THE EVOLUTION AND EXTENT OF ARCHEAN CONTINENTAL LITHOSPHERE: IMPLICATIONS FOR TECTONIC MODELS

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The composition of the subcontinental lithospheric mantle (SCLM), as sampled by xenoliths in volcanic rocks, shows a broad correlation with the tectonothermal age of the overlying crust. Archean cratons have variably depleted SCLM; the SCLM beneath Phanerozoic crust is dominated by compositions that are only moderately depleted compared to the Primitive Upper Mantle; the SCLM of Proterozoic cratons is generally intermediate between these extremes. These variations have been interpreted as suggesting a gradual secular change in SCLM-forming processes (eg Griffin et al., 2003). However, recent developments in seismic tomography and the integrated modeling of geophysical and petrological data (Afonso et al. 2008; Begg et al. 2009; Griffin et al. 2009) have stimulated a major re-evaluation of the original composition and present extent of Archean SCLM.

Most estimates of the composition of Archean SCLM have been based on suites of xenoliths, mainly from kimberlites. These estimates (Table 1) represent depleted garnet lherzolites with high orthopyroxene/olivine. However, these estimates suffer from important sampling biases. The high opx/ol is a feature of xenoliths from the Kaapvaal craton of South Africa, and especially the large dumps from the diamond mines of the Kimberley area, which have supplied ca 85% of the analyses of kimberlite-borne xenoliths in the literature. It is now clear that such high opx/ol is rare in xenolith suites from other cratons. Equally importantly, the published database is strongly biased toward garnet peridotites, because these are the samples for which P-T estimates can be derived using mineral compositions (cpx-opx or gnt-ol for T, and gnt-opx for P).

The previous estimates of Archean SCLM compositions have other problems as well. Advances in the modelling of geophysical data (Deen et al., 2006; Afonso et al. 2008) have shown that it is difficult to account for the high shear-wave velocities measured in the cores of large cratons, if the cratonic roots consist of "typical" depleted garnet lherzolites. These compositions would also predict deeper geoid anomalies and higher elevations than are observed over the cratons. Detailed regional seismic tomography studies of cratons (e.g. Kaapvaal Seismic Project) have outlined high-velocity volumes separated by zones of lower velocity. Combining the tomographic maps with GIS data, it is apparent that kimberlites *preferentially intrude the lower-velocity margins* of the cratons and of sub-blocks within them. This means that that most cratonic xenolith suites represent this low-velocity material, and the high-velocity cratonic SCLM is under-represented in published xenolith databases.

Xenolith suites contain a rich array of rock types, but with little information on their spatial relationships. In recent years several studies of tectonically emplaced peridotite massifs have recognised that these large slabs of SCLM originally were highly depleted, but have experienced refertilisation by the introduction of mafic melts. For example, Le Roux et al. (2007) have demonstrated that the type Lherzolite of the Lherz massif is a metasomatic rock; its protolith was a highly depleted dunite/harzburgite. Similarly, the well-studied garnet peridotites of the Western Gneiss Region of Norway represent relatively small refertilised zones within large volumes of dunite (Beyer et al. 2004, 2006). The refertilisation processes that add Ca, Al and Fe to the SCLM and produce garnet lherzolites also impart a higher density and lower seismic velocity. This explains why the kimberlites, which preferentially sample the low-velocity margins of cratonic blocks, carry a relatively high proportion of garnet lherzolite xenoliths.

We therefore have suggested (Griffin et al., 2009) that most Archean SCLM originally consisted of highly depleted dunites/harzburgites, similar to the Archean orogenic massifs of western Norway. The revised "primitive SCLM" composition (Table 1) has a lower opx/ol ratio than previous estimates, as well as lower Ca and Al, and higher Mg#. Incorporation of such rocks in the cold upper parts of the cratonic SCLM satisfies both the seismic and the gravity data, suggesting that large volumes of these depleted rocks are preserved in the cores of cratons, where they will be poorly sampled by volcanic eruptions.

The roots of most Proterozoic shields generally show somewhat lower seismic velocities than those beneath Archean cratons, and this observation has been interpreted as indicating that the Proterozoic roots were originally less depleted than Archean roots. However, isotopic studies are increasingly demonstrating that these Proterozoic cratons (as distinct from Proterozoic mobile belts) contain significant amounts of Archean material (Figure 1), especially in the lower crust (Belousova et al. 2009; Zheng et al. 2004, 2006, 2008). It seems probable that this Archean crust was underlain by Archean SCLM, and the seismic velocities beneath Proterozoic cratons are similar to those in the metasomatised parts of the Archean SCLM. We therefore now interpret most of the SCLM beneath Proterozoic cratons as consisting of refertilised Archean SCLM.

The extremely depleted Archean SCLM (Table 1), and even its metasomatised variants, are buoyant relative to the asthenosphere (Poudjom Djomani et al., 2001), and

Table 1. Average compositions for xenoliths, Norwegian exposed peridotites and the revised Archean SCLM.

	Average Low-T xenolith	**Average Low-T xenoliths**	**Average dunite/ harzburgite**	**Average lherzolite**	**"Primitive" Archean SCLM**
	Kaapvaal Craton	Slave Craton Canada	Almklovdalen Norway	Almklovdalen Norway	**Calculated**
SiO_2	46.5	42.9	42.8	43.81	**42.9**
TiO_2	0.05	0.00	0.01	0.03	**0.01**
Al_2O_3	1.40	1.10	0.14	2.2	**0.30**
Cr_2O_3	0.34	0.50	0.32	0.41	**0.40**
FeO	6.6	7.2	6.5	7.3	**6.5**
MnO	0.10	0.10	0.11	0.12	**0.15**
MgO	43.8	47.2	49.2	43.8	**49.2**
CaO	0.88	0.60	0.09	1.66	**0.10**
Na_2O	0.10	0.12	0.16	0.27	**0.10**
NiO	0.29	0.31	0.34	0.31	**0.34**
Mg#	92.2	92.1	93.1	91.5	**93.1**
Cr/ (Cr+Al)	0.14	0.10	0.35	0.04	**0.23**

would not be likely to "delaminate" or be subducted. Thus we would expect most of the SCLM generated in Archean time to be still on the surface of the Earth. Mapping of the SCLM worldwide combining global seismic tomography with isotopic data on the age of deep crust and SCLM (see below) suggests that ca 70% of the existing SCLM is Archean in origin. This is consistent with modelling of GEMOC's worldwide database of zircon Hf-isotope data, which suggests that ca 70% of the continental crust had been generated by the end of Archean time (Belousova et al., in prep).

Rather than a gradual evolution in SCLM-forming processes, we suggest a sharp dichotomy between Archean and younger tectonic regimes. Highly depleted peridotites can be found in modern tectonic environments, including subduction zones. However, Archean SCLM is unique in one important respect: whereas Phanerozoic peridotites have 8±1 wt% FeO regardless of their degree of depletion, Archean SCLM typically has significantly lower FeO (mean 6.5%; Table 1). These compositions (Table 1) imply very high degrees of melt extraction (ca 50%) at high T and P, a process with enormous energy requirements. We suggest that these highly depleted rocks were formed in mantle overturns, or very large plumes, and that these geodynamic mechanisms were restricted to the Archean.

The timing of melt extraction from a peridotitic residue can be estimated from Re-Os studies, but the Os-isotope

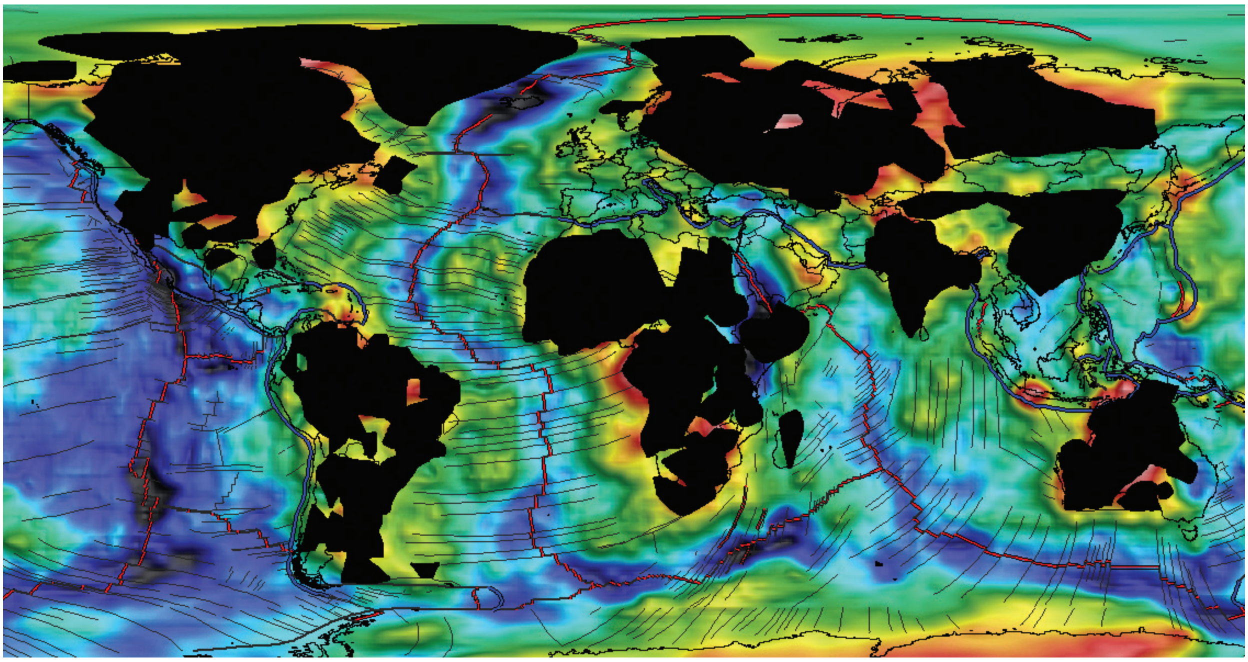

Figure 1. Interpreted extent (conservative) of original Archean SCLM (black) superimposed on a global Vs tomography image (100-150 km depth) provided by Steve Grand (University of Texas, NM). Cool colors are low Vs.

systematics of SCLM peridotites are controlled by the presence of sulfide phases, and any sample may contain >1 generation of sulfides (Alard et al. 2002). Whole-rock Os-isotope data therefore can only provide minimum ages for melt extraction. The analysis of Os isotopes in single sulfide grains (Pearson et al., 2002, Griffin et al. 2004) can avoid the mixing problem, but if all sulfides were removed from the dunite residues along with the melts, the analysis of sulfide grains may date only the re-introduction of subsequent fluids. With these caveats, it probably is significant that Os T_{RD} model ages for sulfides in xenoliths from several cratons show a major peak around 3 Ga, and there are no T_{RD} >3.5 Ga in either the sulfide dataset or among published whole-rock analyses. This suggests to us that most of the Archean SCLM was formed between 3-3.5 Ga ago; we have no evidence of Hadean SCLM, and the existing Archean SCLM may represent a tectonic/dynamic regime that operated in a short transition period between the Hadean and the NeoArchean regimes.

It is important to recognise that the widely studied garnet lherzolite xenoliths, from kimberlites (the major source of our knowledge about the ancient SCLM composition) are metasomatised rocks, rather than primitive melt-residues; their compositions (whether major- or trace-element) thus cannot be used to model their conditions of formation. Specifically, they do not provide evidence for shallow melting, the existence of Archean plate tectonics, or the generation of the cratonic SCLM by underthrusting of ocean-ridge peridotites (e.g. Canil 2002) as traditionally thought. The production of Archean SCLM through large-scale plume/overturn mechanisms may well have coexisted with a regime similar to modern plate tectonics. However, as in the modern situation, oceanic lithosphere generated by melt extraction at mid-ocean ridges would be unstable on cooling, and would rarely be preserved.

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