Geology in the U.S.A: From Passive to Dynamic Earth in 50 years

by John C. Maxwell

Half a century ago there was little opposition in the U.S.A. to the concept of a largely passive Earth characterized by permanent continents and oceans, and affected primarily by slow and reversible vertical movements. Today this has been replaced by a dynamic Earth with great plates in horizontal motion, related to creation of new crust at ocean ridges and destruction of old crust at subduction zones. This article reviews some of the significant observations and ideas that brought about this change.

The Passive Earth Model

Prior to the 1940s, little was known about the geology and topography of the oceans, other than such gross features as the mid-Atlantic Ridge. Most American geologists assumed that the continents and oceans had persisted in their present locations since early in the Earth's history. Abundant evidence existed for large and small vertical movements of land masses, and duplication of strata in orogenic belts pointed also to lateral movements due to crustal shortening up to several hundred kilometres. Lateral movements of thousands of kilometres within Cenozoic time, now evident for some lithospheric plates, was not conceivable to most American geologists half a century ago.

The close association of an abnormally thick sedimentary sequence with the folded Appalachian Mountains led, in the mid-1800s, to a geosynclinal theory of mountain building. In its various forms, this held that a subsiding trough or "geosyncline," with its thick filling of sediments, localized compressive forces responsible for the observed folding and thrusting. The rise in temperature with deep burial caused metamorphism of sediments and emplacement of plutonic rocks. Geosynclines and their contained sediments were subjected to intense study, culminating in a major synthesis by Marshal Kay (1951). Thereafter, emphasis shifted to other controls on sedimentation and causes of mountain building, but the geosynclinal model was widely accepted in the U.S.A. until the early 1960s.

Although the continent-ocean boundaries were presumably fixed throughout geological time, sediments in the Appalachians and other marginal mountain systems had clearly originated from highlands in areas now occupied by oceans. To resolve this paradox, Charles Schuchert (1931) and others proposed that land masses existed offshore prior to Appalachian orogeny to provide the sediments (Fig. 1), subsiding after erosion to form a part of the ocean floor. Figure 2, after P.B. King (1959), shows schematically the inferred history of the Appalachian system, from geosyncline to deformed belt.

The cause or causes of crustal shortening expressed in folded and thrust-faulted mountains were subjects of intense interest and debate. The long-held belief that a once molten Earth was cooling and contracting, thus providing for crustal compression, persisted into the 1930s and 1940s. Vertical movements producing domes and horsts were

recognized as mechanisms for producing localized mountain masses, but most U.S. geologists rejected vertical tectonics and gravitational displacement as adequate causes for observed crustal shortening.

As early as 1910, the American geologist F.B. Taylor suggested that the youthful mountains bordering western North and South America were caused by westward drifting of these continents away from the poles and toward equatorial zones. At the same time, South America and Africa parted from the mid-Atlantic Ridge, and Asia flowed outwardly into the bordering ocean producing the fringing island arcs. Taylor's ideas were compatible with Alfred Wegener's classic studies supporting continental drift.

The drift hypothesis offered an alternative explanation for vanished land masses, such as Appalachia, and for the compression required to produce mountain systems at the continent borders. However, most American geologists rejected the drift concept because the suggested mechanism, involving slow creep of continents over oceanic crust

Figure 1: Border lands and geosynclines of North America. From Schuchert, 1931.

Figure 2: Inferred development of the Appalachian Mountains, from geosyncline to deformed belt. From King, 1959.

under the influence of gravitational forces, was regarded as physically impossible. Evidence in favor of drift thus had to be accounted for in other ways, i.e., disappearing continents to provide sediments, and ephemeral land bridges to explain migrations between similar faunas now separated by great expanse of ocean.

Transition to an Active Earth Model

Publications of a half century ago laid the groundwork for the current widespread acceptance of a dynamic earth model. In 1928 N.L. Bowen provided the foundation for

modern igneous petrology. Subsequent advances in isotope studies and rock-dating methods enabled geochemists and petrologists to investigate the relationship of volcanism and plutonism to tectonics, and allowed the identification of crust and mantle geochemical reservoirs that are sources for distinctive magmas.

Arthur Holmes suggested in 1931 that convection currents beneath a continent could disrupt and passively carry away continental fragments, and that trenches and mountain systems would develop where the leading edge of the fragments stalled above the downgoing limb of a convection current. F. Vening Meinesz (1934) initiated geophysical exploration at sea with a pendulum apparatus of his own design, mounted in Dutch and American submarines. He was able to measure gravity across the North

Atlantic, the Puerto Rican trench and West Indies, and also the East Indies trench and arc, discovering the large, paired negative and positive gravity anomalies associated respectively with the trench and volcanic arc. He calculated that the gravity anomalies reflected a huge downfold of the lithosphere and an accompanying up-arching of the volcanic arc.

A colleague of Vening Meinesz, Phillip Kuenen (1934), constructed a scale model of such a downfold, and suggested that sediments deposited in its developing surface trough would be deformed, creating folded and thrust-faulted mountains. He called this system a "tectogene." H.H. Hess (1939), who had accompanied Vening Meinesz on a gravity measuring cruise in the West Indies and had also studied ultramafic rocks, showed that belts of these rocks are characteristic of both modern island arcs and ancient mountain systems. He proposed that the mountains were generated in tectogenes during crustal compression and shortening (Fig. 3). In his 1939 paper, Hess concluded: "Thus there is probably some relation between basins of sedimentation and deformations, but it may not be the direct cause and effect relationship which is usually postulated."

In calculating the magnitude of forces available for mountain-building, David Griggs (1939) concluded that convection was the most likely driving force, and constructed dimensionally correct scale models. Somewhat later, Hugo Benioff (1955) described the zones of earthquakes that extend to depths of as much as 700 km beneath island arcs and mountains bordering the Pacific Ocean (Fig. 4). These now well-known "Benioff zones" are incompatible with the tectogene hypothesis but favor the plate subduction model introduced later.

The 1950s and 1960s witnessed explosive growth of geophysical and geological exploration of the oceans. Bathymetric and refraction seismic surveys revealed major topographic features on and the regional structure of the ocean crust. Interpretative bathymetric charts of the North Atlantic Ocean compiled by Heezen, Tharp and Ewing in 1959 and Heezen and Tharp in 1968 demonstrate the remarkable increase in knowledge in one decade.

Building on the concept of mantle convection, R.S. Dietz (1961) and Hess (1962) independently suggested sea-floor spreading. Meanwhile, magnetic surveys from offshore California revealed linear, northward-trending magnetic anomalies, offset across great eastward-trending fracture zones (Mason and Raff, 1961). These puzzling features were soon explained, largely as a result of research that established the existence of periodic reversals of the earth's magnetic field (Cox, Doell and Dalrymple, 1963). In

Figure 3: (A) Formation of a "tectogene"; (B) the Alps superimposed on a "tectogene." From Hess, 1939.

survey of the Carlsberg Ridge, Vine and Matthews (1963) demonstrated that magnetic anomaly stripes were symmetrically disposed on either side of the ridge. They showed also that the symmetrical pattern could not be explained by local topography and suggested that it recorded the rise of newly created oceanic crust, which was magnetized in the earth's field as it cooled through the Curie temperature and then spread laterally from the ridge.

The Advent of Plate Tectonics

In the next eight years the bare bones of the plate tectonics hypothesis were fleshed out. A "hot-spot" origin for the islands of the Hawaiian chain was suggested in 1963 by J. Tuzo Wilson, who later introduced the concept of transform faults and outlined the basic kinematics of sea-floor spreading and continental drift (1965). L. Sykes (1967) demonstrated by earthquake data that the sense of motion across a transform fault on the mid-Atlantic Ridge was that predicted by Wilson, and incompatible with a strike-slip interpretation. Work by Isacks, Oliver and Sykes (1968)

Figure 4: Geometry of deep faults based on earthquake zones ("Benioff zones") associated with Pacific Island arcs. From Benioff, 1955.

Figure 5: Origin and consumption of ocean crust, based on earthquake seismic data. From Isacks, Oliver and Sykes, 1968.

provided the seismic basis for the plate tectonics model accepted for ocean crust at regions of spreading and subduction (Fig. 5). The same year, James Heirtzler and colleagues at Woods Hole Oceanographic Institution summarized existing data on magnetic anomalies and on directions and rates of sea-floor spreading, generating a time scale based on geomagnetic reversals.

The enormously productive ocean-drilling program, begun during this period and continuing today, proved early in its operations that the magnetic stripes reflect global magnetic reversals and that the geomagnetic time scale is both valid and useful in ocean exploration and geological mapping (A. Maxwell, 1970). A seminal study by Haxelton and Dickinson (1969) related variations in chemical composition of andesitic volcanics to the depth of the Benioff zone. T.

Atwater (1970) analyzed the progressive interaction of oceanic and continental crust as different sectors of the East Pacific spreading ridge reached and were subducted beneath the North American continental crust, and as the Pacific-North American plate boundary evolved from a trench to a transform fault. The same year an influential study of mountain belts and the new global tectonics was published by Dewey and Bird. Their diagrammatic cross sections (Fig. 6) proved enormously durable, being replicated with minor changes in hundreds of papers since then.

Jason Morgan in 1968 showed that the movement of plates relative to each other can be easily calculated using poles of rotation. Three years later he introduced the concept of plumes in connection with mantle convection (Morgan, 1971). These plumes rise from the lower mantle and impinge on the base of the lithosphere, producing the "hot-spot traces" (chains of volcanic islands and seamounts) recognized earlier by Wilson. This concept has been used for determining the directions and directional changes of plate motions in many parts of the world. H.W. Menard (1973) demonstrated the relationship between age and depth of ocean crust, initiating a series of studies on use of this concept as an age criterion. The first of several maps showing the age of ocean floor rocks based on interpretation of the magnetic patterns was produced by Pitman, Larson and Herron in 1974.

In studying the Tonga-Kermadec and Marianas arc systems, D. Karig (1971) observed a poorly understood phenomenon, later identified in other areas as well and now called "behind-the-arc spreading." Compression and subduction on the trench side of an arc is apparently accompanied by rifting and extension of the older volcanic rocks of the inner arc. Crustal compression and extension obviously occur in close proximity; hence the lithosphere is not subjected to an all-pervasive compressive stress.

In recent years small submarines have allowed direct observation of outcropping ocean rocks. Among the unexpected findings were springs of warm to superheated water on the spreading ridges. Some of the springs yield enormous volumes of hot water and generate polymetallic sulphide deposits identical to known ore bodies on land. These springs indicate that convectively circulating hot seawater has leached metals and non-metallic elements from porous volcanic rock and concentrated them near active vents. The discovery reinforces current views of economic geologists that emphasize the role of groundwater in leaching, transporting and, ultimately, concentrating useful minerals.

In concert with continuing ocean exploration, it is evident that an energetic program of exploration of the continents is required. A principal objective is the application of the

Figure 6: Mountain belts and plate tectonics. From Dewey and Bird, 1970.

The Alps and Himalayas are classic examples of mountains now believed to have formed as a result of continent-continent collision, creating larger continents. Only recently has it been determined that portions of the mountain ranges bordering eastern and western North America are composed of "suspect" terranes (Fig. 8), many of which were accreted to the pre-existing continent. Their composition and paleomagnetic and fossil evidence indicate that these terranes originated as parts of continents, island arcs or ocean crust, far from their present position (Coney, Jones and Monger, 1980; Williams and Hatcher, 1982). In view of the demonstrated importance of this phenomenon on the margins of North America (see also Crowell, and Stone and Wallace, this issue), it is likely that a significant amount of older continental crust, in North America and elsewhere, was assembled in this way.

Exploration of Continental Crust

The systematic exploration of North American continental crust is moving forward in two major programs: deep seismic-reflection profiling and deep exploratory drilling. The Consortium for Continental Reflection Profiling (COCORP) began a program of deep seismic exploration in 1974, undertaking a comprehensive reconnaissance of major crustal features by surveying grids of seismic reflection profiles (Brown et al., 1986). Over 6000 km of line have been completed, and important and unexpected features were found in every area examined (Fig. 9).

The southern Appalachian program, for example, detailed a complex accretion history marked by nearly horizontal thrust surfaces and a doubling of the crust. Equally striking

Figure 7: Formation of blueschist-grade rocks in a subduction zone, followed by erosion of hanging wall and upward transport of blueschist by return flow of *mélange*. From Cloos, 1984.

Figure 8: Suspect terranes, most of which were probably accreted to the western margin of the North American plate (stippled). From Coney, Jones and Monger, 1980.

Figure 9: COCORP program for deep seismic profiles of the United States. From Brown et al., 1986.

are seismic sections in the Basin and Range Province showing low-angle gravity faults cutting through most of the crust to accommodate extreme crustal stretching. Reflection seismic images of the Mohorovicic discontinuity are especially interesting. The base of the crust over much of the U.S.A. is marked by a zone, about 1 km thick, of nearly horizontal but discontinuous reflections. Presumably this layered zone was generated by an interaction of unknown nature between the crust and mantle.

The first deep hole in the U.S. program is now being drilled at Cajon Pass in southern California near the San Andreas fault. A major objective of this drill hole is to investigate the apparently nearly frictionless behavior of rocks in this part of the fault zone, as deduced from smaller than anticipated thermal gradients. Other sites are now being evaluated, including the Katmai fumarolic area in Alaska; an epithermal ore deposit at Creede, Colorado; a regional structure site in the southern Appalachians, and a site to explore deep petroleum-source beds and transitional crust in the Gulf Coast of Texas.

Exploring the Earth's Interior

With the advent of ultra high-speed computers and of global networks offering high-quality digital seismic data, a new process, seismic tomography, has opened exciting avenues for exploring the earth's interior. Data from earthquakes around the world have been analyzed to display velocity variations along ray paths penetrating the mantle and outer core (Dziewonski and Anderson, 1984; Dziewonski and

Woodhouse, 1987). The resulting, very generalized tomographic models depict broad linear regions of relatively low velocity in the upper mantle roughly corresponding to the great spreading ridges, and intervening areas of higher velocities beneath continents and old ocean basins. Similar zones of contrasting velocity are revealed in the lower mantle and the outer core. It is tempting to interpret this velocity distribution as an indication of the temperature variation to be expected in convecting systems within the mantle and outer core. This project, coupled with current seismic investigations of the lithosphere, has the potential to provide a realistic model of a dynamic earth, the beginning perhaps of yet another revolution in the earth sciences.

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