Reports

Oceanic Sediment Volumes and Continental Drift

Abstract. *The volume of sediment off the Atlantic Coast of the United States is at least six times as great as that off the Pacific Coast. This disparity is readily accounted for if the continent is drifting westward and has overrun large volumes of sediment on a former Benioff zone. Such an overrunning is also consonant with many features of the geology of the western United States.*

Gilluly *et al.* (*1*), utilizing the data of the Lamont-Doherty (*2–4*) and Woods Hole (*5*) seismic studies, have estimated that the volume of sediment and volcanic rocks overlying the crystalline basement of the continental shelf and rise and the oceanic crust seaward of the Atlantic Coast of the United States to the base of the Mid-Atlantic Ridge may be at least 10×10^6 km^3. This volume is vastly greater than that of the comparable material off the Pacific Coast, where extrapolations from existing surveys (*6*) suggest a volume of less than 2×10^6 km^3 between the coast and 2000 km offshore. Furthermore, the great bulk of the material off the Atlantic Coast is detritus derived from the continent, with only very subordinate volcanic rocks near Bermuda and, farther north, near the Caryn and neighboring seamounts; a very large fraction of the material off the Pacific Coast is volcanic and not the product of continental erosion. The volume of the Atlantic sediment derived from the continent is probably at least six times as great as that of the Pacific sediment.

This great discrepancy in volume is precisely what would be expected if North America is drifting westward from a widening Atlantic (*7, 8*). Had the continent remained stationary with respect to the Pacific, one would expect the Pacific sediment to be much more voluminous. During the Mesozoic and Cenozoic the drainage areas tributary to each ocean were about the same, and the sedimentary accumulations in each should have been about equal. The Atlantic sediment is all of Mesozoic and younger age, for the pre-Jurassic erosion surface of the Appalachian Piedmont has been traced seismically beneath the coastal plain, the continental shelf, and rise for hundreds of miles offshore, to a junction with the oceanic crust (*2, 3*); with a stationary continent one would expect some Triassic and older sediments to remain off the Pacific Coast—obviously they do not. The magnetic anomalies there have been interpreted to mean that the oceanic crust is of mid-Tertiary or younger age (*8*). The sediment resting on it cannot be older. A young age would be expected also on geologic grounds, as outlined below.

The disparity in volumes and ages of the sediments of the two coasts is consonant with the differing histories of the areas. Relatively little marine sediment has been returned to the continent by the epeirogenic tilting of the Atlantic seaboard, but huge volumes of Mesozoic and Cenozoic marine sedimentary rocks have been returned to the Pacific side of the continent during the orogenies of late Mesozoic to Pleistocene or even Holocene time. The Franciscan rocks of California, of Jurassic and Cretaceous age, have alone been estimated to comprise a volume of nearly 1.5×10^6 km^3 (*9*), a value almost equal to that of all the sediment remaining off the coast. The Great Valley sequence of California, also of Jurassic and Cretaceous age, has a roughly similar volume (*9*). The Tertiary and Quaternary sediments of the Great Valley, Coast Ranges, and Ventura and Los Angeles basins are probably as voluminous as both these older series. When account is taken of all these strata, perhaps half the difference in volume of the sediments off the two coasts is explained. But a large volume of Mesozoic and younger sediment, plus the Paleozoic materials that must have been present, still must be accounted for.

If the Atlantic began to open in Triassic time (*7*) and North America then began its westward drift, overriding the Pacific on an inclined zone such as Benioff (*10*) has suggested now underlies western South America, this might help to explain several noteworthy features of western geology.

It has long been recognized that the Jurassic and Cretaceous plutons of western North America are vastly more voluminous than those of any other part of Phanerozoic time (*11, 12*). If we treat North and South America together, the late Mesozoic plutons are exposed over three times as large an area as those of either Cenozoic or Paleozoic time (*13*). Even though part of the disparity may be explained by burial of Paleozoic plutons beneath younger rocks, the difference is so large as to strongly suggest a significant discontinuity in igneous history—a unique "flare-up."

If a Benioff zone had become activated beneath western America in the early Mesozoic, some of the water-saturated Paleozoic sediments that must once have lain offshore might have been dragged along with oceanic crust far down into the mantle. With a drift rate of 2 or 3 cm/year and a dip of the Benioff zone of 40°, some sediment might be carried to depths of 200 km in 15 million years. Heated both by conduction from the mantle and by frictional heat developed in the Benioff zone, the wet sediments might be expected to reach magmatic temperatures rather promptly. The onset of the tremendous plutonism of the Mesozoic of western America might thus have been related to the beginning of continental drift (*14*), delayed only by the time required for the temperature of the sediments to reach anatectic values.

A Benioff zone that continued variably active until mid-Tertiary time seems a likely explanation for several striking features of the Jurassic-Cretaceous Franciscan Group of California. These rocks lie to the west of the zone of major plutons and thus overlie a shallower segment of the postulated Benioff zone. The widespread, though quantitatively small, masses of blue schist of the Franciscan Group, in close association with masses of aragonite marble, serpentine, and eclogite, constitute a paragenesis that suggests both unusually high pressures and relatively low temperature for its formation (*15*, *16*). An active Benioff zone should supply these conditions: Franciscan sediment dragged to considerable depths of, say, 20 to 40 km, but squeezed upward before it had time to heat up notably, might be in part altered to blue schist and aragonite marble; basalt flows associated with it might be altered to eclogite (*16*). The serpentine may represent fragments torn from the mantle as the rocks were squeezed upward (*17*). The whole mass of variably metamorphosed sedimentary rocks, lava, and mantle fragments would be expected to acquire the chaotic arrangement and abrupt changes in metamorphic grade that characterize the "melange structure" of Hsu (*18*). It is noteworthy that the blue schists of many other segments of the Pacific rim—Kamchatka, New Caledonia, New Zealand, the Philippines, and Central America—also occur where seismic data suggest the existence of Benioff zones (*19*).

Menard (*20*) has suggested that the East Pacific Rise, which has been traced landward nearly to the mouth of the Gulf of California, extends northward beneath the Basin and Range province of Arizona, California, Nevada, Utah, and Oregon—an area that is widening by normal faulting (*12*). The Basin and Range province extends far to the south into Sonora and Chihuahua, and far to the east into Texas and New Mexico, and, in prolongation of the Rio Grande trough, northward into Colorado. A simple prolongation of the East Pacific Rise would thus not account for the whole province, although it is easy to postulate the existence of a transform fault to account for the eastward displacement.

In favor of this hypothesis is the fact that large parts of the Basin and Range province greatly resemble structurally many segments of the East African Rift system in Ethiopia, Uganda, and Tanzania, considered by many as extensions of the rifting along the Carlsberg Ridge. Also in favor is the fact that both the Basin and Range province and the East Pacific Rise are areas of exceptionally high heat flow, although such areas are not linearly arranged on the continent as they are in the sea. Furthermore, the supposedly late Tertiary magnetic patterns offshore have been interpreted (*8*) as having been caused by spreading from beneath the continent.

On the other hand, the East Pacific Rise does not appear to have a closely set fault pattern like those of the Atlantic Ridge and the Basin and Range province (*20*). The splaying out of the pattern of normal faults of the continent, with extensions of narrow fault zones northward into Colorado on the east and through Idaho and Montana to the Canadian border farther west, and the sharp curvatures of the fault trends—from nearly north-south in Nevada and Utah to east-southeast in Arizona and due west in Oregon—find no parallels in the East Pacific Rise. Thus, if this rise does lie beneath the continent, the reaction of the continental crust to its activity has been very different from that of the oceanic crust.

Possibly significant to the problem is the fact that, after the late Mesozoic plutonism, the next most active time of igneous activity in western America was in Oligocene and Miocene time, when Basin Range faulting began also (*12*, *13*). Perhaps this was the time when the continent overran the East Pacific Rise, or when the rise was moved beneath it on a transform fault so that it came to underlie the continent where it could supply both heat for the igneous activity and the stretching of the crust recorded in the normal faulting. The volcanic and plutonic activity of Oligocene and Miocene time, however, was by no means restricted to the Basin and Range province. All in all, there seem to be about as many reasons to doubt the relevance of a subcontinental extension of the East Pacific Rise to continental structure as there are to accept it.

It has been suggested that sea-floor spreading, after a time of relatively slow movement, began to speed up in the Miocene (*21*). Perhaps the speeding up was permitted by the removal of the resistance of the eastward-moving crust that had hitherto been generated at an offshore East Pacific Rise as the rise was overrun by the westward-drifting continent (*22*). Either such an overrun or an offset of the rise on a transform fault would eliminate the postulated Benioff zone because part of the crust generated at the rise would be moving with the continent, not against it.

If, despite the drastic differences in pattern and alignment of the faults and in patterns of heat flow between continent and ocean rise, the East Pacific Rise does exist beneath the Basin and Range province, this might account for the high heat flow, the burst of volcanic activity (the great ash-flow tuffs of the region are chiefly Oligocene and younger), and the tearing apart of the crust to give rise to the innumerable normal faults that dissect the area. It might also account for the abnormally thin crust beneath the province (*23*). This may have come about because the spreading "oceanic" crust of the rise dragged the lower part of the continental crust—westward to form the root of the Sierra and eastward to thicken the crust beneath the Colorado Plateau (*12*). Clearly the Sierra root and the thickening of the plateau crust both developed in late Tertiary time, as both areas stood very much lower during the Cretaceous and early Tertiary and both are in virtual isostatic balance at present.

Whatever the driving mechanism for the crustal spreading that is responsible for the normal faulting still active in the province, the continental spreading is much slower than the estimated rate of spreading of the offshore East Pacific Rise. In the roughly 35 million years since the faulting began, the province has spread only about 50 km (*24*), whereas, if the rate of spreading had been equal to that of the rise, it should have spread about 1300 km (*8*). Perhaps the difference can be accounted for by very weak coupling between the new "oceanic" crust forming at the rise and the older continental crust beneath which it is growing. Certainly there is ample evidence that the continental and oceanic crustal segments are virtually decoupled at the present time, and there is no Benioff zone now active beneath the western United States (*12*, *24*). If the drifting is still going on, as seems very probable, the continental plate is moving over the oceanic plate on a shallow rather than deep-seated surface of discontinuity.

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Fossil Foraging Behavior: Computer Simulation

Abstract. *Meander patterns produced by ancient sediment feeders can be simulated by digital computer with x-y plotter output. Change in input constants (with a single program) produces variation comparable to genetically controlled behavioral differences between species and genera.*

Paleontology is usually confined to the description, distinction, and analysis of purely anatomical information. However, in explaining trails, burrows, and other trace fossils, it is possible to deal with the activities of organisms. Of the many activities (such as hunting, escaping, resting, and burrowing), sediment feeding in benthonic invertebrates produces the most regular patterns. Feeding patterns are best developed in deep-sea deposits (both Recent and ancient) because of the even distribution of food particles in most deep-sea sediments as opposed to the patchy distribution of food typical of shallow water environments (*1*). Uniform distribution of food favors compact grazing patterns that provide maximum coverage of a given area and minimum crossing of existing tracks. A compact pattern appears to be favored also because it reduces the chance of interference between individuals of a population of sediment feeders. These requirements have been met by a multitude of two- and three-dimensional trail and burrow patterns. However, meander systems are used most commonly—just as they are in human contour plowing and other agricultural activities.

Meanders forming in modern sediments are difficult to observe. The few examples known are either hidden within the sediment or restricted to deep-sea floors, beyond the reach of continued observation. The bulk of our knowledge thus comes from rocks of deep-sea origin, where the patterns are readily observed on bedding planes, particularly on the soles of turbidite beds.

Principles for the interpretation of fossil foraging behavior were developed by Richter (*1*). He pointed out that the animal that made the trace fossil known as *Helminthoidea labyrinthica* had its movements during feeding controlled by a set of basic reactions: (i) strophotaxis, that made the animal turn around 180° at intervals; (ii) phobotaxis, that kept it from crossing other tracks, including its own; and (iii) thigmotaxis, that made it keep close contact with former tracks. Richter's model was supplemented by Seilacher (*2*) who also suggested behavioral models for other types of meandering trace fossils, and pointed out that the phylogeny of certain behavioral patterns can be traced on this basis.

With these considerations, we have developed a digital computer program to simulate the foraging behavior. The program assumes that a hypothetical animal can sense its immediate surroundings and can convert the resulting information into behavioral instructions. The track itself is simulated as a sequence of points in a hypothetical two-dimensional space—each point being defined by a pair of coordinates in an x-y system. Each point represents a "step" taken by the animal. As the program is executed (that is, as new steps are generated) the points are plotted on an x-y plotter, and, because the plotter pen is held in the down position, a continuous line is produced.

The "animal" used for the simulation is assumed to be capable of four types of movement. It can move straight ahead, turn toward or away from a preexisting track, or make a full 180° turn. The choice of movements is determined by a search procedure simulating the presumed sensory system of the animal. Before each new x-y point is added to the track, the region of the x-y space in front of and to the side of the leading end of the track is searched for previously computed points. The information provided by this search is used to determine the direction of the step.

Examination of fossil meander patterns indicates that the 180° turns are made not only to avoid obstructions (such as a preexisting track), but also to confine foraging to a relatively small area. There is considerable variation in the frequency of such turns, which leads to variation in meander length; the variation in meander length is simulated in the program with the use of random number generation to determine the lengths of those meanders not terminated by obstructions.

The program provides for a starting configuration consisting of a straight track (of arbitrary length) ending in a 180° turn. The search procedure described above starts only after the initial turn is executed. If the length of the initial straight track is made very small, the simulation starts in effect with a turn. If no other turns are specified (or if meander length is made very long), the result will be an Archimedes spiral—a common pattern in trace fossils.

Several behavioral characteristics were varied from one simulation to the next. Principal among these are: (i) the turning radius for 180° turns; (ii) the mean distance between a developing track and preexisting tracks; (iii) the allowable deviation from this mean distance; (iv) the relative intensities of thigmotaxis and phobotaxis (expressed as the angle of turn made to move toward an existing track relative to that for movement away); (v) the mean length of meanders not terminated by