Composition, thermal structure and density of lithospheric mantle: implications for tectonics and geophysics

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Abstract

The composition of subcontinental lithospheric mantle (SCLM) is strongly correlated with the tectonothermal age of the overlying crust, implying long-term linkage between crust and mantle. Archean SCLM is strongly depleted and highly buoyant compared to the underlying asthenosphere and Phanerozoic SCLM. This intrinsic buoyancy places major constraints on the tectonic behaviour of old continents; replacement of old SCLM by new, less depleted mantle has profound tectonic consequences. The contrasting properties of different mantle domains also suggest a secular evolution in Earth's geodynamics from Archean to Proterozoic time, and an increased importance for lithosphere-delamination processes in Phanerozoic orogens.

Why is the mantle important for geodynamic modelling?

The composition and thermal state of the subcontinental lithospheric mantle (SCLM) determine its density and viscosity, which in turn influence the geodynamic behaviour of the lithosphere. In recent years exciting new tools, collectively termed 4-D Lithosphere Mapping [1], have been developed to map the lithospheric mantle, integrating geochemical and petrophysical properties of mantle materials with tectonic syntheses and geophysical datasets. This methodology provides important constraints on the compositional structure of SCLM formed at different times, the lateral variability of SCLM composition and its effects on tectonics, and the extent to which lithospheric mantle can be recycled into the convecting mantle, or is irreversibly differentiated from it. Recent advances in in-situ analysis of Os isotopes in mantle peridotites can provide more meaningful mantle-depletion ages, while the in-situ U-Pb and Lu-Hf analysis of detrital zircons can provide terrane-scale information on the timing and nature of mantle-derived contributions (material and heat) to the crust. These techniques will allow a more detailed analysis of the linkages between events in the SCLM and the crust than is presently possible.

SCLM composition, evolution and thermal state

Mantle-derived xenoliths carry direct information on SCLM composition, but the sampling they provide is limited in space and time. However, there is a good correlation between the composition of these rocks and the garnets they contain, and garnet xenocrysts are common in many volcanic rocks. The mean composition of the SCLM in >30 localities worldwide, calculated using >20,000 garnet xenocrysts, shows a clear correlation with the tectonothermal age of the crust penetrated by the volcanic rocks [2]. More recently formed/modified crust is underlain by less depleted SCLM, indicating that newly formed or stabilised SCLM has become progressively less depleted from Archean to Phanerozoic time. This correlation implies that crustal volumes and their SCLM have formed quasi-contemporaneously, and can remain coupled together for aeons. Paleogeotherms at the time of eruption can be estimated from xenolith and xenocryst assemblages. Xenolith suites in intraplate basalts typically define advective geotherms, whereas geotherms derived from xenoliths and xenocrysts in low-volume melts such as kimberlites commonly are subparallel to conductive models. Conductive geotherms are lowest beneath Archean cratons and highest beneath areas of Phanerozoic tectonothermal age. Typical SCLM thicknesses (the depth range of depleted peridotites) are correspondingly greater (180-220 km) beneath Archean cratons than beneath Proterozoic (150-180 km) or Phanerozoic (60-130 km) terrains. These differences

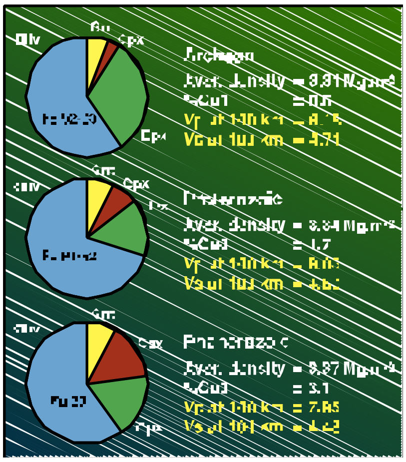

Fig. 1. Properties of mean SCLM types.

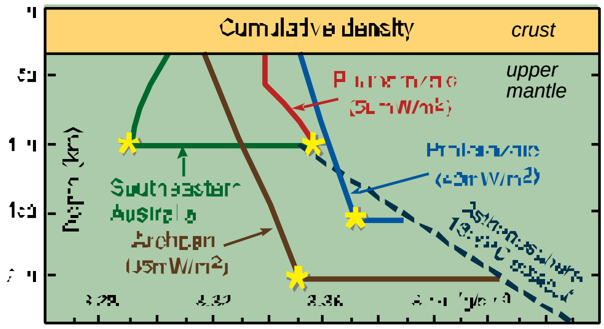

Fig. 2. Cumulative density of SCLM sections

reflect variations in both crustal heat production and mantle heat flow; they produce lateral variations in SCLM viscosity and density that will affect geodynamics.

Density Structure of the SCLM

Archean SCLM is significantly less dense than Phanerozoic or Proterozoic SCLM [3; Fig. 1]. Because of the acoutistic properties of olivine, Archean SCLM also has higher seismic velocities, even at the same temperature. Density-depth profiles calculated for typical conductive geotherms ([3]; Fig. 2) show that the cumulative density of the mantle section increases with thickness, but the density of the underlying asthenosphere (because of its adiabatic thermal profile) increases more rapidly. Typical Archean and Proterozoic sections are significantly buoyant relative to the asthenosphere, and buoyancy increases with thickness. Phanerozoic sections are buoyant only when characterised by advective geotherms.

Tectonic and Geodynamic Implications

The buoyancy of *Archean* SCLM, combined with its refractory nature, means that it cannot be "delaminated" by gravitational forces. However, it can be destroyed by lithospheric thinning and/or rifting; its density also can be increased by infiltration of asthenospheric melts until the lower parts become unstable. 4-D Lithosphere Mapping in eastern China documents the Mesozoic extension of Archean SCLM and the upwelling of asthenospheric mantle; results included dramatic uplift followed by rapid subsidence. Typical *Phanerozoic SCLM* sections are buoyant during formation under conditions of high geothermal gradient. However, they are at best neutrally buoyant after cooling to typical stable conductive geotherms (Fig. 2), and will tend to delaminate and sink. Asthenospheric material welling up into the resulting “space” will cool to form a new SCLM, raising geotherms and causing melting in the crust. As it cools, it in turn will become unstable, and start the cycle again. This cyclic delamination may explain the ubiquitous presence of fertile xenolith suites in basalts erupted through Paleozoic-Mesozoic orogenic belts [2].

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