Evolving mantle convection from bottom up to top down

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When it comes to convection, what goes up must come down. Or is it, what goes down must come up? The truth is, it depends. Although convection must be *mass*-balanced, there is no reason that it must be *force*-balanced: the positive and negative buoyancy forces driving convection up and down, respectively, do not necessarily need to be balanced. The balance, or imbalance, all depends on the top and bottom boundary layers. Thus, convection in Earth's mantle depends on the temperature differences across the core–mantle boundary (CMB) below and the lithosphere–asthenosphere boundary (LAB) above. Convective asymmetry predominated by positive buoyancy, or bottom-up convection, would be driven by plume ascent, whereas if it were predominated by negative buoyancy, or top-down convection, would be driven by plate subduction. Symmetric convection would balance plume ascent and plate subduction. Is mantle convection on Earth balanced, dominantly top-down or bottom-up, or time dependent?

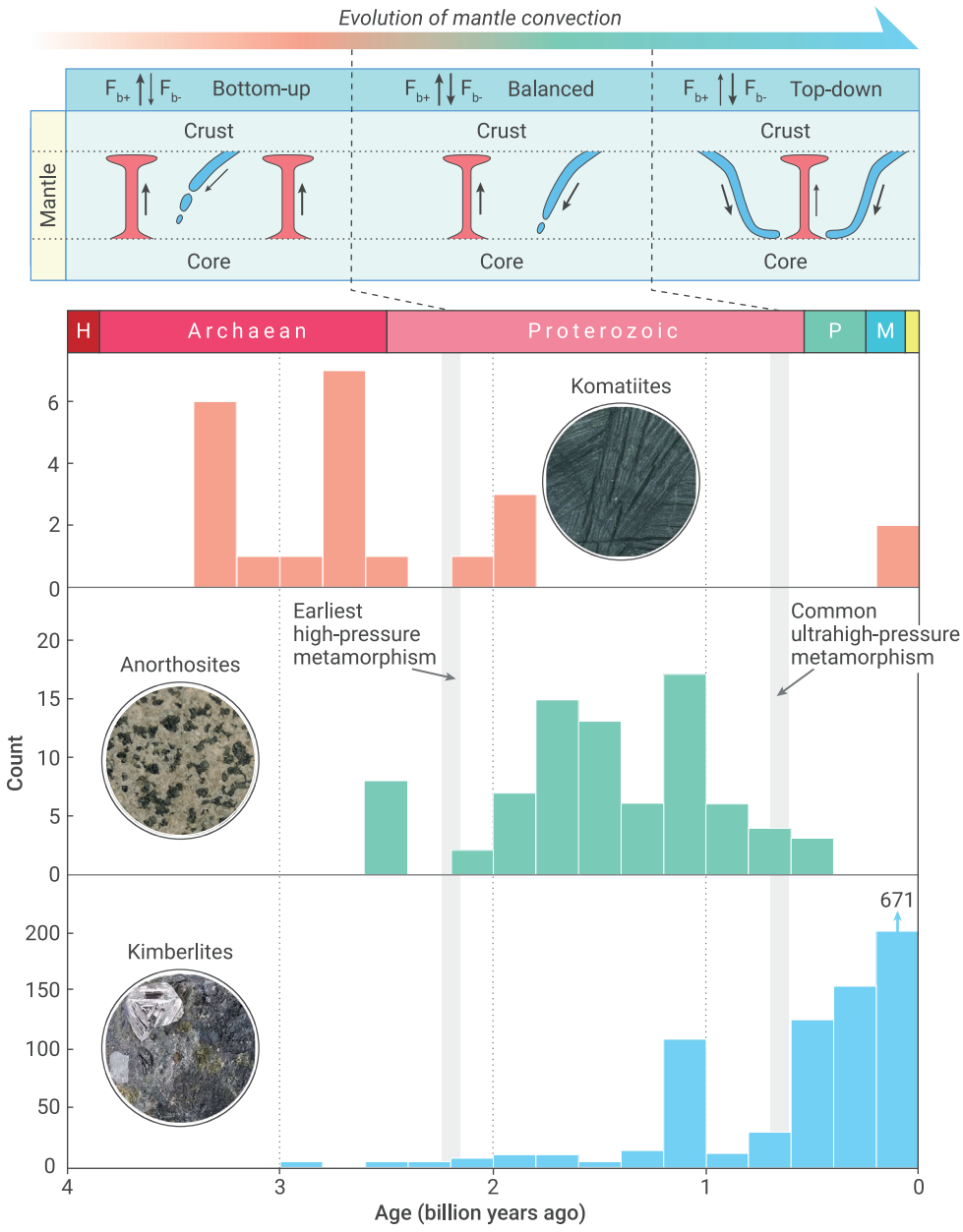

Figure 1. Evidence from changing mantle melts for the evolution of mantle convection over time. Histograms of komatiites,[3] anorthosites,[4] and kimberlites.[2] Gray vertical bars show the ages of the earliest occurrences of high-pressure and ultrahigh-pressure metamorphism, which reflect the evolution of subduction over time.[5] H, Hadean; P, Palaeozoic; M, Mesozoic; yellow, Cenozoic; F_{b+}, positive buoyancy force; F_{b-}, negative buoyancy force.

HYPOTHESIS AND TEST

Symmetric convection—balanced vigor of down- and upwelling—is unlikely for Earth's mantle for various fundamental reasons such as internal heating, temperature-dependent viscosity, and sphericity.[1] Naturally, then, there is debate over whether Earth's geodynamics is predominantly top down or bottom up. Evidence for both deep subduction and deep-rooted mantle plumes exists; however, the antiquity of the former and the prevalence of the latter are often questioned. We propose that convective asymmetry evolving over time—from bottom up to top down predominating, with balanced convection occurring in between—may reconcile these two criticisms. If the balance of mantle convection has shifted from being dominated by upwelling to downwelling through time, then there should be a progression in the conditions of mantle melting.

KOMATIITES AND KIMBERLITES

Two rock types over which a deep mantle (ie, sublithospheric, convective mantle) melting source is generally agreed upon are komatiites and kimberlites. In general, komatiites and kimberlites are abundant early and late in Earth history, respectively, bookending Earth's middle age (Figure 1). It has been suggested that the shift in abundance over time from komatiites to kimberlites reflects subcontinental mantle melting conditions having changed due to secular mantle cooling.[2] As such, komatiites and kimberlites provide clues about the nature of mantle convection over time.

Komatiites are ultramafic volcanic rocks that represent Earth's hottest known primary mantle melts, as indicated by MgO >18 wt % and mantle potential temperatures exceeding 1550°C. Komatiites are defined by their diagnostic spinifex textures as well as high magnesian content and are typically interpreted in terms of the melting of hotter mantle.[3] Most komatiites are Archaean and Palaeoproterozoic in age, with a notable gap between 1.9 and 0.25 billion years ago (Figure 1). Multiple compositional signatures of komatiites—Th/Nb, MgO/Al_2O_3, and FeO/TiO_2—indicate significant changes in melting characteristics over time.[3] These compositional shifts imply a change in the source of the komatiitic melts or a higher degree of crustal assimilation, either way involving a higher crustal component through time. Whether due to secular mantle cooling, increased subduction, or both, a turning point leading to the long-term reduction in komatiite magmatism can be explained by a diminution in bottom-up convection. Because of their exceptionally hot temperatures, komatiites are taken to represent products of bottom-up convection (also known as plumes), which thereby predominated on early Earth—consistent with all thermal models with a hotter ancient mantle.

Kimberlites are most notable for bearing diamonds and mantle xenoliths, and they are thought to derive from a deep mantle melting source.[2] The common occurrence of kimberlites deep in continental interiors, emplaced through thick lithospheric roots, supports an intraplate setting consistent with subcontinental mantle melting. Kimberlites become increasingly abundant through time (Figure 1). The abundance of recent kimberlites is due to the "kimberlite bloom" about 250 to 50 million years ago, which accounts for >60% of all known kimberlites.[2] Kimberlites are a form of mantle melting that appears to respond to tectonic forces exerted by lithospheric motion and deformation.[2] Intraplate continental rifting that may promote most kimberlite eruptions is linked, albeit indirectly, to top-down convection driven by plate subduction, for which slab pull is the dominant tectonic force. Thus, kimberlites are associated with top-down convection because of their deep origins near the base of lithospheric plates where diamonds are stable. We thus propose that this top-down convection style predominates on the modern Earth, consistent with a multitude of observations including seismic tomography of the present-day mantle.

ANORTHOSITES

There is a striking ~1-billion-year-long lull during the transition between abundant komatiites and abundant kimberlites (Figure 1). Extensive anorthosite massifs, signifying elevated heat flow across the crust-mantle boundary (called the Moho, or Mohorovičić discontinuity), fill the gap in between komatiites and kimberlites (Figure 1). In the classic model of anorthosite genesis, mantle-derived high-Al basalts pond at the Moho, where polybaric fractional crystallization and density separation of cumulates produce the plagioclase-rich anorthositic magmas. Because of their broad spatial distribution away from both mantle plumes and subduction zones, anorthosites are taken to represent products of balanced convection, which thereby predominated during Earth's middle age—consistent with the quiescent "boring billion" interval.

FROM BOTTOM UP TO TOP DOWN

We identify changes in the abundances of komatiites, anorthosites, and kimberlites through time that support an evolution from bottom-up asymmetric, to symmetric, to top-down asymmetric geodynamics, respectively. To be clear, we are not proposing a petrogenic connection between these disparate rock types but rather an underlying connection between them as an evolving record of mantle heat. This sequence of rock types reflects high-temperature mantle melting or higher heat flow into the crust dominating, in turn, from komatiites, to anorthosites, to kimberlites through time. Notably, straddling the interval of symmetric convection characterized by anorthosite magmatism, the two transitions—the Palaeoproterozoic demise of bottom-up convection and the Neoproterozoic rise of top-down convection—each coincide with an indicator of the increasing predominance of subduction over time: the earliest occurrence of high-pressure and the beginning of common (or widespread) ultrahigh-pressure metamorphism,[5] respectively (Figure 1).

Presumably, then, the factors controlling mantle convection have evolved through Earth history. For heat input to equal heat output (ie, steady state), to compensate for Earth's sphericity where the core takes up only one-quarter of the area than the lithosphere, upwellings should have large temperature anomalies and velocities compared with downwellings,[1] which appears to have characterized early Earth. But this is opposite to the modern Earth, which is driven by strong subduction-related downwelling. Thus, over time, the nature of core basal heating due to Earth's sphericity has been overcome by the effects of internal heating (retention of primordial heat and generation of radiogenic heat) and temperature-dependent viscosity (stiffening the lithosphere and making convection more platelike), both of which increase the thermal gradient across the upper boundary layer.[1] Extrapolating these effects into the future, at some distant time, Earth's next phase of mantle convection will be that of a stagnant lid, where the rigid surface no longer participates in underlying convection, akin to Venus and Mars.

Clearly, secular mantle cooling relates to the change in convective asymmetry over time, but understanding the effects of changing mantle viscosity and density on convective style with time is complicated. Due to temperature-dependent viscosity, cooling should increase viscosity, thereby reducing plume activity. However, if, at the same time, the mantle is becoming increasingly hydrated by plate subduction, increasing water content could buffer, to some degree, the viscosity change due to cooling. Density change in the mantle over time is equally enigmatic. Large thermochemical structures sitting in the lower mantle today are relatively dense, but hypotheses for their origin range from dense primordial material formed early in Earth's evolution to the accumulated crustal component of oceanic lithosphere that became dense as it sank through the mantle. We suggest that recognizing the transition in convective asymmetry provides a critical geological constraint for understanding how secular trends in mantle cooling and properties have evolved over time.

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DECLARATION OF INTERESTS

The authors declare no competing interests.