

Modeling mantle mixing and the persistence of geochemical reservoirs

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Understanding the dynamics of mixing in the mantle is fundamental to understanding the origins of the isotopic heterogeneity observed in oceanic islands and at mid-ocean ridges. Heterogeneity is introduced into the mantle throughout geologic time by processes associated with melting, alteration, and subduction. Heterogeneity is continuously destroyed by convection, as the stretching and folding common to all kinematic mixing processes stirs the mantle. Thus it has long been a goal of computational geodynamics to understand the factors controlling the rate and efficacy of mantle mixing. The time and spatial scales of mixing are influenced by the kinematics of flow, plate motion, viscosity variations, compositional heterogeneity, and phase transitions. Chaotic mixing is observed in time-varying 2-D flows; by contrast, the factors controlling mixing in 3-D remain somewhat poorly understood. We investigate a series of methods for computing and evaluating mixing in 3-D, and compare their utility for assessing mantle mixing and the interpretation of mantle heterogeneity. We explore a suite of models of convection in a layer and in a spherical shell. Passive tracer particles are introduced into time-varying and steady-state models of mantle flow; the particles are tracked over time as they disperse and deform, allowing the use of quantitative measures of mixing. Mixing can be assessed by calculating a Lyapunov exponent (which characterizes the separation of tracers that are initially close to each other), or by treating the tracers as ellipsoidal strain markers and computing their deformation, or by determining the configurational entropy of the system of tracers. Stirring may be rapid on a regional scale, while heterogeneities at the global scale are retained because of isolation across long-wavelength cells. Essentially, the regions that exhibit high rates of stretching and thinning have the most important influence on mixing, and packets of material that are stirred rapidly in regions of high strain rate are carried wholesale into regions of more sluggish convection.

Geochemical perspectives on local versus global ocean redox at 1.64 Ga

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The chemistry and redox structure of the ancient ocean played a key role in influencing the evolution of life throughout Earth's history. Surface waters in the mid-Proterozoic ocean (~1.8-1.0 billion years old [Ga]) were oxygenated, but a number of lines of evidence point toward anoxic, iron-rich (ferruginous) and sulfide-rich (euxinic) deeper waters. Geochemical data indicate that euxinia was confined to ocean margins and restricted basins. Nevertheless, these euxinic waters may have impeded diversification of eukaryotic life.

We studied a suite of thermally well-preserved black shales from drill core of the 1.64 Ga Barney Creek Formation using detailed biomarker, sulfur isotope, iron speciation, and trace metal redox proxies. High abundances of Type 1 microaerophilic methanotrophic bacteria, as evidenced by elevated 3β -methylhopane indices suggest low marine sulfate concentrations, an inference corroborated by highly variable, heavy pyrite sulfur isotopic values, and likely reflects globally low values exacerbated by local restriction of the Glyde Sub-basin. Iron speciation and organic biomarker data provide evidence for extensive and persistent euxinic waters within the sub-basin.

Despite the presence of oxic surface waters and euxinic deep waters in the sub-basin, the predicted light iron isotope signature of an iron shuttle, like that in the Black Sea, is not observed. Typically, with the shuttle, isotopically light iron from oxic sediments on the shelf is transported to and trapped in sediments of the deep euxinic basin via pyrite formation in the water column. In contrast, our iron isotope values are positive, so the source had to have been isotopically heavy. There are several possible interpretations for this observation. We are intrigued by the possibility that the source of heavy iron was precipitated iron oxide from the redoxcline in a ferruginous ocean, which converted to Fe^{2+} and then to pyrite in a sulfidic local environment, which suggests a relatively high iron ocean with strong redox stratification. It is also possible that the positive values are linked to both removal of isotopically light sulfides in a moderately Fe-rich system and transport of heavy dissolved iron, since sulfide formation may have a positive kinetic isotope fractionation. Both hypotheses necessitate a fundamentally different iron cycle compared to that found in Phanerozoic/modern restricted basins.

Our integrated results point to a sub-basin with oxic surface waters and euxinic deep-waters. This restricted basin was likely connected to an ocean with oxic surface waters, ferruginous deep-waters, and limited expanses of euxinic conditions along productive margins, as well as within other restricted basins. Nevertheless, euxinia in the mid-Proterozoic ocean was likely orders of magnitude more widespread than it is today, and the deleterious impacts on nutrient availability could have been enough to throttle the early evolution and expansion of eukaryotic organisms.