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Contrasting Mantle Convection Models by Modeling Their Geochemical Evolution with the Terra Nova Toolbox (TnT2000)

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The geochemical evolution of the Earth is determined by the differentiation of the mantle due to partial melting at hotspots, mid-oceanic ridges and island arcs, the formation of continental crust, and the recycling of oceanic and continental lithosphere at subduction zones. Second order differentiation processes may include metasomatism of the mantle, alteration of the oceanic crust and chemical erosion of the continental crust. Geochemical modeling approaches tend to focus on a relatively small number of these processes, and they tend to be restrictive in modeling boundary conditions and the number of parameters (elements, isotope ratios) considered. This incomplete geochemical modeling has significantly limited our understanding of the Earth as a dynamic and geochemical system. These limitations led to the development of the Terra Nova Toolbox (TnT2000) hoping to provide a flexible modeling environment for exploring both simple and sophisticated geochemical scenarios including a variety of chemical and physical processes that shape the Earth.

TnT2000 uses a box model approach and accommodates the “complete” array of elements (n=92) and their natural-occurring isotopes (n=287). TnT2000 also has a modular design that allows for different algorithms to define partial melting, alteration, metasomatism, mixing, entrainment and recycling. Reservoirs and their intrinsic properties can be defined to approximate a range of global reservoir geometries (such as whole mantle or two layered mantle convection), their evolution, and the mass fluxes between them. Chemical differentiation by batch, fractional or dynamic partial melting, metasomatism and water-rock exchange are simply described with partition coefficients. Parent-daughter isotope abundances are constantly corrected for radioactive decay. Finally, the mantle differentiation and overturn rates can be changed back through the Earth’s history by choosing either steady-state, linear, exponential or squared heat loss models as proxies for mantle convection and differentiation rates.

In most model calculations, we assumed the squared heat loss model (Phipps-Morgan, 1998; Phipps-Morgan & Morgan, 1999) but varied the mantle overturn rate between 9.5 Myr (Phipps-Morgan & Morgan, 1999) and 5.7 Myr (Kellogg & Wasserburg, 1990). The squared heat loss model seems the best proxy for the rate of chemical differentiation, when assuming that the radioactive heat produced in the Earth is effectively cooled by the subduction of the oceanic plates (Phipps-Morgan, 1998). It should be noted that with this heat loss model the initial mantle convection and differentiation rates are up to 26 times the current rates. As a result, between 15-25% of the entire mantle will be processed in the beginning of the Earth over a time period of 50 Myr, whereas only 1-2% of the mantle will be differentiated at the half-life of the Earth over the same 50 Myr time period. This confines the most important phase of the Earth’s differentiation to the Archean. The sharp decrease in the differentiation rate will be even more exaggerated since in TnT2000 the heat loss models are corrected for the storage of the heat producing elements K-U-Th in the continents. Secular cooling and the heat produced by the crystallization of the inner core are not (yet) taken into account, but these processes will further add to an exaggerated initial heat loss.

We will contrast three different geochemical differentiation models for the Earth: (1) the classical two layered mantle model, (2) the plum-pudding or whole mantle convection model, and (3) the dense deep layer model of Kellogg et al. (1999). In these comparisons we will, in particular, study the evolution of the primitive mantle components for their volumes, the amount of continental crust that is being recycled and how well these different models can reproduce the $^{87}Sr/^{86}Sr$ - $^{143}Nd/^{144}Nd$ mantle array and trace-element abundances.

TnT2000 provides a graphical user interface for the MatLab 5.2 environment, including graphical tools that can be used to monitor the fractionation patterns for different Earth reservoirs. At this moment, a basic toolbox has been established to explore simple geochemical scenarios for the Earth’s evolution, as they are discussed above, based on commonly used geochemical parameters. However, the modular nature of TnT2000 allows for its expansion towards substantially more sophisticated Earth evolution models and to geochemically more complete data sets, even though such expansions will require some compromises largely imposed by the computational power of personal computers. TnT2000 will be made available at http://www-pacer.ucsd.edu/tnt.htm.

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