

Are lithospheres forever?

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The Earth's lithosphere has a conductive (or advective) geothermal profile in contrast to the convecting asthenosphere with its adiabatic thermal gradient. The thickness of the sub-continental lithosphere (SCLM) varies with tectonothermal age: Archaean and Proterozoic SCLM is relatively cold, geochemically depleted and thick, while Phanerozoic SCLM is thinner, hotter and fertile. The SCLM is a palimpsest that carries a geochemical, thermal and chronological record of large-scale tectonic events that have shaped the Earth's crust.

Development of the 4-D Lithosphere Mapping methodology (O'Reilly and Griffin, 1996) has allowed the construction of realistic geological sections of the SCLM in a wide variety of tectonic settings. Mantle-derived xenoliths and garnet and chromite xenocrysts from volcanics (eg basalts, lamproites, kimberlites) provide samples of the lithospheric mantle at the time of eruption. Where sufficient xenoliths and/or xenocrysts of appropriate composition are available, we can determine the palaeogeotherm, the depth to the crust-mantle boundary, the detailed distribution of rock types with depth within the SCLM, the spatial distribution of fluid-related (metasomatic and anatexis) processes and the depth to the lithosphere-asthenosphere (LAB) boundary, within the tectosphere. Volcanic episodes of different ages in one region provide this information for different time-slices corresponding to ages of the volcanism, while geophysical data (seismic, gravity, magnetic, thermal) can be used to extend the geologically-derived profiles laterally or to interpret lithospheric domains with geophysical signatures that can be matched with geologically mapped sections.

Lithosphere traverses

On the Siberian Platform, the Palaeozoic to Mesozoic kimberlites of the NE-SW Olenek trend provide

samples along a 1000-km traverse across several terranes of both Archaean and Proterozoic age. Mapping based on garnet and chromite concentrates from >50 kimberlites along this trend shows that within-craton domains with distinctive mantle stratigraphy coincide with crustal terranes mapped at the surface (Griffin *et al.*, 1998a), implying that individual terranes carried their own lithospheric root at the time of continental accretion.

In the eastern part of the Sino-Korean craton, volcanic eruptions of different age provide snapshots of lithospheric composition and thermal state for timeslices separated by *c.* 400 Ma (Griffin *et al.*, 1998b). Markedly different SCLM sections sampled by Ordovician kimberlites erupted through areas (Liaoning and Shandong Provinces) on either side of the major TanLu fault zone suggest that this fault penetrates the lithospheric mantle and separates two Archaean terranes. In Ordovician time, each of these terranes had a thick cold, diamondiferous and typically Archaean type of SCLM, which probably had survived plate-tectonic movements for at least 2 Ga. In Tertiary time, parakimberlitic rocks and alkali basalts erupted through the same terranes sampled a thin (<120 km), hot and fertile lithosphere.

Irreversible compositional evolution of the SCLM

Mean compositions of garnet-xenocryst suites vary with the tectonothermal age of the crust penetrated by the host volcanics, implying long-term linkage of crust and SCLM, and showing that the Archaean/Proterozoic boundary represents a major change in the nature of lithosphere-forming processes. The mean composition of SCLM beneath terrains of Archaean, Proterozoic and Phanerozoic tectonothermal age, calculated from garnet concentrates, shows a clear secular and apparently irreversible evolution in the degree of depletion, such as Al, Ca,

TABLE 1. Calculated mean compositions, densities and seismic velocities for Archaean, Proterozoic and Phanerozoic SCLM (after Griffin *et al.*, 1998c)

	Archaean Gnt SCLM	Proteroz. Gnt SCLM	Proteroz. xenoliths, massifs	Phaneroz. Gnt SCLM	Phaneroz. spinel perid.	Prim. Mantle (McD. & Sun)
SiO ₂	45.7	44.7	44.6	44.5	44.4	45.0
TiO ₂	0.04	0.09	0.07	0.14	0.09	0.2
Al ₂ O ₃	0.99	2.1	1.9	3.5	2.6	4.5
Cr ₂ O ₃	0.28	0.42	0.40	0.40	0.40	0.38
FeO	6.4	7.9	7.9	8.0	8.2	8.1
MnO	0.11	0.13	0.12	0.13	0.13	0.14
MgO	45.5	42.4	42.6	39.8	41.1	37.8
CaO	0.59	1.9	1.7	3.1	2.5	3.6
Na ₂ O	0.07	0.15	0.12	0.24	0.18	0.36
NiO	0.30	0.29	0.26	0.26	0.27	0.25
mg#	92.7	90.6	90.6	89.9	89.9	89.3
ol/opx/cpx/gnt	69/25/2/4	70/15/7/8	70/17/6/7	60/17/11/12	66/17/9/8	57/13/12/18
density,g/cc	3.31	3.34	3.34	3.37	3.36	3.39
V _p (km/s, 25°)	8.35	8.34	8.34	8.32	8.32	8.34
V _p (km/s, 100 km)	8.19	8.07	8.07	7.87	7.87	—
V _s (km/s, 25°)	4.89	4.84	4.84	4.82	4.82	4.81
V _s (km/s, 100 km)	4.72	4.60	4.60	4.48	4.48	—

mg#, and Fe/Al (Gnt SCLM in Table 1; Griffin *et al.*, this conf.). Cenozoic SCLM, exemplified by Zabargad peridotites and by garnet peridotite xenoliths from young extensional areas of China, Siberia and Australia, is only mildly depleted relative to Primitive Mantle.

Significance of SCLM evolution to geophysical interpretation

Average mineral compositions for each age group have been used to calculate average modes, densities and seismic velocities (Table 1). Archaean SCLM is 1.5% less dense than Phanerozoic SCLM. At 25°C, the V_p and V_s of Archaean SCLM are greater than that of Phanerozoic SCLM by *c.* 0.4% and 1.4%, respectively; the compositional differences thus account for *c.* 25% of the range observed by seismic tomography. Typical geotherms for cratonic and Phanerozoic areas were used to calculate the difference in V_p and V_s at 100 km depth; the Archaean values are higher by ~5%, corresponding to the ranges commonly seen by seismic tomography.

Lithosphere evolution and destruction

These physical property data are important constraints on the delamination and recycling of the SCLM. Typical geotherms, and thermal expansion

coefficients and bulk moduli of the observed minerals, have been used to calculate the density variation with depth for typical SCLM sections. The results show that the entire thickness of Archaean SCLM is significantly buoyant relative to the asthenosphere. For Proterozoic and Phanerozoic SCLM, sections thicker than *c.* 30 and 60 km become buoyant and hence resistant to lithosphere delamination. This effect explains the longevity of Archaean (and thick Proterozoic) lithosphere.

Tectonic or magmatic events that lead to the replacement of old SCLM by younger material cause changes in the density and geotherm of the lithospheric column, with major effects at the surface. For example, in the eastern Sino-Korean craton, the removal of ~100 km of Archaean lithosphere during the late Mesozoic was accompanied by uplift, basin formation and widespread magmatism. In this case, lithosphere replacement involved rifting, with contemporaneous upwelling of fertile asthenospheric material.

Consequences

Archaean (and Proterozoic >30 km thick) lithosphere is forever unless it is physically disrupted (e.g. rifting, thinning and displacement) with associated thermal and chemical erosion (metasomatism). Phanerozoic SCLM <60–80 km thick can remain buoyant while hot, but will be able to delaminate on cooling.