Meetings

Global Tectonics

A Penrose Conference of the Geological Society of America was convened 15–20 December 1969, at Asilomar, Pacific Grove, California, to discuss "the meaning of the new global tectonics for magmatism, sedimentation, and metamorphism in orogenic belts."

Only a year or two ago, the current tectonic model reached its present coherent form by an elegant synthesis that followed 5 to 10 years of observation and analysis of unprecedented imagination and clarity. The fresh interpretations of orogenic processes discussed at the conference are based upon the well-documented theory that the earth's lithosphere, a relatively firm rind perhaps 100 ± 50 kilometers in thickness and composed of the crust plus some underlying part of the upper mantle, is segmented into a number of intact and semirigid slabs or plates with lateral dimensions on the order of 10^3 to 10^4 kilometers. With respect to one another, these plates maintain relative motions that are known to have followed surprisingly consistent geometric patterns for periods of time on the order of 10 to 100 million years in the immediate past. When longer time spans are considered, evidence for inferred reorganizations of the movement patterns becomes apparent. The theory encompasses, but goes beyond, the more simple, older ideas of continental drift and sea-floor spreading, neither of which is satisfying in itself, but both of which are explicable as necessary corollaries of the plate model.

A comprehensive hypothesis of continental drift was offered by Wegener in 1912. Many geologists rejected it for decades because they could not accept the concept that came most readily to mind, namely, ships made of thick continental crust plowing through a passive sea of oceanic crust. Even so, many geologists in the Southern Hemisphere found it preferable to accept the idea, despite the difficulty of explaining it, because certain striking similarities in the early geologic history of the southern continents seemed otherwise incomprehensible. In 1958, Carey in Tasmania published a paper that helped revive global interest in continental drift by emphasizing possible influences of drift patterns on the history and geometry of orogenic belts the world over. In preceding years, Runcorn in England and a number of others had emphasized the drift idea by showing that the orientations of the remanent magnetism in rocks of different ages in various parts of the world strongly suggest that the different continents have indeed occupied diverse positions with respect to the earth's magnetic poles. Moreover, reconciliation of paleomagnetic discrepancies from continent to continent does apparently require the assumption of large relative motions of the continents over the course of time.

The concept of spreading sea floors accompanied by some overturning of the crust and upper mantle also has a long history, but was given its precise meaning in our time by Hess (Princeton) in 1962. He had the advantage of the postwar oceanographic research that had shown a striking paucity of sediment in the ocean basins, hitherto thought by some to be stable and ancient receptacles; and also the data of Ewing and Heezen at Lamont-Doherty (Columbia) indicating the previously unsuspected continuity of the midoceanic rises along which some kind of upwelling was inferred. In a series of papers from 1961 onward, Dietz explored the possible implications of sea-floor spreading for orogenic processes at continental margins, thereby calling attention to a gathering storm of possible new interpretations for orogenic belts. In a popular form, the sea-floor spreading concept made it possible for a while to envision continental drift in terms of light scum shifted around amongst a changing pattern of roiling convection cells in the mantle beneath the oceans. This notion encounters a simple difficulty. Although some continental margins are tectonically active with crumpled rocks of very young age prominent, others appear to have been stable and undisturbed for long periods of time.

The braiding of the two threads of thought, continental drift and sea-floor spreading, into the comprehensive theory of plate tectonics was foreshadowed by two seemingly unrelated lines of research that came to fruition less than a decade ago. On the one hand, Mason and Raff (Scripps, San Diego) showed that large areas of the ocean floor off our West Coast are characterized by linear magnetic anomalies, relatively positive and negative, arranged in parallel arrays. Their initial observations were subsequently duplicated in other regions by many other workers. Meanwhile, students of paleomagnetism had discovered that the polarity of the earth's magnetic field has reversed at intervals in the past. By 1963, Cox, Doell, and Dalrymple (U.S. Geological Survey) had succeeded, by using the K-Ar technique to measure rock ages, in establishing a preliminary quantitative time scale for the last few major reversal events.

Shortly thereafter, Vine and Matthews (Cambridge) in 1963, and independently Morley and Larochelle (Ottawa) in 1964, noted that the magnetic anomaly bands of the oceans were roughly axisymmetric to the generally linear trends of the midoceanic rises. They published the suggestion that the bands were caused by crustal increments formed at the rise crests by cooling through the Curie point during different polarity epochs, and subsequently split in twain and displaced laterally by a movement plan of continued sea-floor spreading. In 1965, Vine (now at Princeton) and J. Tuzo Wilson (Toronto) apparently confirmed the hypothesis by showing that the relative lateral spacing of the centermost few positive and negative anomaly bands along the rise crests is consistently proportional to the independently established time duration of the last few normal and reversed polarity epochs. Wilson also in 1965 gave the developing synthesis a critical nudge with his concept of transform faults as transverse strike-slip features connecting linear regions where crust is created at rises or consumed at trenches. His accompanying discussion of the orogenic implications of the new ideas was almost a full blueprint for subsequent developments.

During 1967 and 1968, a cascade of

papers documented the plate boundaries and motions of the recent past as revealed by the locations of spreading axes, the spacing of magnetic anomaly bands, the orientations of transform faults, and the location and behavior of the earth's seismically active regions, which are linear and curvilinear belts along plate junctures. Morgan (Princeton), McKenzie (Cambridge), and Parker (Scripps) described the inferred nature of the geometry of the movements, and related them to major structural features. LePichon, Heirtzler, and their colleagues at Lamont-Doherty (Columbia) amassed the data on magnetic anomalies, their orientation, their correlation, their spacing, and coordinated the whole into an integrated analysis of rates of plate divergence at rises and rates of plate convergence at trenches.

The most convincing confirmation of the idea came when Isacks, Oliver, and Sykes at Lamont-Doherty (Columbia) analyzed worldwide seismological data. Both the locations of earthquake foci and the sense of first motions calculated for representative earthquakes appear to lead to the same conclusions about plate motions as the other lines of evidence. Their plot of 30,000 earthquake epicenters on the globe reveals the outlines of the major lithosphere plates, and shows that most include both continental and oceanic areas. Failure to recognize the latter was perhaps the main factor that led unsuspecting continental drifters and seafloor spreaders into so many theoretical difficulties in the past.

The fundamentally mobilist concept of geology that has emerged from this past decade of research challenges all past orogenic theories that rest upon stabilist concepts. The plate tectonic model explains orogenic belts, where most mountain-building and rock-deformation occur, as the narrow, elongate regions of juncture between moving plates or segments of lithosphere.

These linear or curvilinear junctions are of three kinds. Where the plates are diverging, mantle upwelling and volcanism form new lithosphere with oceanic crust in the wakes of the separating plates to form typically intraoceanic rises, such as the Mid-Atlantic Ridge. Where the plates are sliding laterally past one another along strike-slip transform fault systems, complex deformation near the adjacent plate edges produces linear trends of folded and faulted crust, such as the oceanic fracture zones, or the California Coast

Ranges beside the San Andreas fault. Where the plates are converging, the geometry requires that one overlap the other in some fashion, hence that some crustal rocks which approach the region of collision either disappear from the surface or undergo some drastic lateral crumpling. The plate tectonic model clearly implies that the mechanical energy available to drive orogenic processes, either directly to deform rocks or indirectly by conversion to heat, is greatest along convergent junctures. As Dewey (Cambridge) has shown, the empirical evidence also favors this view.

In strictly kinematic descriptions of relative plate motions, convergent plate junctures can be called sinks with reference to the fact that the areal dimensions of one or both adjacent surficial plates are reduced somehow as lithosphere is, in effect, consumed by overlapping or crumpling of plates, removed by descent into the deeper mantle, or otherwise destroyed as a surficial entity in some unspecified fashion. The dominant real process is thought to be the descent of lithosphere, with a capping of thin oceanic crust, in the vicinity of intraoceanic trenches and trenches marginal to continents. The course of descent is thought to be marked by the inclined seismic zones that reach deep into the mantle beneath the intraoceanic island arcs, like Tonga and the Marianas, and the marginal continental ranges, like the Andes, where chains of explosive volcanoes stand parallel to nearby trenches. In some exceptional cases, however, lithosphere with a capping of thick continental crust may serve as the descending plate of a converging pair, as in the Himalayan region where at least part of the continental crust of the Indian plate appears to have passed beneath at least part of the Tibetan plate.

The complexity of the telescoping and overlapping of crustal rocks observed along ancient convergent plate junctures became evident from discussions at the conference. Most participants, therefore, adopted a general term, "subduction zone," to describe any linear region along which crustal rocks have been led to descend relative to an adjacent block by folding or faulting or both in combination. The term was coined by Alpine geologists, and recently revived, in its English translation, by the Esso (Houston) research group as a term appropriate for a process of broad crustal significance; the term was introduced to the conference by D. Roeder. As used during the conference in discussions of structural relations among ancient rocks, the term subduction zone served to avoid unwanted implications of bathymetric trenches, or of crustal extensions of inclined seismic zones inferred for the mantle, or of any other particular feature possibly, but not necessarily, closely related to the structures observed in the crustal rocks under discussion.

Many specific geologic features of orogenic belts emerged from the discussions in a fresh light in terms of the plate tectonic model. Some of these can be cataloged as follows, with due allowances for complications, exceptions, and atypical situations.

1) Young andesitic volcanic chains and ancient andesitic metavolcanic belts can be taken as the linear surficial eruptive evidence for inclined seismic zones in the mantle beneath, and stand or stood typically above a region of intermediate depth earthquake foci as noted by Wadati a generation ago in Japan. Moreover, the transverse asymmetry in the total alkali, or potash, content of the volcanic rocks in a cross-arc direction reveals the sense of dip of the seismic zone and, therefore, the side of the arc upon which the associated trench or principal subduction zone is or was located. As emphasized by the late Professor Kuno (Tokyo) in a number of papers, the total alkalinity of the lavas increases as the depth to the seismic zone increases. Hatherton and I have shown that the increase in alkalinity is an increase in the level of potash content, with the level of soda content invariant.

2) As argued forcefully by Warren Hamilton (U.S. Geological Survey), many granitic batholith belts can be taken as the plutonic phase of arc volcanism. The plutons of regions like the Sierra Nevada were probably emplaced in the roots of eruptive arcs, and show the same general transverse areal asymmetry in total alkalinity or potash content as the arc volcanics. As noted by Matsuda (Tokyo), the concept of a volcanic front, the line parallel to a trench marking the edge of an eruptive arc, can be broadened to the concept of a magmatic front as a similar line marking the edge of the combined intrusive and extrusive phases of the arc magmatism. In any given arc with a long volcano-plutonic history, the position of the magmatic front can shift with time in response to some changing dynamics or position of the associated subduction zone. In several major batholith belts of the circum-Pacific region, radiometric age dates of the plutons have also indicated a puzzling episodicity of intrusive phases that appear to be coordinated over large regions. The causes of the episodicity of plutonism and the associated volcanism, the size of the areas over which the episodes are correlative, and the question of whether the episodes are truly periodic in some regular pulsing of activity pose significant challenges for future work.

3) The so-called ophiolite complexes, pseudostratigraphic sequences composed, in ascending order, of alpine peridotite or serpentinite, gabbro, basalt pillow lava or breccia, and chert or argillite, can be taken as the outer rind of oceanic lithosphere that has been incorporated tectonically into orogenic belts at continental margins. Some masses of this kind, and principally the most intact and least dislocated ones, have ridden over subduction zones as part of a structurally high block in a thrust complex. Such masses were described by Blake (U.S. Geological Survey) from California, Davies (Australian Bureau of Mineral Resources) from Papua, and Moores (University of California, Davis) from Cyprus. Similar masses, commonly sliced internally or dismembered by shearing, have ridden into trench-style subduction zones to become mingled with other rock types. Although found now within the orogenic belts formed at convergent plate junctures, many of the complexes presumably formed on midoceanic rises at divergent plate junctures where oceanic crust is mainly generated, and moved to their present sites during sea-floor spreading.

4) Blueschist metamorphism in the high pressure part of paired metamorphic belts, as recognized by Miyashiro, can be taken to reflect the rapid descent of cold surficial lithosphere to great depths along trench-style subduction zones. Despite the announced title of the conference, metamorphic processes were not discussed extensively, but Coleman (U.S. Geological Survey), Ernst (University of California, Los Angeles), and others sparked several impromptu discussions of the puzzling tectonic relations of blueschists.

5) Intracontinental thrust belts like those of the Wasatch and Mojave regions can be taken as a secondary inland expression of parallel trench-style subduction zones and arcs with

movements in the opposite sense. Oriel (U.S. Geological Survey) analyzed the geometry and timing of the late Mesozoic and early Tertiary Idaho-Wyoming thrust belt and found them consistent with those of Canadian counterparts but inconsistent with proposed gravitational models. The geometric relation of the thrust belt to the roughly coeval Sierra Nevada, as reconstructed by Hamilton and Myers, resembles that suggested by Hamilton for the late Cenozoic thrust belt in the eastern foothills of the modern Andean volcanic arc. Burchfiel (Rice) and Davis (University of Southern California) showed how opposed thrust systems of this type can form the major structural elements of a two-sided orogen, with a trench on one side and an inland thrust belt on the other.

An important impression that emerged from the proceedings was the realization that the nomenclature of tectonic elements and stratigraphic facies in orogenic belts requires revision and further evolution. The meaning of the geosynclinal theory, which holds roughly that thick sedimentation in a linear belt precedes and predestines orogeny, must be translated into a new conceptual framework. Past usage has relied heavily on the concepts of eugeosynclinal and miogeosynclinal sequences, supposedly deposited side by side in a single large trough or in complex parallel furrows, as the forerunners of orogenic belts. Eugeosynclinal assemblages are commonly conceived to be rich in volcanic rocks and deep-water turbidites, and to undergo early, protracted, and intense deformation capped by metamorphism and plutonic intrusion. Miogeosynclinal sequences, by contrast, lack volcanic rocks and undergo less deformation of a more surficial kind. At least three kinds of each assemblage can now be identified with reference to modern analogs which can be related to current plate geometry.

One kind of eugeosynclinal sequence, that like the Franciscan assemblage of California, can be called a trench complex, and recognized as pervasively sheared, graywacke-bearing melanges in which terrigenous detrital turbidites are mingled depositionally and tectonically with offshore sea-floor strata including pillow lavas of the oceanic crust. Such sequences are not built in ordinary stratigraphic superposition, but are stacked tectonically over a period of time as materials are successively ridden into a trench and under its inner wall. The pervasive shearing and stratigraphic discontinuity within melanges have been described at length by Hsu (Zurich), who led a preconference field trip to exposures along the coast near the conference site.

A second kind of eugeosynclinal sequence, perhaps the most familiar type, can be called an arc complex, and recognized as largely andesitic and dacitic volcaniclastic strata intruded by partly cogenetic granitic plutons. Such sequences are not accumulated in a topographic trough, but pile eventually to great thicknesses through progressive subsidence as described by Markhinin in the Kurile Islands. Facies range from shallow marine and even subaerial near volcanic centers to deep marine in blocky basins between volcanoes. A third kind of sequence locally called eugeosynclinal is composed of sea-floor lutites and distal turbidites deposited on basaltic crust in deep water beyond the continental slope of stable continental margins.

One kind of miogeosynclinal sequence, the miogeocline of Dietz, can be called a continental terrace complex, and represents the sediment built mainly in shallow water off the edge of a stable continental margin. Such sediment wedges may differ little in facies from platform deposits, but can reach great thicknesses, especially where they are built across the foundering edge of a continent. Rifting associated with the opening of a new ocean causes thinning of the crust where it necks and divides. A second kind of miogeosynclinal sequence, that like the Great Valley sequence of California, accumulates as detritus eroded mainly from an adjacent and parallel magmatic arc, and deposited in an elongate sediment trap between arc and trench. The site of deposition can be a shelf, slope, or trough in this tectonic position, separated from the trench by a bathymetric basement ridge of the type that Karig (Scripps) especially has noted at the top of the inner walls of trenches as a characteristic tectonic element in many modern arc-trench systems. A third kind of sequence, called miogeosynclinal by some and exogeosynclinal by Kay, is the clastic wedge foredeep complex, with the Cretaceous of the continental interior and the Devonian of the northern Appalachians as examples. Such sequences are deposited in variable water depths in troughs apparently associated with secondary subduction zones.

With these interpretations, what becomes of the idea that geosynclinal deposition presages the eventual onset of orogenesis and controls its effective extent? In the cases of the first two kinds of eugeosynclinal sequences and the last two kinds of miogeosynclinal sequences, sedimentation is simply a part of an unfolding process in which some deformation of the strata accumulated is an inexorable sequel. Even so, each case is somewhat different. In the case of the continental terrace, or miogeocline, and its offshore facies equivalents on continental rise or abyssal plain, there appears to be no immediate proclivity for deformation of the strata, as the continental margin is stable. In this case, the time dimension of plate tectonics comes into play. Oceans can be shown to have opened and closed. Once isolated continents come to be sutured together by collisions at subduction zones along which intervening oceanic crust is consumed. Hence, given time, any stable continental margin will eventually encounter a subduction zone at a convergent plate juncture, and will ride either over it or into it. In either case, the flanking sediment wedge will be deformed in some fashion; for a thick sedimentary pile simply to exist at a continental margin thus predestines eventual deformation when, inevitably, the margin becomes active.

In a sense, then, the geosynclinal theory of orogeny remains valid if the causative function of a thick sediment prism is replaced by a notion of coincidence or consequence. In another sense, the theory is perhaps more faulty and potentially misleading. A single, sequential orogenic progression is commonly assumed to be the norm. This notion cannot be expected to remain part of the plate tectonic model of orogeny. As oceans open or close and continents rift or join, as arcs and trenches and thrust belts grow and die with migrations and possible reversals of polarity, as one type of tectonic element is superimposed upon or juxtaposed against another, we have no reason to suppose as yet that there is any unique order in which these events may occur in a given region or happen to a given rock mass. Hence, different orogenic belts may undergo different sequences of deformational events. Each step ought to be one of a finite array of types, but the order of the steps should vary from place to place.

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