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Mantle evolution; dynamics of the lithosphere and superplumes

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A review is presented on numerical models of the earth's mantle convection with plate tectonics and mantle magmatism to understand why plate tectonics operates on the earth, how superplumes arise in the earth's lowermost mantle, and how the earth's mantle has evolved under the influence of plates and superplumes.

The uppermost part of the mantle behaves as the lithosphere when the temperature dependence of the rheology of mantle materials is sufficiently strong. A necessary condition that this lithosphere is split into several pieces, each of which moves as a rigid plate, is that

S is less than Spi but is greater than Spm, (1)

where, Spm, S, and Spi are the coupling strength at plate margins, the stress induced within plates by their own weight, and the rupture strength of stable plate interiors, respectively. It is likely that Spm is low enough to allow plate tectonics on the earth because the surface water plays the role of lubricant. Further numerical studies of mantle convection with magmatism suggest that superplumes develop in the lowermost mantle as piles of subducted basaltic crusts on the core mantle boundary, only when the criterion (1) is satisfied and the internal heat source is sufficiently weak. The superplumes are more enriched in heat producing elements and hotter than the surrounding mantle. The resulting thermal buoyancy of superplumes is mostly in balance with their compositionally induced negative buoyancy and superplumes stably sit on the core mantle boundary for billions of years. Occasionally, the uppermost parts of superplumes ascend as narrow plumes to induce new ridges, and this new ridge formation allows plate tectonics to continue for billions of years. In the strongly heated mantle of the early earth, however, the superplumes become convectively unstable and the instability repeatedly lets the hot materials in deep mantle ascend as bursts. The resulting mantle magmatism is vigorous enough to induce magma pond and to split the lithosphere into many tiny fragments. In contrast to the well-ordered plate motion we observe today, the motion of the lithospheric fragments is chaotic. The bursts also induce strong convective stirring and make the mantle chemically rather homogeneous. The earth's mantle is , therefore, most likely to have evolved from the regime dominated by mantle burst and chaotic plat motion to the regime dominated by stable superplumes and well ordered plate motion. The inferred change in the style of plate tectonics is consistent with many observations on the structure of continents formed at various ages from the Archean to the present. The inferred chemical evolution of the mantle is also consistent with the observations on the isotopic ratio of Hf and other trace elements in the mantle.