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PASSIVE CONTINENTS, SPREADING SEA FLOORS, AND COLLAPSING CONTINENTAL RISES

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ABSTRACT. A tectonic model of the Earth is suggested whereby the continents and the sea floor are immobile (that is, resistant to internal deformation). Entire continents have cratonic stability although they do drift passively under the influence of tectonic forces originating in the mantle. The sea floor is likened to a conveyor belt, driven by thermal convection cells in the Earth's mantle, so that it is movable even though not mobile. Prisms of sediment on the continental rise are the principal realms of orogenesis. These collapse into orogens and are accreted to the continental block when decoupling permits the sea floor to underthrust the continental block.

Some geological arguments in support of this interpretation are the following: (1) Collapsed eugeosynclinal prisms (fold belts or orogens) may be interpreted as resulting from continent-sea floor interaction rather than from continental collapse forming tectogenes. (2) The lack of deformation in Precambrian supracontinental strata of great antiquity suggests continental immobility as does also the persistence of ancient circular structures. (3) The accretionery pattern of North America is best explained in terms of cratonic stability; even the deformation of miogeosynclinal belts like the folded Appalachians is probably superficial, by décollement not affecting the basement. (4) Sub-bottom acoustic reflection results suggest that the sediment layers on the sea floor are not orogenically crumpled; however, a large-scale conveyor-belt type of movement seems likely.

INTRODUCTION

Students of geology have, over many decades, been trained in the philosophy of great crustal unrest. *Terra firma* has been considered an illusion; instead the continents are said to have been seized again and again by the mountain-making paroxysms. This view of intense and repeated mobilization has received considerable criticism and is no longer as popular as it once was. In general, and especially in Europe, there has been a shift of opinion toward stable cratonic heartlands margined by mobile belts. In this paper, I will take a further step in the direction of continental stability by suggesting that it is the "peri-margin", the continental rise, that truly is the realm of great mobility.

To assist the reader in following the argument, I will outline my thesis at the outset. I suggest that the Earth is divided into active and passive realms but not ones that are areally disposed over the surface of the Earth. Rather, thermal convection in the Earth's mantle is the tectonic prime-mover, so that geotectonics are controlled by a two-layered model. The continents are passive iceberg-like blocks which may be rifted and drifted but are non-deforming. The sea floor is entrained by mantle convection so that it is movable, but it is not mobile in the sense of fold-

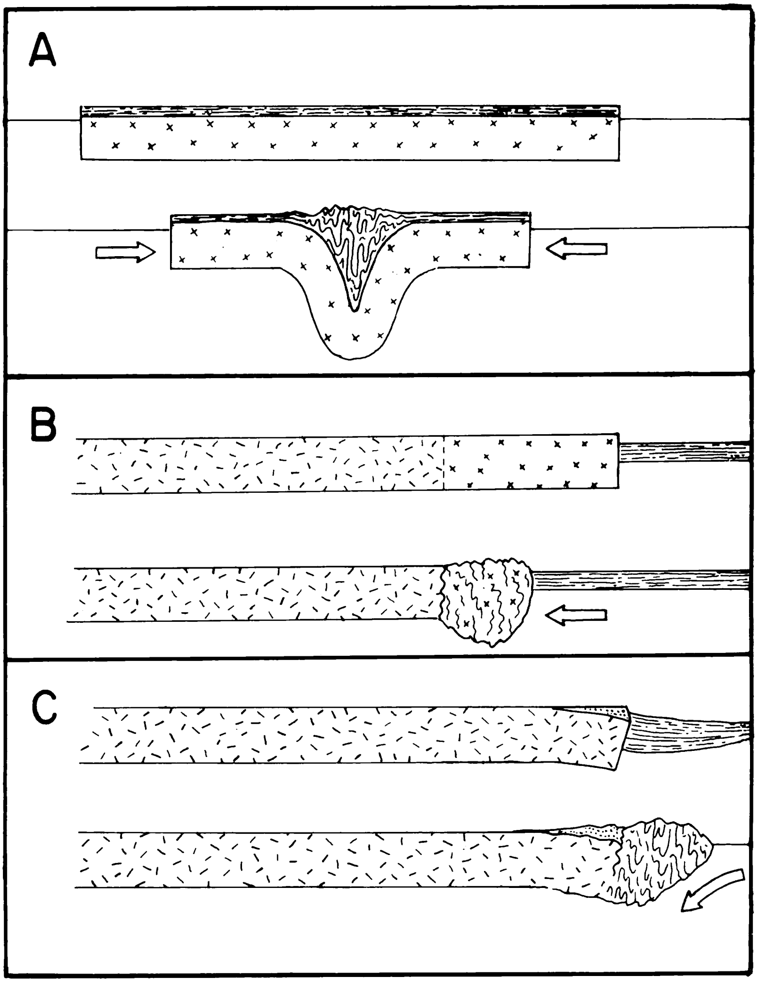

Fig. 1. Contrasting models for the deformation of continents.
A. Interior deformation of a continent, with tectogene buckling. Continent is shortened.
B. Marginal deformation of a continent with rigid "heartland" and a mobile border. Continent is shortened.
C. Non-deforming continents with continental accretion of a collapsed continental rise prism. Continent grows larger.

ing or being deformed into tectogene-like collapses. The interaction between the moving sea floor and the continental block creates the principal realm of mobility by folding and plutonizing the ensimatic continental-rise prism.

In essence, then, I propose a geotectonic model in which both the continents and the sea floor are unyielding, in which the sea floor behaves as a conveyor belt and the continents are passively movable and in which continental rises are subjected to collapse, causing continental accretion.

There are, of course, many other models or "philosophies" for the general scheme of Earth tectonics. We may mention, for example, the fixed-earth concept, with mountain making controlled by vertical displacement and gravity tectonics, for which Bucher (1933, 1955) was a leading advocate. Bucher, to be sure, envisioned compressional shortening as well, but Beloussov (1958, 1960, 1962) and Brock (1956) expressed strictly "verticalist" views, whereby a mega-mosaic of horizontally disposed cratonic blocks episodically squeezes intervening mobile belts. Such strict verticalists suggest gravity tectonics as the prime mover and find the evidence for horizontal shift largely illusory.

My view is "horizontalistic" in accepting the reality and importance of horizontal shifts of the Earth's crust. I take issue, however, with the two common models of geotectonism and propose a third (fig. 1).

No attempt will be made in this paper to comment on the views of the verticalists. Rather, it is my purpose to show that my concept is not inconsistent with the modern evidence of continental and marine geology. Some basic precepts of geology, however, must undergo radical revision. To this end the discussion that follows is geological in essence. Nature is, of course, complex, and many exceptions to the broad generalizations

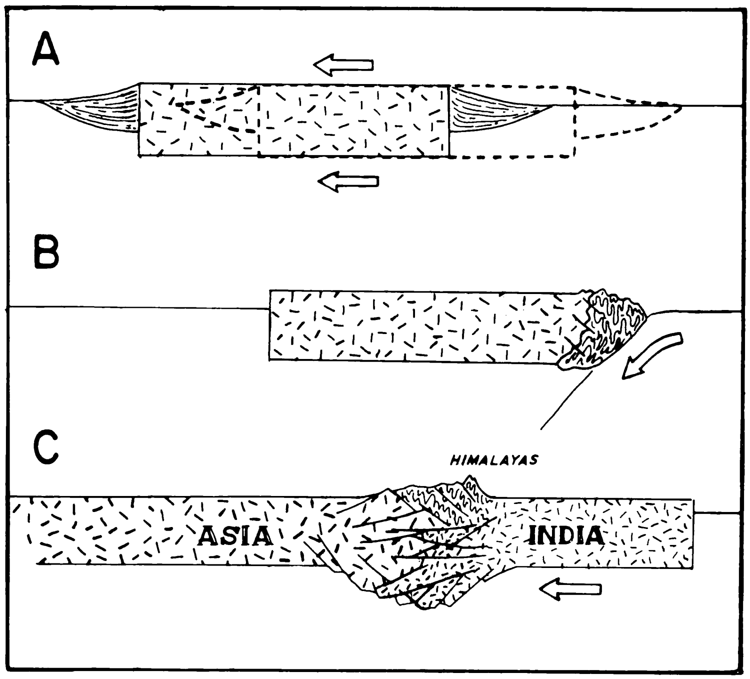

Fig. 2. Types of deformation presumed to affect movable continents.
A. Passive continental drift on a moving mantle. No deformation.
B. Continent decoupled from mantle motion. Accretion to continent of collapsed continental rise.
C. Collision of continents with interleaving of sialic blocks.

offered will occur to the reader. I ask him to weigh these generalizations in terms of the usual rather than the exceptional.

Following are some aspects of the proposed geotectonic model (see fig. 2):

1. The oceanic crust is closely coupled to thermal convection-current flow in the mantle. The sea floor acts as a conveyor belt with large moving sectors bounded by shear zones.

2. The oceanic Moho is not a shear boundary but, following Hess (1962, p. 613), is a transition from peridotite to serpentinized ultramafics and not to a basaltic "oceanic layer". Hence this layer is actually a "rind" or partially hydrated phase of the mantle and not properly a crust.

3. Continents can drift passively with the mantle or can become decoupled because of the buoyancy associated with their composition. The Moho beneath the continents differs from the Moho beneath the oceans and is a transition from sial to peridotite. The continental Moho is a boundary of major shearing whereas the oceanic Moho is not. This model does not imply great physical rigidity of continents but isolation from the source of tectonic forces in the mantle. The continent is isolated from sub-crustal currents like the isolation of scum from the flow of water.

4. The continent is essentially unyielding, except for minor marginal effects, so that the terms "continent" and "craton" are synonymous.

5. Since the craton is isolated but not rigid, it cannot transmit forces for long distances; if it yields, the deformation is localized in fractures or surficial "rugfolding" of miogeosyclinal deposits. This accounts for undeformed platform sediments as much as 2.5 aeons old without resorting to rigid or fixed continents.

6. The ensimatic sedimentary prism on the continental rise is the principal site of deformation. When the continents and the sea floor are decoupled, the prism is accreted to the continent. Former accretions that are an integral part of the continental block are no longer affected by primary orogenic forces.

ACKNOWLEDGMENTS

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CONTINENTAL MOBILITY AND GEOSYNCLINES

The case for continental mobility is doubtless based largely on the existing chains of folded mountains plus the ancient foldbelts — the so-called mountain roots of the Basement Complex. The making of folded mountains is entirely referable to geosynclinal theory, since they result from collapsed geosynclines. According to both the tectogene and the mobile continental margin concepts, geosynclines are said to have been laid down on a sialic foundation, hence to be ensialic. By this chain of reasoning, folded mountains indicate that the continental plate has collapsed in some manner.

The chain of reasoning just given is, however, not an inevitable path. If *eugeosynclines*, the type of geosyncline that is the precursor of folded mountains, are laid down on sima instead of sial (Wells, 1949), then orogenic folding could reflect mobility of the sima relative to the sial.

I have offered elsewhere a scheme whereby eugeosynclines are ensimatic prisms laid down at the base of the continental slope as continental rises like those found in modern seas (Dietz, 1963). A detailed discussion of this concept is beyond the scope of this brief paper; it suffices here to present a time-sequence diagram (fig. 3).

This is an actualistic concept, since modern continental rises are equated with the ancient collapsed eugeosynclinal prisms that form the folded mountains of today. It fits well with the new finding of marine geology that the great bulk of sediments eroded from the continents is not trapped within the continental framework or even on the shelf and the slope. Instead this detritus is deposited as a continental-rise prism at the base of the continental slope.

By this model folded mountains are a by-product of continental accretion, created while becoming an integral part of the continental block. It is not the margin of the continent which is mobilized nor even the sea floor; instead, it is a prism of ensimatic sediments which abuts the continental block. Accordingly, collapsed eugeosynclines do not provide evidence of continental mobility. Not even the margin of the continental block is mobilized; instead the orogenesis may be said to be "pericontinental".

The crux of the problem is, of course, whether or not eugeosynclines are really ensimatic, as suggested here. Eugeosynclines described in the literature are generally said to lack any known sialic basement. They characteristically contain pods of serpentine and ultramafics, which may be construed to be a portion of the simatic basement upon which the eugeosyncline was deposited. Moreover, the appearance of a certain amount of sialic basement is not in disagreement, since by my concept a continental rise prism up-laps the continental slope on its landward side, so that sialic basement would underlie the inner portion of a eugeosyncline formed from a continental rise prism.

SEA FLOOR: MOVABLE BUT NOT MOBILE

By the geosyncline-continental accretion model advocated, it is not necessary to assign mobility, in the sense of buckling or internal deformation, to the sea floor. Orogenesis and continent building result from interaction along the margin of an active sea floor and a passive continental block. The sea floor does need to be movable by acting as a conveyor belt driven by mantle convection currents, that is by sea-floor spreading (Dietz, 1961). At times the continent may be coupled with this

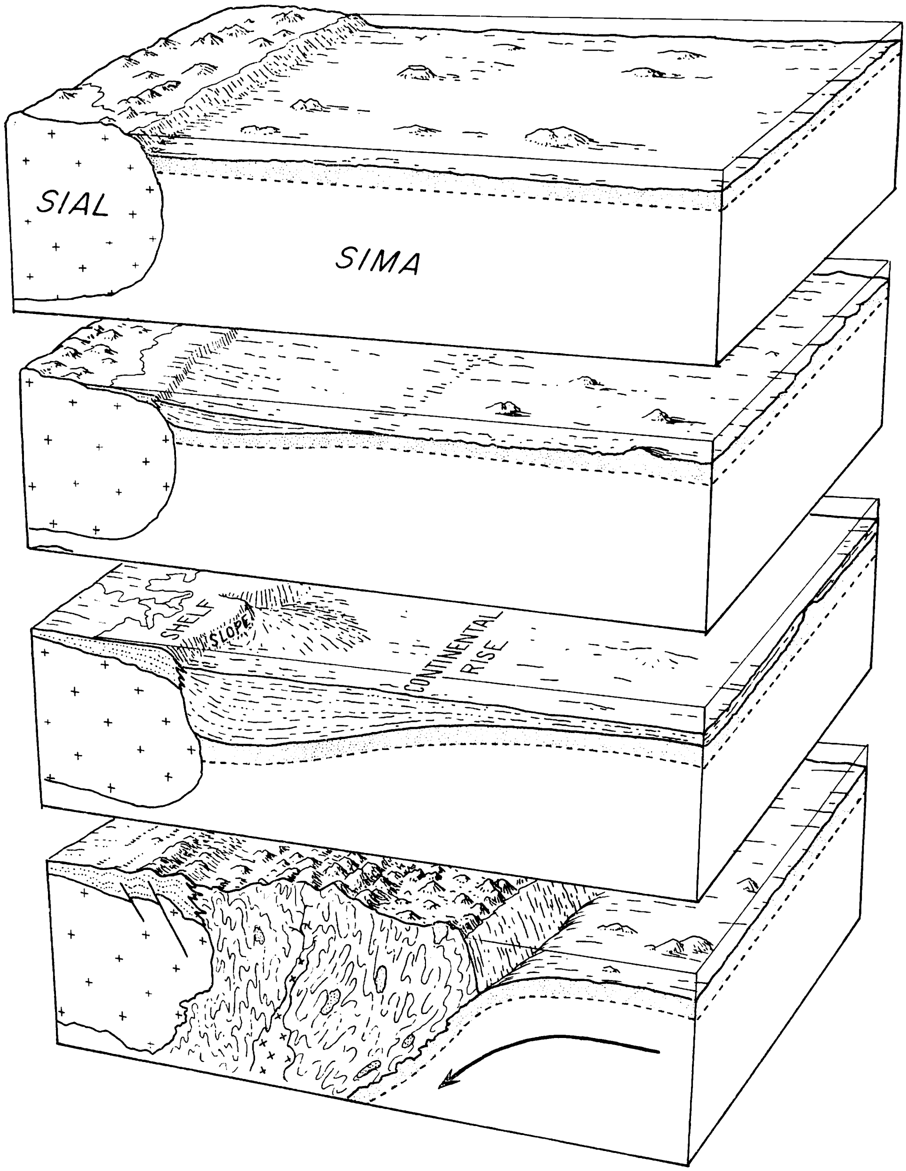

Fig. 3. The geosynclinal mountain and continent building cycle according to the writer (Dietz, 1963).

This actualistic concept suggests that prisms of sediment under the continental rise at the base of the continental slope collapse by sea-floor thrusting to form folded mountains of graywacke or flysch lithofacies. By this interpretation the mobility observed in eugeosynclinal mountains indicates activity of the sea floor rather than collapse of the continental sialic plate. The sea floor is active, and the continent is passive. This is in contrast to the tectogene hypothesis or to the island arc-tectonic borderland view (Kay, 1951). By the writer's concept, the terms continent and craton become essentially equivalent. (From Dietz and Holden, in press.)

conveyor belt and continental drift will ensue; at other times decoupling may occur along one margin of the continent, mobilizing the continental-rise prism lying at the base of the continental slope.

Ewing, Ludwig, and Ewing (1964) and Ewing and Ewing (1964) have made extensive sub-bottom seismic reflection traverses over the ocean floors of the world. This excellent reconnaissance has shown the unconsolidated sedimentary layers to be thin and undeformed, a result they suggest is inconsistent with both continental drift and sea-floor spreading. They are concerned about the pattern one might expect in the "wake" of a drifting continent. This is a proper concern under Wegener's type of active continental drift, but with passive drift there is no wake. The thinness of the sediments is certainly consistent with drift by the conveyor-belt model, as this would have tended to destroy all pre-Mesozoic sedimentary layers.

The lack of deformation does not eliminate sea floor movability but only mobility (internal deformation). If the sea floor spreads in large plate-like sectors, margined by shear fracture zones, the superimposed sediments would be carried along passively without deformation. The deformation of the ocean "rind" would be extremely localized because of its close coupling to the mantle movements and confined to the great fracture zones of shear and the block fracturing of the mid-oceanic rises. The physiographic diagrams of the oceans by Heezen and Tharp (1958, 1962, 1964), especially the diagram of the Indian Ocean, suggest that the shear yielding of the oceanic rind may have considerable fine detail, as seen in the great abundance of linear fractures aligned approximately north-south. Nevertheless, individual belts of moving "rind" show little indication of folding or buckling at the right angles to the fracture zones and lineations. Shear fractures are common in the ocean basin structures, and folds are probably quite rare.

ANNULAR ZONATION OF NORTH AMERICA

It has been recognized for a decade or two that North America exhibits a rude zonation. A central nucleus of ancient rock is surrounded by zones of progressively younger rocks. This has been intepreted either in terms of migrating orogenic seizures or as continental accretion (fig. 4).

Choosing the first option to explain this zonation, Gastil (1960) suggested that the roughly concentric arrangement of mineralogenic provinces in North America was caused by the gradual withdrawal of crustal instability from the continental interior. He supposed that overlapping and successive orogenies and their associated granitic intrusions were ever more peripheral. Accordingly, the marginal zones were subjected to repeated orogenies, but the central "eye" perhaps to only one. This hypothesis assumes high continental mobility with the marginal foldbelts reactivated many times. If this were true, the exterior zones should be more intensely metamorphosed than the ancient central nucleus. There is little evidence for this as each foldbelt apparently had a

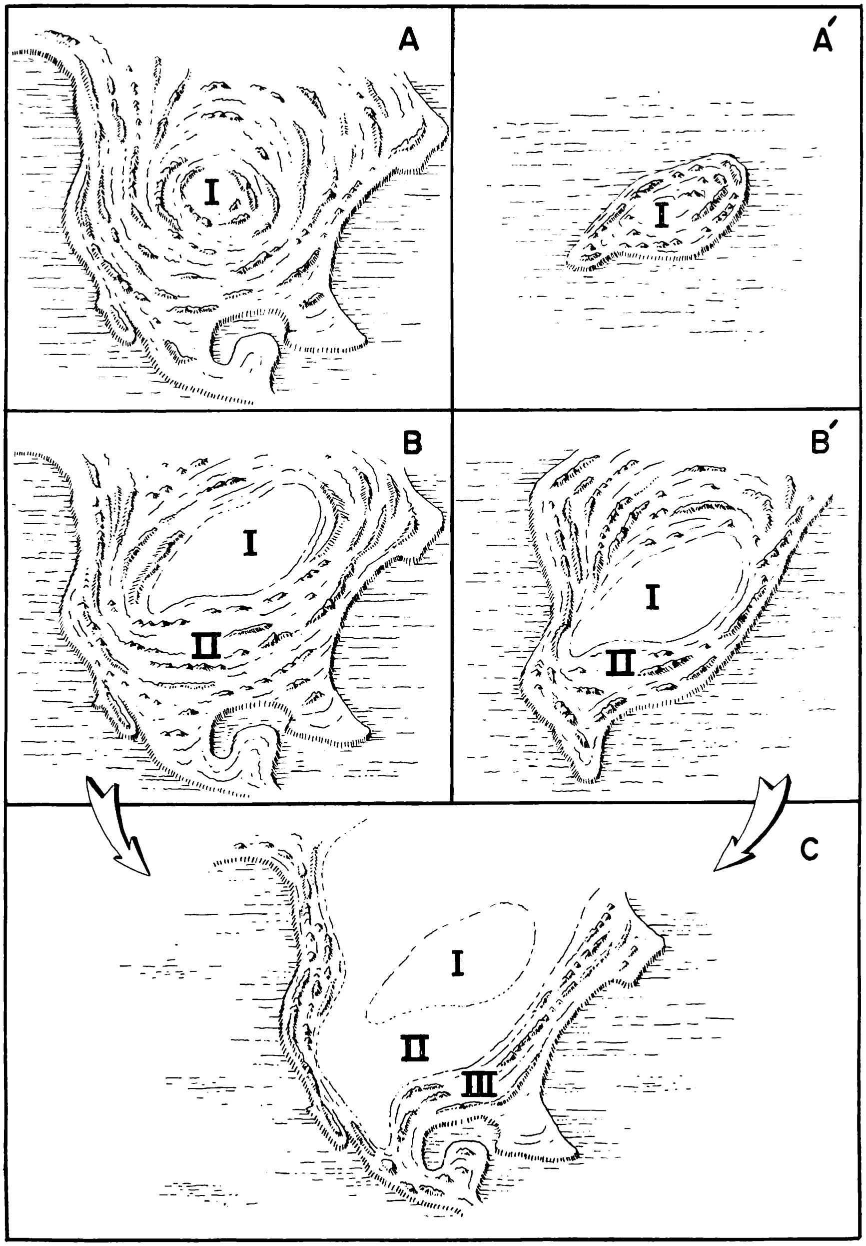

Fig. 4. Two contrasting concepts explain radiometric dating results and reveal the oldest rocks to be present in the central region of North America, with progressively younger zones toward the continental margin.

The left sequence (A, B, C) shows how early orogenies might have affected the entire continent, with subsequent orogenies being ever more peripheral. The radiometric date stamped on a particular rock zone would simply mark the date of the quite similar history, and they display similar degrees of metamorphism. Also the zones appear to be quite clean cut rather than vaguely merging as would be expected under a scheme of gradually withdrawing orogenies.

Continental accretion seems a better interpretation for North America's zonation. As Pettijohn (1943) has emphasized, the Basement Complex is composed everywhere of "mountain roots", a mesh of folded eugeosynclines; thus eugeosynclines may well have been the elements that have accreted. By the geosynclinal scheme of Kay (1951), involving tectonic borderlands and island arcs and with the geosynclinal prism being laid down on the continent's sialic margin, a concept of heartland stability and marginal mobility results. On the other hand, if the folded geosynclines are collapsed ensimatic continental rises, the entire continent becomes an immobile craton which has not yielded to orogeny at all. The terms craton and continent become synonymous.

In summary, the annular zonation of North America seems not consistent with any view that the continents are highly deformable or internally mobile. Perhaps the accretionary appearance of North America could be interpreted in terms of marginal mobility alone in accordance with the borderland type of geosynclinal concept, for example, of Kay. This accretionary appearance, however, is a direct result of the hypothesis of collapsing continental rises, and the immobility of continents is a corollary.

PRECAMBRIAN EVIDENCE FOR UNYIELDING CONTINENTS

Arthur Holmes (1965) recently wrote: "For me probably the most dramatic and unexpected surprise of a decade packed with surprises was the announcement of the great age of the Bushveld Complex, about 2,000 million years, and the consequent realization that the Transvaal Group of strata must be still older . . . For over half a century the Transvaal 'System' was confidently thought to be of late Precambrian age and, lithologically, a typical representative of the Algonkian (Proterozoic). Yet it has turned out to be immensely older than such characteristically Archean rock sequences as the Grenville of the Canadian Shield and the Svecofennian of the Baltic Shield".

We may cite some examples that reveal the remarkable antiquity of many Proterozoic beds. The gold-bearing Witwatersrand beds of South Africa were considered Eo-Cambrian until quite recently. The sandstones are unmetamorphosed, and they have suffered little tectonism. Minor sedimentary structures such as ripple marks and crossbedding are

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youngest orogeny. The right (and preferred) sequence (A′, B′, and C′) shows how continental accretion could account for the radiometric dating results. Although highly diagrammatic zone I intends to show rocks of the Superior, Wyoming, and Slave Lake zones (3.0 to 2.5 b.y.); zone II to show rocks of the Churchill, Central, Western, and Grenville zones (3.5 to 1.0 b.y.); and zone III to show rocks of the Appalachian and Pacific zones (1.0 b.y. to present). (Zone data adapted and simplified from Engel, 1963.)

excellently preserved. But these beds have now been dated as 2150 million years old or more than three times as old as the Cambrian (Nicolaysen, 1962). The deposition of the Athabaska formation in Canada has been similarly pushed back in time as has the Belt Series in western North America. This is also true for the once supposedly coeval strata of the so-called Keweenawan. Rocks of this 'age' around Lake Superior are now dated as 1.1 billion years (King, 1959) whereas those at Sudbury (the Whitewater Series) are dated as older than 1.6 billion years (Fairbairn, Hurley, and Pinson, 1960). Thus the elapsed time between the deposition of these two Keweenawan sequences alone is as long as all of Phanerozoic time. These are but a few examples; many more could be cited easily.

Holmes' reaction is shared by most geologists, for certainly the radiometric dating of Precambrian rocks is causing a revolutionary reappraisal of early Earth history. For some this has been an agonizing reappraisal; others express disbelief. Some skepticism about details is healthy, but the overall results must be correct — and reappraise we must.

We may generalize about these new dating results as showing, first of all, a Precambrian time-span far longer than all expectations. Against this spectacular unfolding of long vistas in time are two other aspects relevant to the discussion here. (1) Most rock sequences thought to be Late Precambrian (Eo-Cambrian), simply because they were little deformed, have been shown to be vastly older, even three or four *times* as old. (2) On the other hand, many Archean or basement complex orogens ("mountain roots") have turned out to be much younger than anticipated.

Not only was our sense of Precambrian time telescoped, but the relative ages of Proterozoic and Archean were badly in error. This must mean that the degree of metamorphism and tectonic mobilization is a poor guide to antiquity. It also means that the great hiatus between "Proterozoic" and "Archean" units in any one area is tectonically profound, but that a long time interval did not necessarily pass.

It was customary to relegate many, if not most, Proterozoic beds to the Late Precambrian and often as gradational into the Cambrian. This Eo-Cambrian age was assigned because of their slight metamorphism, lack of extensive faulting, and almost flat-lying attitude. In fact, these sequences seemed to resemble lower Paleozoic beds in all aspects except that they are without fossils, at least stratigraphically useful ones. Actually radiometric dating has revealed so few Late Precambrian dates (that is, between 1000 and 600 million years) that considerable support is given to Walcott's concept of the Lipalian Interval.

We are faced with a seeming dilemma. The Precambrian provides evidence of great stability on the one hand and of intense orogenic paroxysms on the other. This conflict is not unresolvable; we can account for it satisfactorily as follows: Orogens are tectonized only once, so the original age of plutonization persists through geologic time; hence mountain-roots are not commonly restamped with new radiometric ages. Ancient age does not greatly increase the likelihood of ensialic strata becoming orogenized. The resistance of the continental block to yielding, in fact, permanently protects these beds from orogenesis. Their ensialic position rather than their youth determines this. On the other hand, beds laid down at the base of the continental slope are destined to become orogenized.

The term Basement Complex is best interpreted as a lithofacies term pertaining to the tightly and complexly folded wacke-type metasediments and migmatites intruded by granites. The Archean facies appears to represent folded eugeosynclinal belts or the roots of folded mountains of the alpine type originally laid down on sima. In any single region, attempts to break down the Archean into subdivisions have been unsuccessful. This inherent unity supports the view that the Archean is a single lithofacies — the eugeosynclinal graywacke suite. The Proterozoic sequences could then be ensialic stratiform sheets overlying these mountain roots and separated from them by an angular unconformity. This unconformity is certainly "profound" in degree of metamorphism and angularity, but the separation in time need not be long. Although it is usually construed to be so, radiometric dates fail to bear it out. The Archean beds seem better interpreted as a structural facies rather than necessarily primordial.

Archean beds can be of any age within the Precambrian. The Ep-Archean unconformities simply are not synchronous. The lithofacies concept of the Archean may even, with some reasonableness, be carried forward into Phanerozoic time. The Franciscan suite of California and the Appalachian crystalline rocks seaward of the Blue Ridge would be simply latter-day examples of the "Archean" structural facies.

A better interpretation of the two-part Precambrian classification would seem to be that the Proterozoic beds were laid down on passive continents not given to buckling, so that the beds are preserved as relatively undeformed and unmetamorphosed sheets. On the other hand, the Archean beds represent collapsed continental-rise graywacke prisms laid down on the ocean floor, resulting in continental accretion. Once welded to the continent each orogen becomes passive, so that it tends to remain stamped with the radiometric age of the group of granitizing events that accompany or follow shortly after the collapse of the eugeosyncline.

All this bespeaks continental passivity accompanied by sea-floor thrusting. Beds laid down at the base of the continental slope become intensely buckled. This is consonant with passive continents built up of orogenic implacements caused by sea floor thrusting. Once again, in this context, the terms *continent* and *craton* become synonymous. The "profound" Ep-Archean unconformity, in terms of angular discordance and metamorphism, becomes understandable if *only* continental rises are subjected to mobilization.

I am inclined to question the common belief that continental rocks, and especially the Basement Complex, have been subjected to repeated orogenies during geologic time. The evidence from radiometric dating seems most consistent with orogenies followed by immobility associated with craton formation. The collapsing of continental rises offers a single-event mechanism which is sufficient to account for the intensity of the deformation and metamorphism observed in the Basement Complex, as compared with "Proterozoic" and later ensialic strata, without recourse to multiple orogenies. At the same time, I am aware that this brief treatment of orogenesis is, at best, sketchy and grossly oversimplified. A mountain-building "event" involves a complex interplay of sedimentation, volcanism, tectonism, and granitization, the intricacies of which remain poorly understood. The cycle can follow many paths with involved timing of events. My purpose here is simply to suggest that orogenesis may be largely pericontinental and ensimatic.

CIRCULAR STRUCTURES

The persistence of circular structures on continents provides a useful criterion for judging the intensity and the repetitiveness of orogenic seizures. Circular structures are created by vertical forces, usually endogenic events rising from the deep crust or mantle, but exogenic events, with the forces impressed from above, also produce them (for example, astroblemes or meteorite impact scars).

Endogenic circular structures are common and of many types. Ring dikes, cone sheets, alkaline complexes, volcano root structures, and granitic plutons are but a few examples. In spite of the great antiquity of many of these, they commonly retain their original circular pattern with no obvious squashing, suggesting that there have been no later orogenies.

Precambrian orogenic belts commonly display zones of migmatites and metasediments intruded by rudely circular and unmetamorphosed granites (fig. 5). The strongly contrasting degree of metamorphism between the metasediments and the granite plutons within the same orogen suggests not repeated orogenies but a single orogenic cycle consisting of compression and collapse of a geosynclinal sedimentary prism followed in the waning stages by plutonic intrusion. Orogens, once formed, would seem to resist later remobilization. Such an interpretation is the simplest explanation for the rudely zoned concentric orogens of North America as shown by the radioactive dating of granitizing events (Engel, 1963).

More than a score of highly circular structures have been identified on the Canadian Shield, many of which appear to be astroblemes (Innes, 1964; Dence, 1964). Some of these are filled with undisturbed early Paleozoic sediments indicating that the shield has not been subjected to orogenic failure at least in Phanerozoic time. The non-deformation of the Canadian Shield since the Precambrian is now, of course, a widely accepted conclusion for other reasons as well.

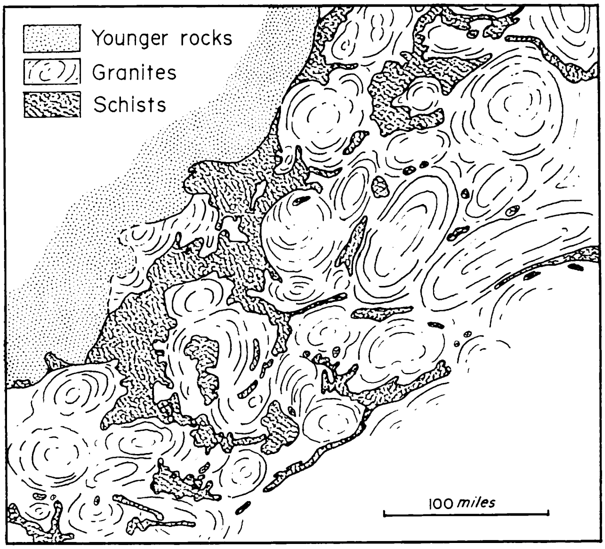

Fig. 5. Metasediments intruded by plutons in the old Precambrian basement of South Africa (after Macgregor, 1951).

Zones of old Basement Complex rock commonly consist of irregularly shaped areas of metasediments which occupy the spaces between rudely circular and often unmetamorphosed granitic plutons. It is well established that these intrusions occur in the later part of the geosynclinal cycle. Since the granites are little altered by metamorphism and retain their original circular form, it would appear that only a single orogeny has seized the geosynclinal zone and that the observed metamorphism of the sediments largely occurred in the early phase of the deformation by the original geosyncline.

A fine example of a circular structure is the Vredefort ring of South Africa, about 70 kilometers across. The Vredefort event occurred not in the late Precambrian as formerly supposed but about 2000 million years ago (Nicolaysen, 1962). Its retention of circularity provides proof that this part of South Africa has not been orogenically deformed since early Precambrian time.

MARGINAL YIELDING OF THE CONTINENTAL BLOCK

Although I doubt that continents collapse to form tectogenes, I do not intend to imply that they are wholly unyielding. Marginal portions of a continental block seems especially to be subjected to a certain amount of surficial folding and perhaps thickening. Thus with the emplacement of the crystalline Appalachians, presumably by the collapse of a continental rise in late Precambrian and early Paleozoic time, the sedimentary Appalachians lying to the west and resting on the continental block were sympathetically folded. The eugeosynclinal crystalline Appalachians appear to have been the primary mountains whereas the miogeosynclinal folded Appalachians seem merely a secondary effect. This is in accord with my premise that sima is active while sial is passive. The

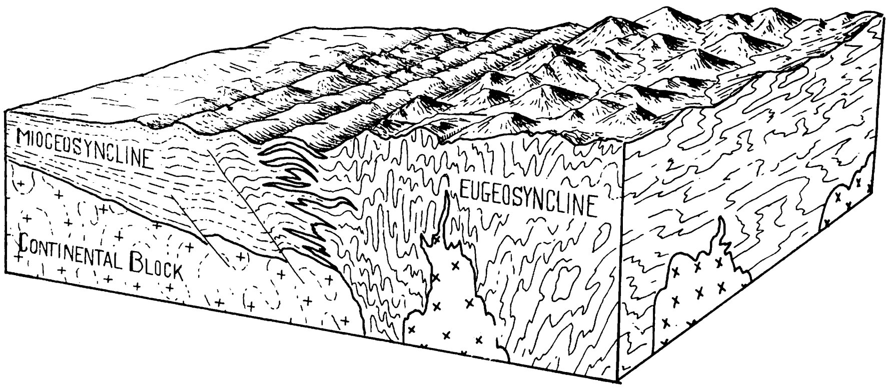

Fig. 6. A representation of a portion of the Appalachian Mountains at present. The crystalline Appalachians (to the right) are a highly deformed and plutonized mass. These are presumed to have been laid down on the ocean floor sima so that their tectonic complexity reflects sea floor movement. The folded Appalachians (to the left), laid down on the continental sial, were protected from intense orogenization by continental immobility. Hence the miogeosynclinal mountains are only moderately folded in response to forces impressed by the crystalline Appalachians and gravity tectonics.

eugeosyncline, laid down on the sea floor as a sedimentary prism on the continental rise, was severely collapsed and plutonized whereas the miogeosyncline, deposited as a monocline on the continental terrace, was protected from major mobilization by the underlying sialic block, and was only subjected to minor folding.

An opinion gaining increasing support is that there is no compressional shortening of the continental block beneath the folded Appalachians (Rodgers, 1964). The folding is considered to be "carpet folding" over an unyielding basement. Accordingly, the continental block provided a completely unyielding foreland when the crystalline Appalachians were orogenically emplaced (fig. 6).

The deformation that seems to have affected the North American continent differs from the Tethyan deformation exemplified by the Himalayas. The tectonics there seem to suggest a continental collision of India against Asia. The Himalayan Plateau is about as high as the oceans are deep. Assuming that isotasy prevails, the sialic layer should be about 70 kilometers thick instead of the usual 35 kilometers. This elevation may be explained by the interleafing of two continental plates (fig. 1C) or by the Indian plate underthrusting the Asian plate.

Examples of mobilization of the central region of a continent can be cited, but at least some of these may be illusory. The Sudbury structure, probably a basin filled with an extrusive lopolith, may be taken as a case in point (fig. 7). This structural basin is 1700 million years old and was formed on a craton which is about 2200 million years old. The genesis of the structure, whether it is a tectono-volcanic feature

(Speers, 1957) or an astrobleme (Dietz, 1964), is not critical to this discussion. The essential point here is that the Sudbury basin apparently was tectonically compressed about 1100 million years ago, from an original circular form into its present squashed or oval shape, by orogenic forces transmitted from the Grenville province on the southeast. Accordingly it might be argued that this is an example of the internal tectonic yielding (the deformation was not sufficient to term this a collapse) of the continental block. However, given the assumption of continental accretion, we can interpret this as marginal yielding of the continental block. The Grenville rocks probably are a peripheral emplacement against the older portion of the Canadian Shield. The Grenville orogeny occurred about 1100 million years ago. If we subtract the Grenville zone, then the squashing of the Sudbury Basin occurred within a few miles of the continental edge and not within the central heartland of a continent. The Sudbury example is still in general accord with the thesis of continental immobility.

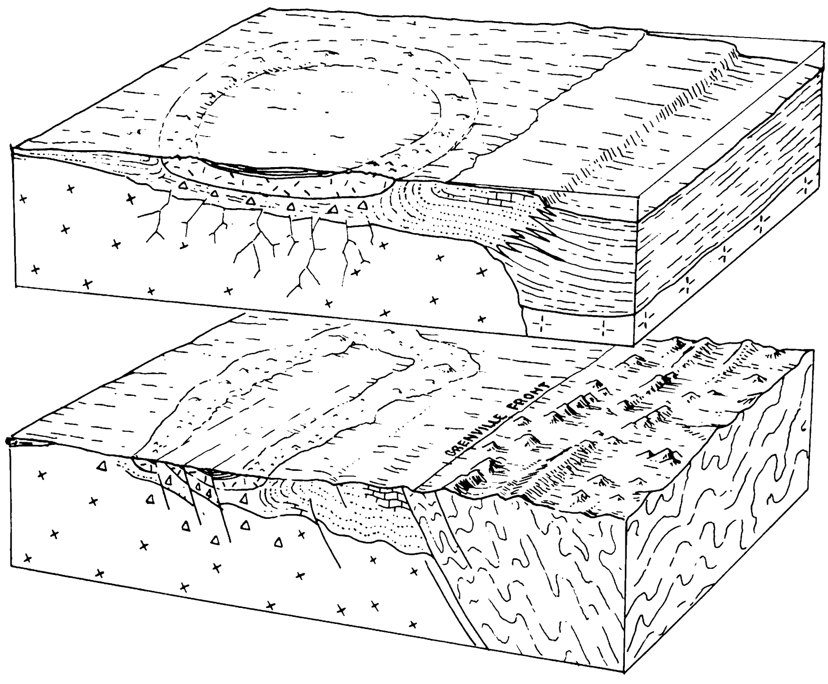

Fig. 7. The Sudbury structure in Canada may provide an example of an original circular basin which was somehow impressed on the continental plate 1.7 billion years ago and later was moderately deformed. Quite likely it was near the continental margin at that time and remained so until the Grenville accretion took place 1.0 billion years ago. Although the Sudbury structure was formed on the immobile crust, some folding and thrusting was caused by the proximity to the Grenville orogeny, much as the folded Appalachians were affected by the emplacement of the crystalline Appalachians.

CONCLUSION

New knowledge concerning the ocean floor structure and the collapse of the traditional Precambrian stratigraphic edifice calls for reappraisal of our standard geotectonic concepts. I have attempted to show here that we can adapt to the new observations by assuming a model for geotectonism based upon an active mantle, which entrains the sea floor, and a passive sialic crust. This in turn implies the assumption of thermal convection in the mantle, which remains an unproven but highly useful concept. A two-layer pattern of tectonism results, which is based on the difference of chemical composition between the continental crust and the oceanic sector. Transcurrent faulting and rifting become dominant modes of failure, emphasizing the importance of horizontal primary forces, which are not an illusion as the verticalists sometimes contend. Passive continental drift is permissable by the model and in fact expected. Continents are nondeformable on the scale of their entire thickness (that is, a tectogene). The sea floor does not yield by folding or net shortening but does show differential movement in the fracture zones bounding strips or blocks of ocean floor. The collapsing of continental rises by the interaction of the movable sea floor with the continental blocks provides the principal realm of mobility and the basic substance of orogens.

REFERENCES

Beloussov, V. V., 1958, Some factors governing the development of the earth's crust: Endeavour, v. 17, p. 173-180.

——— 1960, Development of the earth and tectonogenesis: Jour. Geophys. Research, v. 65, p. 4127-4146.

——— 1962, Basic problems in geotectonics: New York, McGraw-Hill, 816 p.

Brock, B. B., 1956, Structural mosaics and related concepts: Geol. Soc. South Africa Trans., v. 59, p. 149-197.

Bucher, W. H., 1933, Deformation of the Earth's Crust: Princeton, New Jersey, Princeton Univ. Press. Reprinted 1964, New York, Hafner Pub. Co., 518 p.

——— 1955, Deformation in orogenic belts, *in* Poldervaart, Arie, ed., Crust of the earth, a symposium: Geol. Soc. America Spec. Paper 62, p. 343-368.

Dence, M. R., 1964, A comparative structural and petrographic study of probable Canadian meteorite craters: Meteoritics, v. 2, p. 249-270.

Dietz, R. S., 1961, Continent and ocean basin evolution by spreading of the sea floor: Nature, v. 190, p. 854-857.

——— 1963, Collapsing continental rises: An actualistic concept of geosynclines and mountain building: Jour. Geology, v. 71, p. 314-333.

——— 1964, Sudbury structure as an astrobleme: Jour. Geology, v. 72, p. 412-434.

Dietz, R. S., and Holden, J., in press, Deep-sea deposits *in* but not *on* continents: Am. Assoc. Petroleum Geologists Bull., in press.

Engel, A. E. J., 1963, Geologic evolution of North America: Science, v. 140, p. 143-152.

Ewing, Maurice, and Ewing, J. I., 1964, Distribution of oceanic sediments, *in* Studies on oceanography, Hidaka Commemorative V. [Tokyo]: p. 525-537.

Ewing, Maurice, Ludwig, W. J. and Ewing, J. I., 1964, Sediment distribution in the oceans: The Argentine Basin: Jour. Geophys. Research, v. 69, p. 2003-2032.

Fairbairn, H. W., Hurley, P. M. and Pinson, W. H., 1960, Mineral and rock ages at Sudbury-Blind River, Ontario: Geol. Assoc. Canada Proc., v. 12, p. 41-66.

Gastil, R. G., 1960, The distribution of mineral dates in time and space: Am. Jour. Sci., v. 258, p. 1-35.

Heezen, B. C., and Tharp, Marie, 1958, Physiographic diagram of the North Atlantic: New York, Geol. Soc. America.

———— 1962, Physiographic diagram of the South Atlantic: New York, Geol. Soc. America.

———— 1964, Physiographic diagram of the Indian Ocean: New York, Geol. Soc. America.

Hess, H. H., 1962, History of ocean basins, *in* Engel, A. E. J., James, H. L., and Leonard, B. F., eds., Petrologic Studies: a volume in honor of A. F. Buddington: New York, Geol. Soc. America, p. 599-620.

Holmes, Arthur, 1965, Introduction, *in* Rankama, K. K., ed., The Precambrian: New York, John Wiley & Sons, Inc., Intersci. Pub., p. xi-xxiv.

Innes, M. J. S., 1964, Recent advances in meteorite crater research at the Dominion Observatory, Ottawa, Canada: Meteoritics, v. 2, p. 219-241.

Kay, G. M., 1951, North American geosynclines: Geol. Soc. America Mem. 48, 143 p.

King, P. B., 1959, The evolution of North America: Princeton, New Jersey, Princeton Univ. Press, 189 p.

Macgregor, A. M., 1951, Some milestones in the Precambrian of Southern Rhodesia: Geol. Soc. Proc. South Africa, v. 54, p. xxvii-lxxi.

Nicolaysen, L. O., 1962, Stratigraphic interpretation of age measurements in southern Africa, *in* Engel, A. E. J., James, H. L., and Leonard, B. F., eds., Petrologic Studies: a volume in honor of A. F. Buddington: New York, Geol. Soc. America, p. 569-598.

Pettijohn, F. J., 1943, Archean sedimentation (southern Canadian Shield): Geol. Soc. America Bull., v. 54, p. 925-972.

Rodgers, John, 1964, Basement and no-basement hypotheses in the Jura and Appalachians Valley and Ridge, *in* Lowry, W. D., ed., Tectonics of the southern Appalachians: Virginia Polytech. Inst. Dept. Geol. Sci., Mem. 1, p. 71-80.

Speers, E., 1957, The age relation and origin of common Sudbury breccia: Jour. Geology, v. 65, p. 497-514.

Wells, F. G., 1949, Ensimatic and ensialic geosynclines [abs.]: Geol. Soc. America Bull., v. 60, p. 1927.