A PLATE TECTONICS MODEL INVOLVING NON-LAMINAR ASTHENOSPHERIC FLOW TO ACCOUNT FOR CERTAIN KIMBERLITE PIPES

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The Colorado Plateau is an anomalous region of uplift in the North American Plate which is pierced by Cenozoic kimberlite pipes containing eclogites which do not correspond to the eclogites normally found in kimberlite pipes (Helmstaedt et al., 1972). The cause of uplift of the Plateau and the pattern of magmatism exposed there have remained unexplained by the theory of plate tectonics. Also unexplained is the mechanism for concentration of volatiles in the mantle which is generally agreed to have been a necessary prerequisite for kimberlite and carbonatite eruption of material from the deeper mantle beneath the Plateau (Watson, 1967; McGetchin, 1968). McGetchin et al. (1973, p.1867) state that "the ultimate source of these volatiles is both unknown and of great significance...The details of the occurrence and the mobility of the mantle volatiles are important and interesting questions because they bear on the outgassing of the earth, petrogenesis of basalt and kimberlite, and the physical state of the upper mantle."

In this paper we introduce an extension of plate tectonics theory to account for the almost random nature of magmatism in this region (which greatly contrasts with a simple pattern of magmatic transgression in time which would have been predicted as a consequence of overriding of the Pacific Plate in Mesozoic and Cenozoic time). The mechanism represents a means by which deep material can be brought from considerable depths in the mantle to higher levels where accumulation of volatiles could trigger kimberlite eruptions.

Gilluly (1970) has emphasized the difficulties in explaining the structural and magmatic history of the southwestern United States by a conventional plate tectonics model. As he indicates, "it can be safely inferred from the distribution of Cenozoic volcanism that there are great local variations in temperature, and hence, plasticity, of both crust and mantle" (Gilluly, 1970, p. 53) in the western United States. He notes that in this region, "the continental crust varies dramatically in thickness and elastic properties from place to place...The upper mantle, too, varies greatly in elastic properties" (Gilluly, 1970, p. 67).

Sbar and Sykes (1973, p. 1878) report that at the present time, the Colorado Plateau is "a region of east-west compressional stress" between two regions of extension, the Rio Grande Graben and the Intermountain Seismic Belt. The presence of an uplifted plateau in compression, surrounded by zones of extension,has been attributed to "convective flow in the asthenosphere in which upwelling occurs beneath two zones of extension" or, alternatively, to "a number of mantle plumes as proposed by Morgan (1972), or a single major current" (Sbar and Sykes, 1973, p. 1878). Wilson (1972,p.91) also postulated the existence of a mantle plume beneath the Colorado Plateau.

Gilluly (1973, p. 509) suggested that "differences in depth and configuration of the decoupling zone beneath the drifting continent would tend to cause flowage within the crust and upper mantle, first in one direction and then in another."He notes that "the youngest magmatism has been in the western Cordillera, not the eastern... while tectonism has indeed migrated eastward in the eastern Cordillera, it migrated westward in the western part and is now most active there" (Gilluly, 1973, p.507).

Radiometric ages of igneous rocks plotted by Armstrong and Higgins (1973, Figs. 2-3) and Armstrong and Suppe 1973, Fig. 2) show irregular patterns in time for magmatic activity in the western United States. The distribution of volcanism and plutonism during the Cretaceous, and the existence of paired metamorphic belts in the western part of the plate are more easily explained by plate tectonics theory. The onset of anomalous magmatic patterns may have coincided with the cessation of subduction of the Farallon Plate and the overriding of a Pacific ridge system.

The regional geology is difficult to reconcile with fluid dynamic models of mantle motion for regions in the neighborhood of Benioff zones. The geological evidence demands a process which produced random effects in time and space in the lithospheric plates which resulted from some irregularities imposed on steady laminar flow in the asthenosphere.

While the value for viscosity for mantle material is not agreed upon, it is generally recognized that the Reynolds number must be very small so that laminar flow would be expected. Laminar and highly viscous flow imply that flow streamlines would be expected to conform faithfully to the geometry of lithospheric boundaries. Induced flow from the downgoing slab might possibly cause stress variations along the lithospheric boundaries, or eddies away from the boundaries, but it is difficult to predict from fluid dynamic theories any variations in motion "first in one direction and then in another" as suggested by Gilluly (1973,p. 509). It is likely that volatiles rising through a moving mantle would have a large component of drift in the direction of flow near the lithosphere-asthenosphere boundary.

The irregular flow patterns deduced from southwest U.S. and Colorado Plateau regional geology are at odds with regular unidirectional patterns expected from fluid dynamics in the context of plate tectonics. We propose a solution to this discrepancy by consideration of a special case of fluid dynamic flow near plate boundaries. The required dynamic mechanism must produce irregular patterns in the surface manifestations of the flow proceeding in the corner between the overriding plate and the downgoing slab. The flow mechanism must account for several features: irregular distribution of magmatic activity in space and time; the presence of alternating zones of compression and extension in the lithosphere (uplift in one region, crustal thinning and extension in an adjacent region); great irregularities in plate thickness; and great areal variations in gravity and mechanical properties of the plate. This desired special fluid dynamic mechanism need not be invoked at most plate boundaries where magmatism and tectonism are in harmony with anticipated flow patterns in the asthenosphere.

It seems to us that the geology of the southwestern U.S. implies that there have been several regions of reverse flow near the lithosphere-asthenosphere boundary. In fluid dynamic theory, reverse flow at a boundary is often correlated with the onset of turbulence which produces eddies, but we are not suggesting the existence of turbulence in the mantle. The mechanism of reverse flow is produced by changes in the pressure gradient along the boundary; we believe that reverse flow occurs where the pressure gradient along the boundary is such that there is a pressure increase in the direction of flow of sufficient magnitude to overcome inertial and viscous forces. We propose that the overriding of a ridge system and the establishment of the San Andreas fault boundary for the North American plate (Atwater, 1970) caused a pressure gradient to be created in early Mesozoic time. We postulate that the pressure gradient was positive from east to west and that it caused several regions of reverse flow to develop near the lithosphere-asthenosphere boundary under what is now the southwestern U.S. This phenomenon caused surges of mantle material which not only induced regions of reversed flow along the boundary, but also promoted upwelling of material drawn from deep within the asthenosphere under the Colorado Plateau. This mechanism could provide an alternative to the plume under the Plateau proposed by Wilson (1972, p. 91). With this model, we can account for the movement of material upward from the deeper mantle to give rise to kimberlite and carbonatite intrusion. Several regions of reverse flow could also account for the complicated structural and magmatic patterns described by Gilluly.

The relaxation time of flow in the mantle material is apparently so large that this flow probably persisted millions of years after the Farallon Plate was consumed. An upward surge could be responsible, in our view, for the existence of the "crust-mantle mix" of Cook (1962) as well as the surface manifestations summarized by Gilluly and by Armstrong. The surge could be responsible for the transport of source material for the kimberlite pipes in southern Utah and northern Arizona.

The idea for the existence of surges of mantle material came from examination of the flow streamlines in photographs of the Susitna and Malaspina Glaciers of Alaska (Post and LaChapelle, 1971). Glacier ice has a very high viscosity (10^{13} poise) and a very low Reynolds number. The creep law of ice (Weertman, 1973, p.292,Eq.10) has a relationship between strain rate and stress which functionally resembles the creep law for dunite (Stocker and Ashby, 1973, p. 405, Fig.5) and presumably the creep laws for other mantle material. Experiments under the physical conditions presently achieved show that glacier ice and olivine both greatly depart from Newtonian creep. It seems reasonable, therefore, that if reverse flow can occasionally occur at the boundaries of glaciers, it should be possible for reverse flow to occur occasionally near the boundary between the lithosphere and the asthenosphere. Reverse flow in the mantle would be a rare phenomenon because establishment of an adverse pressure gradient would only be the product of unusual circumstances.

ARMSTRONG and HIGGINS, 1973, Bull. Geol. Soc. Amer. 84, 1095-1100.
ARMSTRONG and SUPPE, 1973, Bull. Geol. Soc. Amer. 84, 1375-1393.
ATWATER, 1970, Bull. Geol. Soc. Amer. 81, 3513-3536.
COOK, 1962, in Advances in Geophysics, 9, 295-360.
GILLULY, 1970, in The Megatectonics of Continents and Oceans, 47-73.
GILLULY, 1973, Bull. Geol. Soc. Amer. 84, 499-514.
HELMSTAEDT, ANDERSON, and GAVASCI, 1972, J. Geophys. Res. 77, 4350-4365.
McGETCHIN, 1968, The Moses Rock Dike, Ph.D. Dissertation, Caltech, 405p.
McGETCHIN, NIKHANJ, and CHODOS, 1973, J. Geophys. Res. 78, 1854-1869.
MORGAN, 1972, Bull. Am. Assoc. Pet. Geol. 56, 203-213.
POST and LaCHAPELLE, 1971, Glacier Ice, 111p.
SBAR and SYKES, 1973, Bull. Geol. Soc. Amer. 84, 1861-1882.
STOCKER and ASHBY, 1973, Rev. Geophys. 11, 391-426.
WATSON, 1967, in Ultramafic and Related Rocks, 261-268.
WEERTMAN, 1972, Rev. Geophys. 10, 287-333.
WILSON, 1972, in The Upper Mantle, 73-94.