g14 Dynamic theory of plate tectonics

< rock, over time, has no strength; cooled plates actively sink >

> Throughout most of the Earth the geotherm is determined mainly by convection, except in the lithosphere where conduction is the principal means of heat transfer. But even here the oceanic part of the lithosphere is involved in convection through ocean-floor spreading and subduction.
> —Anthony R. Philpotts *Principles of Igneous and Metamorphic Petrology*, 1990.[1]

Rocks are rheids that under different conditions of rate of strain, temperature, and confining pressure, deform elastically, break brittlely, deform plastically, or creep viscously. Glacial-ice well exhibits rheid behavior (elastic upper part that crevasses, and plastic at higher confining pressure below). Simple dynamic modeling treats rock as a viscous compressible fluid. When other factors do not obtain, heating makes rock positively buoyant and cooling makes it negatively buoyant. Complications are metamorphism, metasomatism, and sometimes partial melting.

For ten years beginning in 1923, Felix Andries Vening Meinesz (1887-1966), while uncomfortable for his giant height [2] in a submarine courtesy the Netherlands Navy, made area-gravity measurements of the East Indies seafloor.[3] Between volcanic island-arcs and the ocean trench that parallels each on one side, he consistently found a profound negative-gravity anomaly. This, he conjectured in 1934 was due to mantle-sima convections that at convergences buckles, and holds down against isostasy, the less-dense sialic crust.[4] Much effort, by many, was spent in refining this (wrong) picture of a crustal downfold for which H. H. Hess in 1938 [5] coopted the term “tectogene” that E. Haarmann had coined in 1926 for his somewhat similar image of an orogen at its inception.[6] Seismic information by mid-1950s scuttled these models but not the need for an explanation involving a dynamic process.

Layering of the upper mantle is known from one dimensional (radial) analysis of seismic waveforms. Global models show that the boundaries are not at uniform depth and this can be explained by (and thereby implies) convective flow. The upper mantle has a viscosity that can be modeled as 10 to 30 times less than the lower (below 660 km depth) mantle.

Earth’s figure, or *geoid*—term introduced in 1872 by Johann Benedict Listing (1808-1882) for a surface as the calm sea (see OED2) orthogonal to Earth’s gravity field—can be analyzed to justify a dynamic model.[7] In 1995, to coincide with like ERS-1 satellite data published by the European Space Agency, the US Navy released formerly classified Geosat (launched in 1985) gravity survey data obtained by radar ranging the height of the sea. After waves and tides are filtered out, geoidal *local* relief features match in a subdued way (about one thousandth the relief of) the seafloor topography. Revealed are discrete features larger than 1 km high and 10 km wide and so a stunningly detailed view of the deep seafloor that geodesist William (Bill) Mason Kaula (1926-2000) had originally anticipated in 1977.[8]

Geoidal *regional* relief features are the sum of often opposed dynamic causes that together limit proposed mantle-convection models. Mantle convections are evidenced by hotspots and by dynamic (but seemingly static being on a geologic time scale) geoidal deformations not accounted for by topography or crustal geology, seismically-detected boundary topographies in the upper mantle, and seismically-detected temperature variations in the lower mantle.

In the upper mantle, 410- and 660-km depth seismic reflectors (discontinuities) show variations in their depth of as much as 30 km. (For comparison, Mt. Everest is 8.844 km high.) Their topographies are negatively correlated. Mineral physics experiments show this can be due to through-going convection:

At the 410-km discontinuity, a phase change between α- and β-olivine is an exothermic (gives out heat) reaction with a positive Clapeyron slope (dP/dT) that should move the phase boundary down in a heat driven up-flow. Resulting buoyancy forces that would return the phase boundary to its unperturbed level will assist the through-flow.

At the 660-km discontinuity, a transformation γ-spinel to perovskite+magnesiowüstite is an endothermic (takes in heat) reaction with a negative Clapeyron slope that should move the phase boundary up in an up-flow. The resulting density perturbation will oppose the up-flow. For the same reason, the 660-km discontinuity phase boundary opposes down-flow through it (it is perturbed in the direction of the flow).

Plate motion, while an expression of and possibly initiated by mantle convection, has a life of its own not tied to underlying mantle-flow directions (which its motion can influence). "Force-balanced [*sic*] models" include all the forces that aid and oppose plate motion (due to *unbalanced* forces).

Plates cool top-down and can become active components by achieving negative buoyancy.[9] Where topped by oceanic crust, the ~100 km thick plate slides horizontally to where it turns down as a subducting slab. Slab weight in turn pulls on the plate. Horizontal "plate pull" (Elsasser, 1969)[10] to either side of a ridge results in divergence (***Figure g14.1A***). The plate separation allows the asthenosphere to passively well-up there. Magma and asthenosphere in the ridge above the level of the abyssal depths is a laterally unsupported weight so "plate push" (McKenzie, 1969)[11] is outward on the plates to either side (***Figure g14.1B***). Where topped by continental crust, plates, buoyant with high geothermal gradient during their formation, cool to have (since the Archean) subcontinental lithosphere mantle that (vulnerable to Rayleigh-Taylor instability) can delaminate and sink.[12]

Yu-Shen Zhang in 1991 found that the spreading rate of plate divergence at the ridge is matched by a decrease of S-wave velocity (a measure of the increase in the fraction of decompression melting) at depths above 35 km.[13] Three-dimensional seismic reflectivity imaging of the East Pacific Rise has shown that along the entire length of the ridge, magma normally originates directly below places of eruption. About 20 cubic kilometers of basaltic seafloor-crust is added per year at ridges.[14]

Radial asthenosphere flow away from the Iceland hotspot has resulted in localized plate-push. South of Iceland, ridges in the seafloor are symmetrical about the spreading axis but are obliquely transgressive to the magnetic-anomaly pattern. Such ridges, as first interpreted by P. R. Vogt in 1971, were generated by pulses of anomalously hot asthenosphere flowing south along the spreading axis.[15]

Rollback (subsiding back towards the ridge) of a subducting slab produces suction that causes the asthenosphere to flow toward it, around its sides,[16] and under it to its front (***Footnote g14.1***).

The descending slab may penetrate the 660-km discontinuity but what appears to be a continuation of it deep into the mantle, could be the descent below the 660-km discontinuity of material chilled by cold lithosphere settling on the discontinuity (***Figure g14.2***). Geochemistry of magmas from hotspots support the second possibility as, according to Richard Monastersky, geochemists hold to a "split-level scheme" in which "the lower mantle remains essentially cut off from Earth's surface.[17] This isolation has kept the deep rock in a pristine state, so it retains the primordial elements that Earth had in its infancy." In contrast, the upper mantle, Don L. Anderson in 2003 writes, "is not dry, homogeneous, isothermal, refractory peridotite but is variable in fertility, volatile content, melting point, and temperature. The upper mantle is close to or above the solidus almost everywhere between 50-100 and 200-300 km., except in cratonic lithosphere. Melts drain and collect (pond, underplate) beneath the plate until lithospheric stress conditions (horizontal least-compressive axis) allow dikes and extrusions, and hence, volcanoes to form. All of this is aided by decompression melting." [18]

The topography of Earth's solid surface is mostly well explained by thickness variations of continental crust that floats in the solid but yielding rocks of the mantle, and by the cooling of the seafloor lithosphere with age away from oceanic ridges. This isostatic model does not explain, however, the African "superswell" where the elevation is about 500 meters higher than crustal thickness would have it. In 1998, Carolina Lithgow-Bertelloni and Paul G. Silver showed that the topography is dynamically supported by a large-scale mantle upwelling (inferable from seismic shear-wave data) beneath southern Africa. The divergence of the flow at its top also provides a driving force for the tectonic plates in the region.

Jeannot Trampert's satellite-gravitation constrained model in 2004 that explains seismic velocities finds that superplume buoyancies in the mantle's lowermost 1000 kilometers are due to composition variations and not temperature differences (the effect of which pressure greatly diminishes).[19] ❑

Footnote g14.1 [20] Maximum seismic-wave velocity parallel to the plate-motion direction is usually thought to indicate olivine with its a-axis parallel to the mantle-flow direction. However, Tomoyuki Mizukami in 2004 documented an exhumed slab of mantle that evidently overlay and was permeated by water released from a subducting slab, with 'B-type' olivine with its a-axis perpendicular to the direction of flow.

Figure g14.1 [21] *A.* Passive motion due to plate-pull (slab-pull)

Plate-pull results in passive mantle-flow by drag away from, and upwelling to beneath, the ridge line. Shear produced pressure gradients focus melt-flow towards the ridge (one side is shown). Basalt lavas that erupt at a distance from the ridge (off-axis eruptions) should be characterized by low trace-element concentrations of Ba, K, P, Zr, Ti, Y, and V. Marc Spiegelman and Jennifer R. Reynolds in 1999 found this to be so for the fast spreading East Pacific Rise at 12ºN.

B. Active motion due to plate-push (ridge-push)

Heat-driven buoyancy upwelling establishes the ridge and laterally pressures away the accreting crust and lithosphere (one side is shown).

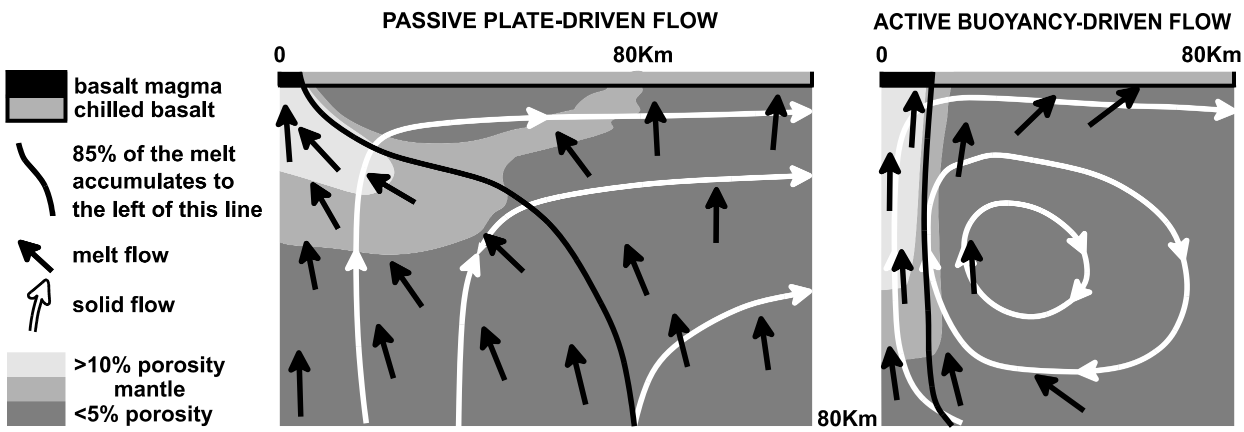

Figure g14.2 Geochemical studies indicate a long standing separation of mantle rock above and below 660 km depth. This indicates that convection does not routinely penetrate the 660 km boundary. However, convection in a fluid that expands when heated can be caused by heating its base or by cooling its top. The relatively cold mantel below 660 km could be lower mantle cooled by subducted lithosphere settling on the 660 km boundary. The old part of the subducted lithosphere above the 660 km boundary in turn becomes heated and vanishes in seismic temperature imaging. The chilled lower mantle remains visible by contrast to the hotter lower mantle into which it sinks and to the hotter lower mantle which is drawn in over it. There is however a problem. If deep mixing of upper and lower mantle has not been a feature of plate tectonics, then the flow in the upper mantle must somehow move mantle material around the ends of, or back round the world to, subducting lithospheric slabs.[22] Also, slabs of "folded lithosphere," presumably sunken, have been "imaged" littering the base of the mantle.[23]