Making and unmaking continental mantle: Geochemical and geophysical perspectives

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Introduction

Earth Scientists have two ways of examining and mapping the structure and composition of the subcontinental lithospheric mantle (SCLM): geophysical surveys, and studies of mantle samples from volcanic rocks or exposed terranes. Interpretation of both types of data requires an understanding of some basic strengths and limitations of each approach.

Making the SCLM

Continents survive through time only if they have a thick, stiff, buoyant underlay (the "life raft") of depleted SCLM; without this support, the weak continental crust will ultimately be "stirred" back into the convecting mantle. It is important to recognize that a buoyant lithospheric mantle requires not only a high Mg# (the result of melt extraction) but a low content of FeO (<8 wt%). Such FeO-depleted mantle is not produced by the melting processes that function on Earth today, e.g. at spreading ridges or beneath Large Igneous Provinces. Regardless of the degree of depletion, the FeO content of the residues of these "modern" processes stays constant at around 8%, and they are gravitationally unstable relative to the convecting mantle. Experimental studies suggest that such Fe-depleted mantle residues were produced by a specifically Archean process, involving high-temperature, high-degree melting at depths of >150 km. These residues range from dunite to harzburgite (olivine + orthopyroxene); the extracted magmas may have been broadly komatiitic in composition.

A worldwide compilation of Re-Os data on mantle peridotites (both whole-rock and single-sulfide analyses) has failed to find any Os T_{RD} model ages older than 3.5 Ga, and shows a single major peak from ca 3.1 Ga to 2.5 Ga. This suggests that no significant volumes of SCLM were generated before ca 3 Ga, and that the processes responsible for its formation did not function after ca 2.5 Ga. This one simple observation suggests that the scarcity of EoArchean to PaleoArchean crustal rocks simply reflects the lack of an SCLM "life-raft". The available zircon data (U-Pb, Hf- and O-isotopes) suggest that from 4.5 Ga to ca 3.4 Ga, Earth's crust was essentially stagnant and dominantly mafic in composition. This quiescent state was broken by pulses of juvenile magmatic activity at ca 4.2 Ga, 3.8 Ga and 3.3–3.4 Ga, and this scarce information from the oldest crustal rocks contain clues to the genesis of the SCLM.

Thermodynamic modeling of the early Earth suggests that a "stagnant lid" scenario, punctuated by major mantle-overturn events that declined in intensity and frequency with time, dominated Earth's tectonics for its first billion years. These models imply that the high-degree melting of rising lower-mantle plumes was responsible for the generation of cratonic SCLM. Recent studies of Earth's xenon-isotope systematics suggest that subduction of crustal materials into the deep Earth did not begin before 2.5 Ga; this implies that the major change in tectonic style and crustal composition at this time reflects the initiation of plate tectonics. It can be argued that the development of cratonic roots was in fact a pre-requisite for the existence of stable plates as we now know them, and hence for the development of plate tectonics as we know it.

An alternative view is that the cratonic roots reflect "subduction stacking" of oceanic slices of oceanic mantle, generated at shallow spreading centers. However, modern seismic tomography images of subducting slabs shows that most descend steeply into the Earth, down to at least the Mantle Transition Zone, rather than accumulating at shallow depths. Where flat-slab subduction is observed, it does not obviously produce a thick, or especially depleted, SCLM. It also is not clear how such "uniformitarian" models could produce the unique chemistry of the Archean SCLM.

Modifying the SCLM

Later processes related to plate tectonics and related metasomatic activity have progressively modified and destroyed the primary depleted SCLM, and reworked the old crust that it supports. However, most of the primary SCLM appears to have survived, at least to some extent. Our Global Lithospheric Architecture Mapping (GLAM) project, working over 15 years to integrate geophysical, geochronological, tectonic and petrological data, has concluded that at least 75% of Earth's continental crust currently is underlain by SCLM of Archean heritage. However, the geophysical (seismic, gravity, geoid) signatures of this SCLM range from the typically cratonic, to much less depleted (denser, lower Vp and Vs, more conductive), particularly toward the margins of Archean cratons, and beneath Proterozoic shields. Petrology offers some indications of why this gradation exists, and what the geophysical data are trying to tell us.

In the broadest sense, this gradation in SCLM properties from Archean to Proterozoic regions reflects an increasing degree of refertilization of the original dunite-harzburgite SCLM. Cartoons of this process, based on studies of xenoliths in kimberlites and other volcanic rocks, commonly treat it as a uniform invasion of melt/fluid, lowering the Mg# and raising the Fe, Al, Ca contents of the bulk mantle. However, it is important to remember that the mantle sample provided by such volcanic rocks is highly biased. The integration of detailed seismic tomography, mantle chemistry and electrical conductivity over the Kaapvaal Craton shows that kimberlites (and other volcanic rocks) were erupted along translithospheric zones of weakness, repeatedly used by mantle-derived melts/fluids, and hence strongly metasomatised. Outside of these zones, the bulk SCLM may retain much of its original character. This "small-scale" heterogeneity is most visible in MT surveys, and the integration of MT with seismic tomography can help to refine the interpretation of both.

The GLAM project has also demonstrated the impact of tectonics on the survival of cratonic SCLM (a subject familiar to Chinese researchers working on the North China Craton), and our ability to recognize it in geophysical data. Where large cratons collide, or continental margins are attacked by subduction and the development of arcs, a zone of reworking (refertilisation) may develop, while leaving easily-identified cratonic roots mostly intact. However, where smaller blocks are rifted off the margins of a large craton (e.g. East African Rift, or the opening of the Atlantic Ocean), their SCLM may be progressively "decratonised" during drift, interaction with melts, and their eventual collision with a larger block. This can be seen in global seismic tomography, where small volumes of high-Vs mantle are found in ocean basins; in some cases, such as the Cape Verde islands, xenoliths in basalts sample both old SCLM and younger, oceanic mantle (Coltorti et al., 2010).

Conclusions

The deployment of major geophysical surveys such as SinoProbe and the USArray, and integration of multiple geophysical and geological datasets by multi-observable probabilistic modeling, offer a great opportunity to enhance our understanding of the behavior of both cratonic and newly-generated lithospheric mantle through a range of tectonic settings. Extracting the full range of information from such exercises will also require petrological "spot checks" from xenoliths in volcanic rocks wherever possible, while keeping in mind the limitations of both the petrological and the geophysical approaches.

References

Begg, G.C., Hronsky, J.M.A., Griffin, W.L. and O'Reilly, S.Y., 2017, Global- to District-Scale Controls on Orthomagmatic Ni-Cu(-PGE) and PGE Reef Deposits. In Mondal, S. and Griffin W.L. (eds.) Processes and ore deposits of ultramafic-mafic magmas through space and time. Elsevier. pp. 1-46.

Coltorti, M., Bonadiman, C., O'Reilly, S.Y., Griffin, W.L. and Pearson, N.J., 2010. Buoyant ancient continental mantle embedded in oceanic lithosphere (Sal island, Cape Verde Archipelago). Lithos, 120, 222-233.

Griffin W.L, Begg G.C., O'Reilly S.Y., 2013, Continental-root control on the genesis of magmatic ore deposits. Nature Geoscience 6: 905-910.ffin W.L. Belousova E.A., O'Neill C., O'Reilly, S.Y., Malkovets, M., et al., 2014, The world turns over: Hadean-Archean crust-mantle evolution, Lithos 189:, 2-15.