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Plate Tectonics in Geologic History

New global tectonic theory leads to revised concepts of geosynclinal deposition and orogenic deformation.

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Geologists have long recognized that drastic changes in regional geologic features and organic evolution in the past are recorded by rocks and fossils. Despite these ruling concepts of change as the order of the world, many geologists until recently had a stabilist view of global geographic features in earth history. The permanence of continents and ocean basins was accepted widely, although many allowed for the intermittent accretion of mass to the margins of continents. During the past decade the emergence of a mobilist view, here called the *plate tectonic theory*, has changed the outlook. Several challenging ideas of dramatic sweep but previously uncertain significance now appear to be corollaries of the plate tectonic model. Continents are drifting in relative motion with respect to one another. The oceanic crust of the sea floor undergoes semicontinuous renewal at intraoceanic *rises* from which the sea floor is spreading away on both sides. Complementary consumption occurs at *arc-trench systems*, where continental crust is also generated by several coordinate means. Such major changes in global geography and geology are related facets of the processes that govern the pattern of motions of large blocks or plates of the earth's stiff outer rind, called the *lithosphere*.

Acceptance of the mobilist view changes many ideas about geologic history. Current concepts of processes in mobile belts at continental margins are partly invalid legacies from the stabilist geology of the past. This article traces the evolution of some salient concepts and shows how they can be modified to fit plate tectonic logic. I assume that tectonic elements of the mobile present are keys to past geologic history—but only to the extent that records of similar tectonic elements can be read from the rocks. Rock associations that signal particular plate tectonic regimes are here called *petrotectonic assemblages*.

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Uniformitarian Priniciple

The standard approach to geologic history rests on the uniformitarian postulates of Hutton (*1*). His method of thinking had two main struts: (i) The landscape and the rocks are the products of the long-continued operation of ordinary processes that gradually run their course; and (ii) the earth is an indivisible system in dynamic balance. These postulates retain their value even though unfamiliar processes may at first seem extraordinary and some components of the total system are poorly understood. The uniformitarian postulates imply that observed products of present processes, and the balance of present subsystems, are keys to correct interpretations of past events. Similar results and patterns in the geologic record must mean that analogous things happened in the past and that past subsystems were also related. Uniformitarian thinking compels us to recognize, in the record of the rocks, the slow unfolding of diverse sequences of events whose full display is beyond our immediate experience. Plate tectonic concepts, although fresh and startling, are fully compatible with uniformitarianism.

Hutton used simple observations of the surficial processes that mold the face of the earth to infer the broad outlines of weathering, erosion, and sedimentation. His systemic approach then led him to grasp the general implications of the degradational aspect of the history of continents: the way sediments are derived from them and washed into the seas. He saw continental denudation and oceanic deposition as a linked chain of events, despite his ignorance of many subtle details of the processes concerned. His precepts paved the way also to an understanding of the then unsuspected facets of erosional and depositional history, notably the great continental glaciations (*2*).

Hutton's triumphs in the field of surficial geology were not duplicated for processes and events within the solid earth, a realm for which his day had few sensors. His most magnificent inference, that rock masses undergo uplift, was the one he could least elucidate, although he reported surficial evidence for its occurrence. Great masses of fossiliferous marine strata, now exposed high above sea level where they are fractured and contorted and metamorphosed, imply that forces exist by which sedimentary beds, originally horizontal in a submarine setting, can be uplifted. Such a fundamentally constructive process also offers a logical counterbalance to the destructive process of erosion; it makes his theory of the world as a coherent system tenable. Neither Hutton nor Lyell (*3*) after him was able to suggest a convincing cause of uplift; both attributed it to vague thermal expansion resulting from the acquisition of heat, from some unknown sources, by some unspecified volumes of rock at depth. His continued emphasis on thermal expansion and contraction as causes of uplift and subsidence led Lyell to conceive of "aqueous and igneous agents" as "antagonist forces," the former acting to level the earth's surface by complementary erosion and sedimentation while the latter acted to renew the uneven contours on a large scale.

Geosynclinorial Theory

Geologic mapping has shown that many mountain ranges are neither volcanic nor a surface reflection of deeper igneous activity masked by a sedimentary cover. Their positions are commonly explained instead by variants of the inductive "geosynclinorial theory" (*4*), which touches on both rock deformation (or *tectogenesis*) and mountain-building (or *orogenesis*), a useful distinction that is worth emphasizing (*5*). The theory holds that elongate belts of deep subsidence and related thick sedimentation called *geosynclines* are the precursors of later mountain ranges in which the exceptionally thick geosynclinal strata are exposed by grand uplift following or accompanying thorough folding and partial metamorphism.

The geosynclinal idea came from Hall (*6*), who noted that the folded and locally metamorphosed Paleozoic strata in the Appalachians are much thicker than correlative but less deformed strata beneath the Allegheny Plateau to the west. As both sequences bear fossil evidence of deposition in shallow waters, he concluded that the site of the folded mountain range, whose fold axes parallel its length, had been first an elongate belt in which subsidence and coordinate sedimentation had been more rapid than in adjoining tracts. Rejecting Hall's initial notion that folding was contemporaneous with downwarping, Dana (*7*) showed that the rumpling of the geosynclinal prism implied postdepositional contraction of the visible part of the crust across the whole folded belt. The reversal of motion from subsidence to uplift can be interpreted as an isostatic response to achieve gravitational balance for the crumpled prism of relatively light rock, but the crumpling itself is not explained thereby.

Dana thus distinguished three successive phases of a geosynclinorial cycle: sedimentation, tectogenesis, and orogenesis. Metamorphism and magmatism he regarded as incidental to the scheme and dependent on local conditions during downbuckling. Familiarity with American mountain belts at the continental margins led Dana to regard geosynclines as zones peripheral to continental masses. As source regions for some of the voluminous geosynclinal detritus, Dana postulated companion and parallel uplifts, or geanticlines. He was forced to this hypothesis by sedimentological evidence (preserved internally within geosynclinal strata) that some detritus was delivered from uplands that lay on the side of the folded belt away from the continental interior. These ephemeral highlands became the borderlands of later literature.

The provinciality of American ideas based on the Appalachian region was eventually challenged, beginning with Haug (*8*), by European ideas based on the Alpine chain. Where Hall and Dana had spoken of geosynclinal sedimentation keeping pace with subsidence, meter by meter, Haug emphasized an elongate trough of deep water that was only gradually filled with sediment. In this, he foresaw later inferences of early, deep-water *flysch* deposits contrasted with later, shallow-water *molasse* deposits (*9*), and he also alluded to the migration of the main axis of sedimentation in response to tectonism and orogeny during sedimentation. He supposed that crumpling during deposition gave rise to intrageosynclinal ridges, for which he took the term geanticline, which could divide a geosyncline into multiple furrows. Drawing on his Eurasian experience of mountain belts bounded on both sides by extensive land masses, he visualized his troughs or multiple troughs as parts of mobile zones situated between stable continental masses.

By the mid-20th century, a patient analysis of field data from many orogenic belts had led to a reconciliation of these contradictory viewpoints into a single body of concepts. The key step in amalgamation was the discovery that many orogenic regions contain, in elongate belts lying side by side, deformed rock masses that appear to represent deposition in both *miogeosynclinal* and *eugeosynclinal* sequences, two main kinds of geosynclinal settings named by Stille in Europe and Kay in America (*10*). Miogeosynclinal sequences lacking volcanic rocks were deposited wholly or partly in shallow water; eugeosynclinal sequences including volcanic rocks were deposited wholly or partly in deep water. During the eventual orogenic consolidation of a geosynclinal belt into an emergent stable block, called by Kober (*11*) an *orogen*, deformation is commonly supposed to begin first and be most intense for the eugeosynclinal masses, which supposedly also become preferred loci for plutonic intrusion by granitic batholiths (*12*). The successive welding of deformed geosynclinal prisms, or orogens, to the margins of continents can also be viewed as incremental additions to continental crust (*13*). This view stems from observations that the bottoms of miogeosynclinal successions locally rest depositionally on continental basement rocks, whereas the depositional floors of eugeosynclinal sequences, though largely unseen, probably are oceanic crust in many cases.

Most syntheses of geologic history rely heavily upon the geosynclinorial theory. As this theory was built mainly upon inferences from stratigraphic relations exposed on continents, its origins were untroubled by detailed information about the submarine world or the ages of rocks that lack fossils. The classic conceptual models of miogeosynclinal and eugeosynclinal regions are not matched well by any present oceanographic realms. Also questionable is the notion of a tidy cycle of tectonic events proceeding neatly from protracted geosynclinal deposition to a terminating "revolution" of tectonic, metamorphic, and magmatic events which culminate in the uplift of a consolidated orogen. Radiometric data on the timing of igneous and metamorphic events lead instead to the concept of persistent *mobile belts* (*14*) affected by repeated and intermingled episodes of magmatism, metamorphism, and sedimentation. For example, metamorphic rocks once thought to be part of an ancient basement beneath the Appalachian geosynclinal prism are now regarded as deformed and heated parts of the pile.

By building upon, but stepping beyond, geosynclinorial theory, geosynclinal rock masses can be understood better as characteristic products of various plate tectonic regimes in the past (*15*). This approach does no injustice to previous workers, for whom the geosynclinal rock masses themselves have been the objects seen and described. The geosynclines were always the inference.

New Global Tectonic Theory

The plate tectonic theory is a comprehensive descriptive model for the kinematic pattern of current tectonic movements on the globe (*16*). The theory braids the concepts of continental drift, sea-floor spreading, and transform faults (*17*) into a common synthesis based on the inference that the firm outer rind of the earth is segmented into intact, semirigid slabs or plates hundreds or thousands of kilometers across. The plates of lithosphere, perhaps 75 to 125 kilometers thick, move about with respect to one another by riding upon a less rigid undermass called the *asthenosphere*, whose upper part is probably the low-velocity channel for seismic waves in the upper mantle. Rafts of continental crust 25 to 50 kilometers thick form the upper tier of parts of some lithosphere plates, but the Mohorovicic discontinuity is everywhere well within the lithosphere. The movement plan of the plates may reflect the geometry of slablike, pseudolaminar convectional flow in the upper mantle, but this inference encounters logical objections in the geometry of known movements. The observed kinematics of the surficial plates does not depend directly upon any dynamic assumptions.

Junctures between plates coincide with the world's active seismic belts. The three types of junctures (Fig. 1) are as follows.

1) *Divergent*, in which plates move away from one another, mainly along the intraoceanic rises that form a semicontinuous, branching web. Receding plate margins grow by the volcanic and diapiric emergence of material from the mantle beneath to fill the opening slot in the lithosphere by constructing successive increments of suboceanic crust and upper mantle. The rate of spreading can be determined from characteristic spatial arrays of colinear, axisymmetric positive and negative geomagnetic anomalies, which correspond to strips of oceanic crust composed of igneous rocks that cooled through the Curie point and acquired thermoremanent magnetization during successive polarity epochs in which the earth's magnetic field was alternately normal and reversed (*18*).

2) *Convergent*, in which plates move toward one another along arc-trench systems or crumpled mountain ranges, or both. First-motion studies of seismic wave trains from earthquakes occurring along belts of inclined seismic zones that correspond to convergent plate junctures yield approximate directions of relative convergence. Typical convergent junctures in oceanic areas or at continental margins lie along oceanic trenches, depressions that mark the descent of plates of oceanic lithosphere moving downward into the mantle. The edges of the overriding plates are marked roughly by chains of active volcanoes that stand subparallel to the nearby trenches. As the descending plates move downward along the inclined seismic zones that reach deep into the mantle beneath the eruptive arcs, their descent somehow generates magmas that feed the volcanism and associated plutonism in the arcs. This magmatism and the events associated with it are probably the main means by which subcontinental crust and upper mantle are formed (*19*).

3) *Simple shear*, in which plates slide past one another along transform faults. The orientations of transforms closely specify the directions of relative motions but give no indications of motion rates. Surface area is conserved along transform boundaries.

By using the indications of relative motion given by relations at the various types of plate junctures and by assuming a fixed surface area for the globe, the relative motions of all the present major plates can be calculated as angular velocity vectors. Rates of relative motion are so large, and so incongruent on a global scale, that major rearrangements of plate boundaries and motions must be expected when long time intervals are considered. Even without gross changes in patterns, the evolution of complex and shifting triple junctions where three plates are in contact must lead to a succession of different plate tectonic regimes along given plate boundaries (*20*). Where the origins of particular rock associations can be related to specific kinds of plate junctures and plate interiors, their ages and occurrences can be used to monitor past changes in plate tectonic regimes. These petrotectonic assemblages can be used to decipher the geologic history of orogenic belts without recourse to the geosynclinorial theory. Plate convergence and its consequences place a unique stamp on the rock masses of orogenic belts, but rocks formed under other plate tectonic regimes are also significant components

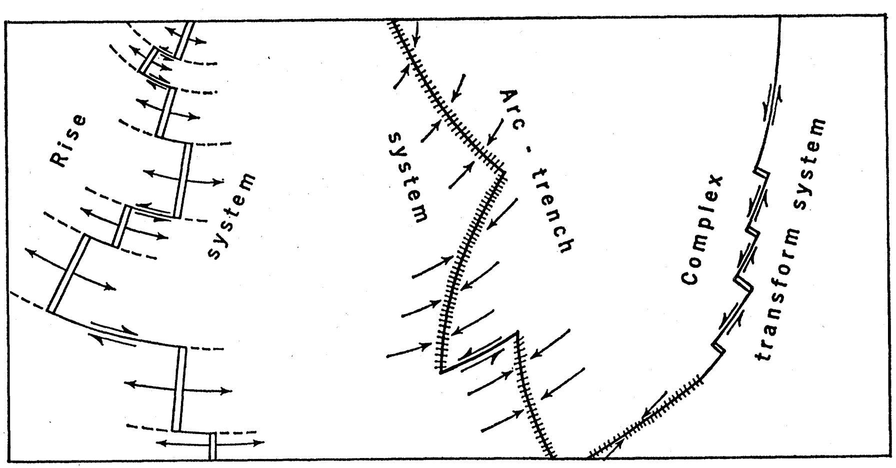

Fig. 1. Diagrammatic display of typical relations between lithospheric plates with boundaries along rises (double lines), arc-trench systems (hachured lines), and transforms (single lines). Dashed single lines are crustal scars along inactive transforms. Pairs of vectors show approximate relative motions between plates at divergent (rise), convergent (arc-trench system), and shear (transform) boundaries. Vectors are omitted for some short transforms and rise segments. In harmony with the spherical geometry of plates in motion on a sphere, observed spreading rates along the lengths of given rise crests vary according to sine functions, as required for consistent angular velocity between adjacent plates, whose divergence leaves a shutter-like opening in their mutual wake, as if the two plates were hinged at a virtual pole of rotation. Similarly, trends of transform faults are small circles concentric about such virtual poles of relative movement between two plates in contact along transform boundaries of simple shear. Calculated directions and rates of relative convergence at arc-trench systems obey similar geometric constraints. As shown, divergent junctures tend to lie nearly normal to relative motion vectors and to form rectilinear patterns with linked transforms, but convergent junctures commonly stand oblique to relative motion vectors.

of all major orogenic belts. The selective consumption of lithosphere beneath arc-trench systems means that rock masses originally formed in widely separated localities at different times can later be juxtaposed along convergent junctures.

In the scheme of plate tectonics discussed here, only the relative motions of lithosphere plates are considered. Some statements and inferences may need modification if semiabsolute motions of lithosphere plates with respect to possibly semistable underlying mantle can be established from the trends of certain aseismic oceanic ridges or from some volcanic island chains, active at one end and dormant at the other (*21*). These features may prove to be streamlines of lithosphere movement with respect to semifixed features at deeper levels.

Key Petrotectonic Assemblages

Rocks embody the record of past geologic events but do not record all kinds equally well. The three rock assemblages most diagnostic of plate tectonic regimes are those formed at divergent junctures, near convergent junctures, and along continent-ocean interfaces in plate interiors. At other plate-interior sites and along transform junctures, major events or long intervals may leave scant record; hence, data are equivocal at best. Even for the three attractive settings, the rock record is inherently incomplete for two reasons. Rocks destroyed by erosion at some time in the past are represented in the stratigraphic record by buried erosion surfaces, called *unconformities*, whose full significance is always uncertain. Rock masses can also be removed from view by being carried downward at convergent junctures. Such regions of crustal consumption have been given the general name *subduction zones* (*22*). Just as unconformities represent missing pieces of the rock record in a vertical sense, subduction zones represent missing pieces of the rock record in a horizontal sense.

The petrotectonic assemblage typical of divergent junctures is the oceanic crust less the scum of slowly accumulated sediment added later as the oceanic crust rides away from rise crests. Dredge hauls and geophysical observations at sea indicate that pristine oceanic crust consists of mafic igneous rock. At the rise, the crust apparently consists of submarine basalt lava, of the low-potash variety called *abyssal tholeiite*, overlying partly metamorphosed basalt and more coarsely crystalline intrusive rocks, dolerite and gabbro, of the same chemical composition (*23*). This mafic igneous carpet, commonly 5 to 7.5 kilometers thick, evidently fractionates from the ultramafic mantle upon which it rests. Where diapiric masses of hot asthenosphere attempt to rise upward to fill the slot between the trailing edges of two receding plates of the lithosphere, release of confining pressure induces partial fusion of peridotite. The resulting basaltic magmas of low density are injected upward buoyantly to feed the volcanism and subvolcanic intrusions that create oceanic crust along rise crests.

As the oceanic crust moves across ocean basins away from rise crests, three kinds of materials can be added to it: fine sediments, turbidites, and lavas. The nearly ubiquitous fine sediment, which includes dispersed terrigenous clay and silt, airborne dust and volcanic ash, and tests and skeletal fragments of organic origin, settles steadily on the crust to form thin layers of shale or argillite, micritic limestone, and chert. Coarser grained and more rapidly deposited turbidites form sandy and silty layers intercalated within oceanic sediments in basins close enough to the submarine slopes of land masses to draw turbidity currents. The added lavas are the substance of volcanic seamount and island chains built in plate interiors.

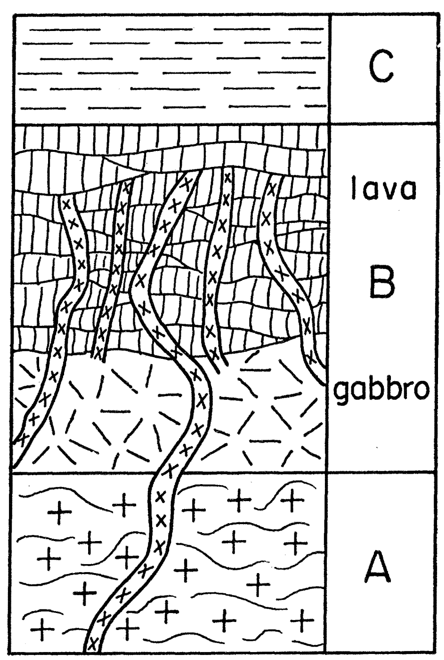

Fig. 2. An idealized section of ophiolite sequence composed of (A) anhydrous peridotite or hydrated serpentinite sheet of refractory residual mantle; (B) gabbro, dolerite, and pillow lava with pillow breccia, in roughly ascending order but all partly intermingled with gradational and intrusive contacts (lower parts of the composite igneous pile are hydrothermally metamorphosed); and (C) chert and argillite containing only pelagic marine organisms as fossils.

Petrotectonic assemblages of rises and ocean basins come to view on land only where slabs of upper oceanic lithosphere are incorporated as thrust slices within or above subduction zones at convergent plate junctures. Erosion following isostatic uplift then exposes them as apparently native tectonic elements of orogenic belts. These tectonic slabs (*24*) are pseudostratigraphic sequences called *ophiolite assemblages* (Fig. 2).

The contrasting petrotectonic assemblages characteristic of convergent plate junctures are those made in arc-trench systems (Fig. 3).

The descent of relatively cold lithosphere beneath the trench and the adjacent arc-trench gap, coupled with the ascent of relatively hot magmas beneath the arc, creates contrasting geothermal gradients within the crust on the arc and trench sides of the system. Metamorphism beneath the trench and arc-trench gap involves recrystallization at low temperature/pressure ratios, typically in the blueschist or low greenschist facies, whereas metamorphism beneath the arc involves recrystallization at high temperature/pressure ratios, typically in the high greenschist or amphibolite facies. The result is the formation, at depth, of paired metamorphic belts whose later exposure by uplift and erosion affords evidence for the polarity of consumption in the arc-trench system that formed them (*25*).

The subduction zone beneath the inner wall of the trench is stuffed with sea-floor materials as plate consumption proceeds (*26*). Oceanic basalt may invert to eclogite and disappear into the mantle, but the lighter sediments on a descending plate probably cannot go so deep but, instead, scrape off against the edge of the overriding plate edge. The multiple thrusting of subduction commonly creates a mass of intricately sliced turbidites and ophiolitic shreds in the structural style of *mélange*, used here to describe terranes

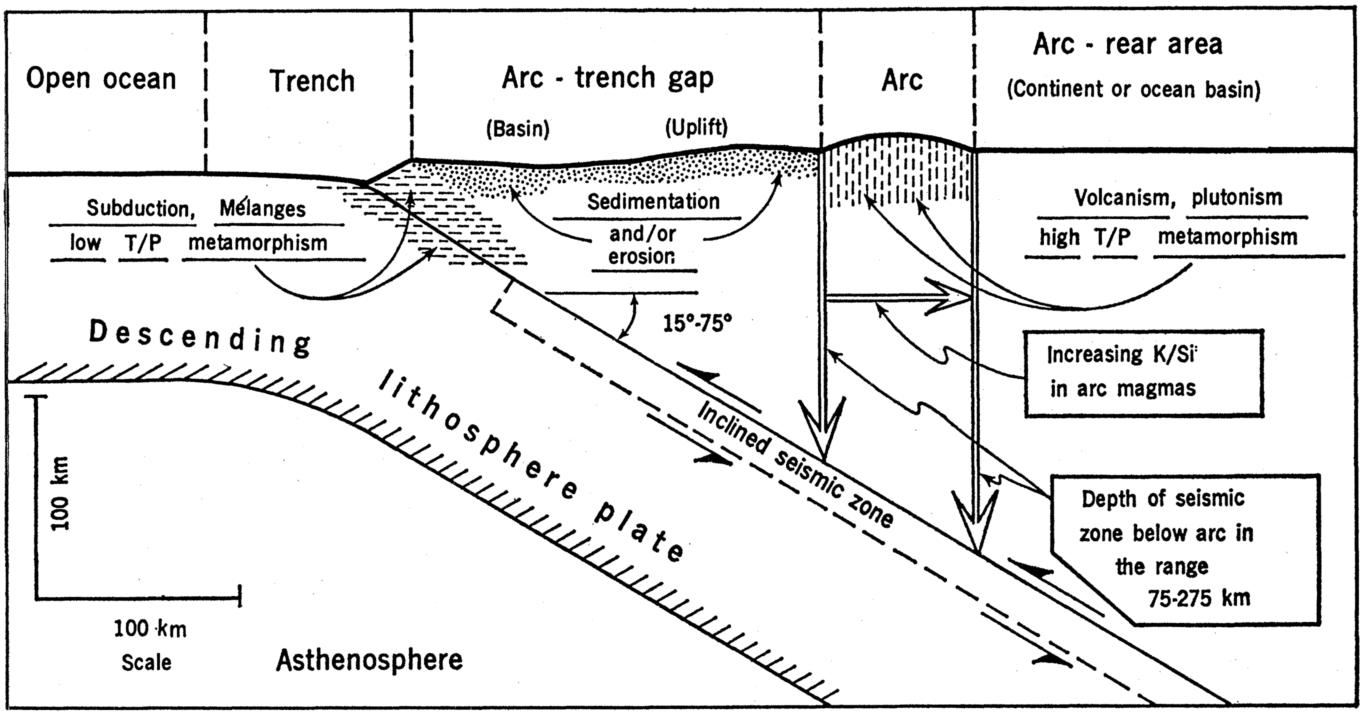

Fig. 3. Generalized transverse section of an arc-trench system showing characteristic features of the three main parallel tectonic elements: oceanic trench; arc-trench gap (*30*); and magmatic arc, which is either insular or marginal to a continent (*T/P*, temperature/pressure ratio).

in which shear surfaces supplant bedding or schistosity as the dominant structural features. The ultimate tectonic thickness of a mélange belt depends upon the amount of turbidite sediment fed into the subduction zone from the nearby arc or from land masses behind it, and upon the duration of subduction without gross shifts in position. The tectonic mélange thickness does not depend upon the stratigraphic thickness of layers piled in orderly fashion on any particular segment of oceanic crust that is subducted or consumed at the convergent juncture.

The magmatic arc is a volcano-plutonic orogen composed of volcanic and volcaniclastic strata intruded by comagmatic plutons (*19, 27*). Characteristic igneous rocks are andesitic extrusives and granitic intrusives, but suites are varied. Intraoceanic insular arcs, built directly on oceanic crust, may contain large proportions of generally tholeiitic basalt and generally lack lavas more silicic than dacite, whereas arcs on continental margins erupt large proportions of rhyolitic ignimbrites and probably harbor much larger granitic batholiths at depth (*26, 28*). Potassicity of the igneous rocks always increases in the direction away from the trench, as the depth to the inclined seismic zone beneath increases, and is another valid test for the polarity of the arc-trench system (*19*). Although the arcs stand topographically high, progressive subsidence of surficial layers as younger volcanic and volcaniclastic rocks are piled on them can effect a net accumulation of strata.

The arc-trench gap, commonly 125 to 250 kilometers wide, is bounded on one side by the frontal volcanoes and plutons of the arc and is separated from the trench by a buried submarine ridge or lip of "acoustic basement" beneath the top of the trench's inner wall (*29*). The internal structure of this dividing barrier is unknown, but it may be composed in part of subducted mélange materials lifted isostatically by the buoyancy of younger mélange subducted beneath them. Uplifted areas occur within some arc-trench gaps, but many contain instead, or also, elongate sediment traps containing undisturbed stratified sequences at least several kilometers thick. Of varied bathymetry, these include shallow shelves receiving sediment, slopes traversed by transverse turbidity currents, and troughs followed by longitudinal turbidity currents. Accumulation of undeformed sedimentary strata

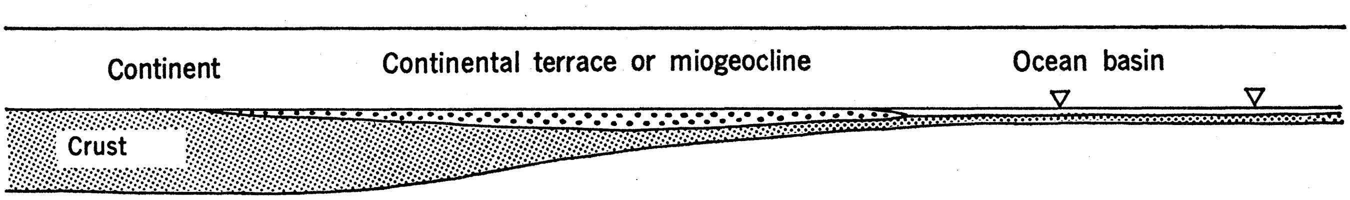

Fig. 4. Hypothetical section of a continental terrace accumulation; roughly to scale with continental crust 50 kilometers thick and oceanic crust 5 kilometers thick. Inland sources of sediment find ready receptacles along the adjacent continent-ocean interface, where water deepens and tapering crust allows easy subsidence under sedimentary loading. Sediments deposited in shallow water on continental crust form miogeocline. Adjacent sediments deposited offshore in deeper water form continental rise. The sketch is grossly generalized, as the nature of the transition from thick continental crust to thin oceanic crust is poorly known.

in arc-trench gaps is concurrent with stratal dislocation in adjacent trench mélanges and with thermal recrystallization in nearby arc roots. Beyond the arc, on the side away from the trench, roughly analogous strata may accumulate in "back arc" or "foreland" basins. These, too, are largely free of the magmatism and metamorphism that affect the arc and trench assemblages but are commonly cut by contemporaneous thrust faults that carry rocks of the arcs, or of highlands behind the arcs, over the edges of the depositional basins (*26, 30*).

The strata deposited along tectonically quiet continental margins in plate interiors also constitute a diagnostic petrotectonic assemblage (Fig. 4). Most such margins are formed where continental blocks are rifted apart at divergent plate junctures, but possibly also where active continental margins at convergent plate junctures become quiescent when convergence ceases for any reason. A wedge of sediment is built as a continental terrace masking the continent-ocean interface. Water depths vary as the wedge grows upward and outward, commonly as coarse sediment dumped rapidly at first, and then as carbonate platform deposits laid down slowly (*15, 31*). The very base of the sequence commonly contains basalt lavas erupted during initial rifting.

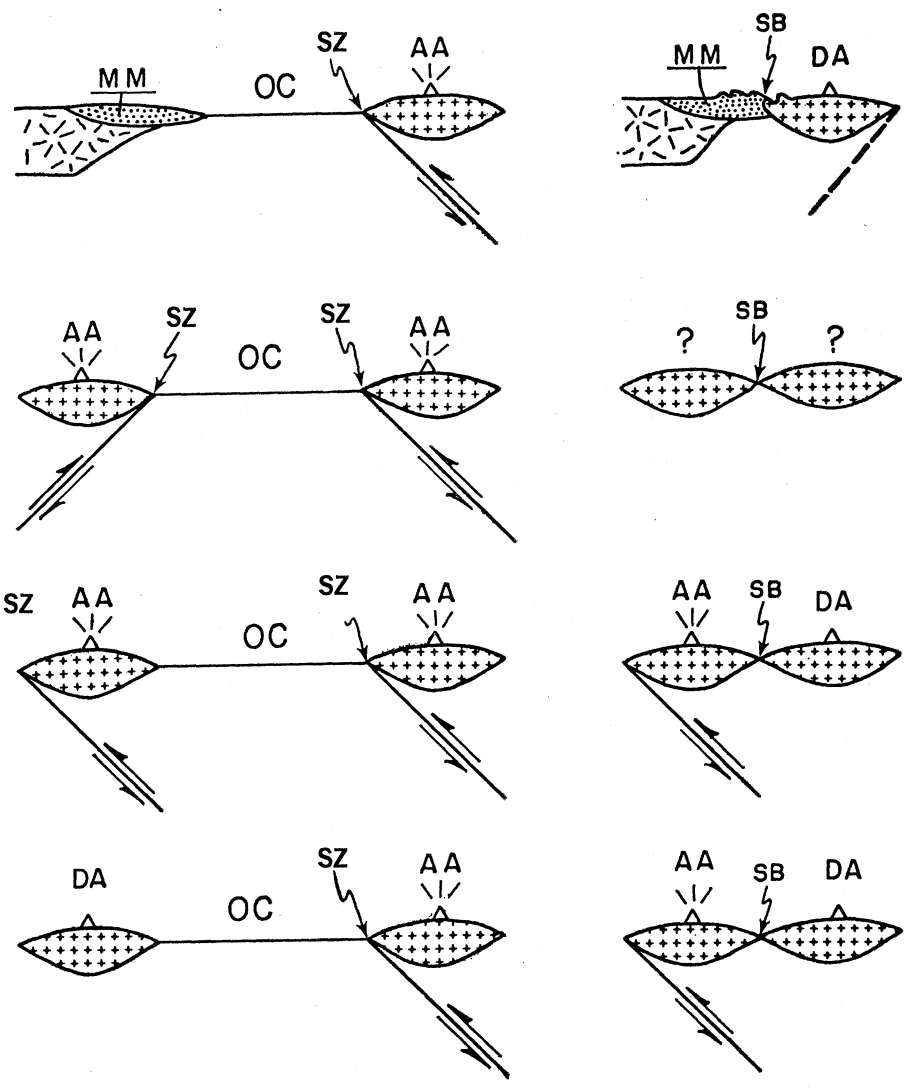

Fig. 5. Four salient collision scenarios illustrated in section, before (left) and after (right). *MM* is miogeoclinal margin; *OC* is ocean basin (ophiolitic assemblage) being consumed; *SZ* is active subduction zone at trench; *SB* is closed suture belt; *AA* is active magmatic arc; and *DA* is dormant arc. The arc-trench systems (crosses) may be either insular or marginal to continents; partial subduction of thick crustal masses is not shown but is possible in all cases. If the colliding arc is intraoceanic in the first case, crustal consumption may continue along an activated continental margin, where the subduction zone flips in sense and transfers to the opposite side of the accreted arc (see dashed line).

Interpreting Geologic History

The continental terrace assemblage, when preserved as an elongate belt of deformed sedimentary rocks, is the miogeosynclinal sequence of classic terminology. It has recently been called *miogeoclinal* (*32*) in recognition that one side is open to the ocean. Sequences of arc-trench gaps and arc-rear settings have also been called miogeosynclinal locally to indicate their lack of volcanic rocks. Petrotectonic assemblages of open oceans, trenches, and arcs have all been called eugeosynclinal because of deep water, volcanic components, or both. Realistic versions of geologic history can be written only if these different kinds of eugeosynclinal and miogeosynclinal assemblages are identified properly as indicators of different plate tectonic regimes. There is no single fixed geosynclinorial cycle; rather, there is a repertoire of types of plate tectonic events that can occur in certain logical sequences (*33*). Things like phantom borderlands and intracontinental geosynclines are mistaken imagery, artifacts of the mental effort to fit a mobile geology into a mold of global stabilism, which can be explained instead by the separation or junction of drifting crustal masses at appropriate times.

Convergent plate junctures marked by belts of plate consumption and crustal contraction are the loci of tectogenesis and orogeny (*26, 34*). The rock masses of orogenic belts include the indigenous petrotectonic assemblages of arc-trench systems and other petrotectonic assemblages that have either been brought against a convergent juncture by consumption of the intervening lithosphere or been mangled near an arc-trench system by initiation of plate convergence and crustal subduction at a new site. Within orogenic belts, the present geographic arrangement of various petrotectonic assemblages need not reflect their relative positions when formed.

Juxtaposition of once separate petrotectonic assemblages can be accomplished by consumption of intervening ocean basins, whose former presence may be marked by narrow bands of ophiolitic mélange only. Continental crust is probably too thick and light to be consumed by subduction; hence, consumption of oceanic crust probably leads to collision of continents and, consequently, to braking of subduction, an effect that might influence global patterns of plate motions (*35*). The semioceanic and semicontinental underpinnings of magmatic arcs might respond to attempted subduction in intermediate ways that would involve partial collision and partial consumption.

Present positions and relative ages of appropriate petrotectonic assemblages can be used to infer events of rifting and collision involved in continental fragmentation and assembly. For example, initiation of miogeoclinal deposition on a continental margin could date a rift, and termination of miogeoclinal deposition through terminal flysch and molasse stages of deposition, accompanied by folding and thrusting, might date a collision. Truncation of old basement trends along the inland flank of the miogeoclinal wedge strengthens a rift interpretation. Evidence for collision might include belts of ophiolitic shreds marking sutured ocean basins, and suitable volcanic or batholithic rocks marking magmatic arcs. At least one member of each collision pair must be an arc-trench system; otherwise, collision is impossible (Fig. 5).

Old orogenic "rules" find fresh plate tectonic formulations. In collisions between previously quiescent miogeoclinal margins and active arcs or continental margins, the "miogeosynclines" inevitably precede orogeny only in the sense that they must form before they can be deformed. Orogeny begins earliest in the "eugeosynclines" only in the sense that the arc-trench systems must actively consume oceanic lithosphere before collisions. Granitic batholiths seemingly prefer "eugeosynclinal" prisms because they are emplaced in arc roots, and so on. Troublesome "exceptions" to the old rules are inherent in alternate successions of plate tectonic regimes; for example, development of an arc-trench system through newly initiated subduction at a previously quiet continental margin will yield a different pattern of "orogeny" than will collision of such a margin with a long-active arc-trench system.

The geography of paired metamorphic belts, mélange-batholith relations, sequences of arc-trench gaps and arc-rear settings, and especially, the gradient of potassicity in the volcano-plutonic orogen can be used to establish the polarity of old arc-trench systems. At active continental margins marked by arc-trench systems consuming adjacent ocean, arrays of oceanic mélanges and intraoceanic arcs can be successively accreted and joined with indigenous arc rocks to form a growing belt of newly continental crust (*26*). In such complex terranes, arcs may be built through and upon older mélanges or arcs alike. Following either collision or accretion events, subsequent deposits of clastic sediments in *successor basins* (*31*) on top of various kinds of older "geosynclinal" strata are special kinds of petrotectonic assemblages whose relations can be diagnosed.

Recent thought (*26, 33, 34*) suggests that the approach to geologic history urged here can ultimately define all the major tectonic events of the Phanerozoic (roughly 500 million years) in terms of plate tectonic regimes. There is the further exciting possibility that the major tectonic patterns of even older Precambrian rocks, in which fossils are scarce and age relations more obscure, may yield to the same kind of analysis. Long familiar is the idea that each of the main age belts of Precambrian rocks, dated by radiometric methods, represents the cumulative imprint of a related chain of orogenic events (*31*). In plate tectonic terms, each age belt may record the setting, or resetting, of radiometric clocks in Precambrian crustal rocks either (i) by the gathering of accretionary progressions of arc-trench assemblages and subducted materials around the growing peripheries of continental nuclei, or (ii) by deformation of broad areas of continental margins involved in continental collisions. The petrology of Precambrian rocks, generally similar to Phanerozoic rocks, suggests that petrotectonic assemblages related to plate tectonic regimes can provide the prime basis for understanding the last 2.75 billion years of earth history. Before that, the rock record is dim.

References

1. J. Hutton, *Trans. Roy. Soc. Edinburgh* **1**, 209 (1788).
2. J. L. R. Agassiz, *Études sur les Glaciers* (Jent et Gassmann, Neuchâtel, Switzerland, 1840).
3. C. Lyell, *Principles of Geology* (Murray, London, ed. 12, 1875).
4. A. Knopf, *Amer. J. Sci.* **258A**, 126 (1960); *Geol. Soc. Amer. Bull.* **59**, 649 (1948).
5. J. Aubouin, *Geosynclines* (Elsevier, Amsterdam, 1965).
6. J. Hall, *N.Y. Geol. Surv. Paleontol.* **3**, 66 (1859).
7. J. D. Dana, *Amer. J. Sci.* **5**, 423 (1873).
8. E. Haug, *Bull. Soc. Geol. Fr.* **28**, 617 (1900).
9. R. Trumpy, *Geol. Soc. Amer. Bull.* **71**, 843 (1960).
10. M. Kay, *Geol. Soc. Amer. Mem.* **48**, 1 (1951).
11. L. Kober, *Der Bau der Erde* (Gebruder-Borntraeger, Berlin, 1921).
12. P. B. King, *The Evolution of North America* (Princeton Univ. Press, Princeton, N.J., 1959).
13. J. T. Wilson, *Trans. Roy. Soc. Can.* **43**, 157 (1949).
14. R. H. Dott, Jr., *Amer. J. Sci.* **259**, 561 (1961).
15. W. R. Dickinson, *Earth Planet. Sci. Lett.* **10**, 165 (1971); A. H. Mitchell and H. G. Reading, *J. Geol.* **77**, 629 (1969).
16. D. P. McKenzie and R. L. Parker, *Nature* **216**, 1276 (1967); W. J. Morgan, *J. Geophys. Res.* **73**, 1959 (1968); B. Isacks, J. Oliver, L. R. Sykes, *ibid.*, p. 5855; D. P. McKenzie and W. J. Morgan, *Nature* **224**, 125 (1969).
17. J. T. Wilson, *Nature* **207**, 343 (1965).
18. F. J. Vine, *Science* **154**, 1405 (1966); J. R. Heirtzler, G. O. Dickson, E. M. Herron, W. C. Pitman, X. Le Pichon, *J. Geophys. Res.* **73**, 2119 (1968); X. Le Pichon, *ibid.*, p. 3661; A. Cox, *Science* **163**, 237 (1969).
19. W. R. Dickson, *Rev. Geophys. Space Phys.* **8**, 813 (1970).
20. T. Atwater, *Geol. Soc. Amer. Bull.* **81**, 3513 (1970).
21. A. Wegener, *The Origins of Continents and Oceans* (Dutton, New York, 1924), pp. 151–152; J. T. Wilson, *Nature* **207**, 907 (1965); W. J. Morgan, *Trans. Amer. Geophys. Union* **51**, 822 (1970); R. S. Dietz, *J. Geophys. Res.* **75**, 4939 (1970); P. J. Coney, in preparation.
22. D. A. White, D. H. Roeder, T. H. Nelson, J. C. Crowell, *Geol. Soc. Amer. Bull.* **81**, 3431 (1970).
23. A. Miyashiro, F. Shido, M. Ewing, *Deep-Sea Res.* **17**, 109 (1970).
24. T. P. Thayer, *Geol. Soc. Amer. Bull.* **80**, 1515 (1969).
25. A. Miyashiro, *J. Petrol.* **2**, 277 (1961); *Medd. Dan. Geol. Foren.* **17**, 390 (1967); H. Takeuchi and S. Uyeda, *Tectonophysics* **2**, 59 (1965).
26. W. Hamilton, *Geol. Soc. Amer. Bull.* **80**, 2409 (1969); *ibid.* **81**, 2553 (1970).
27. Y. K. Ustiev, *Int. Geol. Rev.* **7**, 1994 (1965).
28. P. Jakes and J. Gill, *Earth Planet. Sci. Lett.* **9**, 17 (1970).
29. D. E. Karig, *J. Geophys. Res.* **75**, 239 (1970).
30. W. R. Dickinson, *Pac. Geol.* **3**, 15 (1971).
31. P. B. King, *U.S. Geol. Surv. Prof. Pap. 628* (1969), p. 1.
32. R. S. Dietz and J. C. Holden, *J. Geol.* **65**, 566 (1967).
33. P. J. Coney, *Geol. Soc. Amer. Bull.* **81**, 739 (1970).
34. J. F. Dewey and B. Horsfield, *Nature* **225**, 521 (1970); J. F. Dewey and J. M. Bird, *J. Geophys. Res.* **75**, 2625 (1970).
35. D. P. McKenzie, *Geophys. J. Roy. Astron. Soc.* **18**, 1 (1969).