971) indicates that both arcs and microcontinents were probably involved even in the parts of the collision zone most remote from the old western Australian continent.

The Tasman zone reaches a maximum width of more than 1500 km. Such great widths are apparently characteristic of areas that have been subject to arc and microcontinental collision but have escaped collision by major continents. In a zone as wide as this the record of divergent, convergent and sideways plate motion although preserved in highly disrupted style is more complete than in a simple suture like parts of the Indus suture. Because there are faunas preserved in many of the Tasman sediments that enable stratigraphy to be worked out, it seems likely that an unusually complete record of suture zone history will eventually be established for the Palaeozoic of Eastern Australia. Coherent preliminary plate-tectonic interpretations are already available (e.g., Oversby, 1971; Solomon and Griffiths, 1972; Scheibner, 1972) although the flow seems to have dried up in recent years.

Proterozoic sutures

Davidson (1973) has interpreted the mafic and ultramafic rocks in the Musgrave block of Central Australia (55) as marking a suture formed during the Upper Proterozoic. There is doubt as to the extension of this suture westward, possible paths passing south of the Yilgarn Archean block, between the Yilgarn and the Pilbara blocks and north of the Pilbara block. We have shown the last on Fig. 1. Eastward extension takes the Musgrave suture zone to a middle Proterozoic zone of continental rupture (54). A continental rupture event here at about 1400 m.y. left the Amadeus and the early (north opening) Adelaide aulacogens striking at high angles into the continent. Farther north evidence of aulacogen formation associated with continental rupture appears rather older (~1800 m.y.) and convergent phenomena in that area have led to preservation of graben facies rocks associated with this event in the Mt. Isa—Cloncurry district (56).

The oldest Proterozoic suture in Australia appears to lie in the dog-leg structure around the Kimberly basin (57). The right-angled bend of this structure is similar to the bends in younger orogenic belts which are increasingly being recognized as recording original right-angled bends in continental margins (Dewey and Burke, 1974).

Because Australian geologists have made few attempts, as yet, to interpret their Precambrian geology in terms of the Wilson cycle, these inferences are based on our interpretation of published work, especially such reviews as those in Rutland (1973) and Brown et al. (1968) and the tectonic map of Australia (1971). For this reason they are no doubt capable of considerable refinement.

CONCLUSIONS

This review of Phanerozoic and Proterozoic sutures is intended to show that a case can be made for considering many fold belts as products of operation of the Wilson cycle. Many other fold belts are not sufficiently well preserved to permit full analyses of their history and it will probably never be possible to work out their development fully. Taken with our demonstration of the compatibility of Precambrian paleomagnetic data with operation of the Wilson cycle (Burke et al., 1976b) and our demonstration of the operation of the Wilson cycle in the Archaean (Burke et al., 1976a) we conclude that there is no necessity to seek for evidence of other non-uniformitarian orogenic processes in the past as all orogenic belts could have been produced by the plate-tectonic processes involving continental rupture and arc, microcontinental and continental collision that we observe today.

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