

Earth Evolution and Dynamics (Arthur Holmes Medal Lecture)

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While physicists are fantasizing about a unified theory that can explain just about everything from subatomic particles (quantum mechanics) to the origin of the Universe (general relativity), Darwin already in 1858 elegantly unified the biological sciences with one grand vision. In the Earth Sciences, the description of the movement and deformation of the Earth's outer layer has evolved from Continental Drift (1912) into Sea-Floor Spreading (1962) and then to the paradigm of Plate Tectonics in the mid-to-late 1960s. Plate Tectonics has been extremely successful in providing a framework for understanding deformation and volcanism at plate boundaries, allowed us to understand how continent motions through time are a natural result of heat escaping from Earth's deep interior, and has granted us the means to conduct earthquake and volcanic hazard assessments and hydrocarbon exploration, which have proven indispensable for modern society.

Plate Tectonics is as fundamentally unifying to the Earth Sciences as Darwin's Theory of Evolution is to the Life Sciences, but it is an incomplete theory that lacks a clear explanation of how plate tectonics, mantle convection and mantle plumes interact. Over the past decade, however, we have provided compelling evidence that plumes rise from explicit plume generation zones at the margins of two equatorial and antipodal large low shear-wave velocity provinces (Tuzo and Jason). These thermochemical provinces on the core-mantle boundary have been stable for at least the last 300 million years, possibly the last 540 million years, and their edges are the dominant sources of the plumes that generate large igneous provinces, hotspots and kimberlites.

Linking surface and lithospheric processes to the mantle is extremely challenging and is only now becoming feasible due to breakthroughs in the estimation of ancient longitudes before the Cretaceous, greatly improved seismic tomography, recent advances in mineral physics, and new developments in our understanding of the dynamics of true polar wander. Dramatic improvements in computational capacity and numerical methods that efficiently model mantle flow while incorporating surface tectonics, plumes, and subduction, have emerged to facilitate further study — We are now capitalizing on these recent advances so as to generate a new Earth model that links plate tectonics with shallow and deep mantle convection through time, and which includes elements such as deeply subducted slabs and stable thermochemical piles with plumes that rise from their edges. It is still unclear, though, why lower mantle structures similar to today would have existed since the Early Phanerozoic (540 Ma), and perhaps for much longer time. Could large-scale upwellings act as an anchor for mantle structure that also controls where downward flow and subduction occurs? Or could it be that subduction keeps itself in place? These are open questions, and at the moment we do not even know with certainty whether Tuzo and Jason were spatially stable for much longer than 300 Myr; we can only state that their stability before Pangea formed is consistent with palaeomagnetic and geological data, but is not necessarily required.