# Archean Lithospheric mantle: its formation, its composition and today's refertilised remains

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### Continental Archean lithospheric mantle

Archean subcontinental lithospheric mantle (SCLM) is distinctive in its highly depleted composition, commonly strong stratification, and the presence of rock types absent in younger SCLM. Is Archean SCLM part of a compositional continuum that shows a secular evolution varying broadly with the age of the last major tectonothermal event in the overlying crust, or was the Archean mantle formed in a different way in a distinctive tectonic regime? Did subduction play a major role in Archean SCLM formation? What is the composition of original Archean mantle and how much persists today?

The "typical" Archean mantle composition used in geochemical/geophysical modelling is a depleted garnet lherzolite. This composition is derived from peridotite xenoliths in kimberlites, mainly from the SW Kaapvaal Craton, and a few from Siberia. However, most such "typical" Archean xenoliths have experienced repeated metasomatism, leading to a progression from dunite/harzburgite through "depleted" lherzolite to "fertile" lherzolite, mirroring the secular evolution of the SCLM as a whole (Fig. 1; Griffin et al., 2007). Similar refertilisation processes can be studied *in situ* in peridotite massifs (e.g. Western Norway, Lherz), showing the lherzolites to be the products of melt infiltration into magnesian dunite/harzburgite protoliths (e.g. Beyer et al., 2004). The most depleted rocks are poorly represented in the published record; the bias partly reflects the collecting of rocks useful for P-T studies, but also has a geological basis. High-resolution seismic tomography of Archean cratons shows high-Vs volumes surrounded and dissected by zones of lower Vs. The low-Vs parts can be modelled using the "typical" garnet lherzolite compositions, while the higher-Vs volumes require much more depleted rocks. In detail, kimberlites avoid the high-Vs volumes to preferentially follow older zones of fluid passage and metasomatism, hence biasing our "mantle sample" toward the metasomatised zones. A revised estimate of the composition of "original" Archean SCLM yields a dunite/harzburgite with 49% MgO, 6.6% FeO, 0.4% $Al_2O_3$, 0.34% $Cr_2O_3$ and 0.2% CaO (Griffin et al., 2008). Seismic tomography suggests that this material still underlies the bulk of Archean cratons to depths of 1 km but is poorly sampled by kimberlites. Relict Archean mantle is also imaged as buoyant high-Vs blobs in oceanic regions (see below), a likely source for "recycled" geochemical signatures in some ocean island basalts and old Os-isotope ages in abyssal peridotites. These observations provide new evidence on actual mechanisms of continental breakup and the behaviour of ancient lithospheric mantle domains.

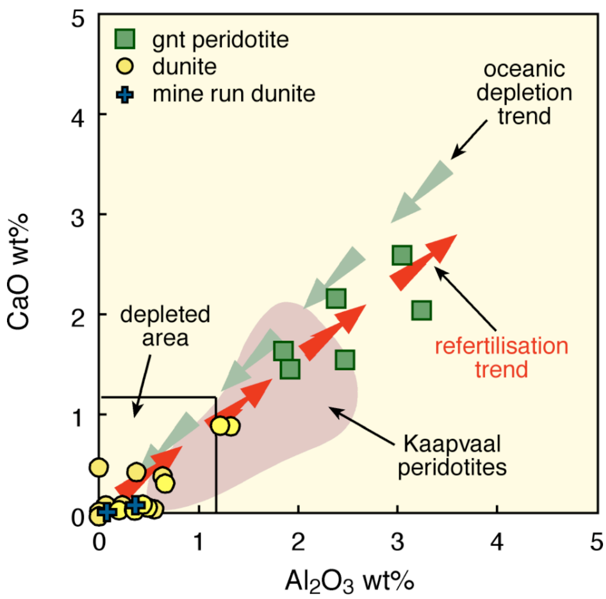


Fig. 1 The refertilisation trend shown in a depleted peridotite massif (Western Norway) mimics the compositional range of the classic Archean xenolith population from the SW Kaapvaal Craton, which usually is interpreted as a depletion trend ("oceanic trend" of Boyd, 1999). After Beyer et al. (2006).

Hf-isotope data on zircons show that much Proterozoic crust, especially in shield areas, has Archean protoliths, suggesting that the underlying SCLM also was originally Archean. Seismic tomography commonly shows high-Vs roots, requiring depleted compositions and low geotherms, under many of these areas; clearly juvenile Proterozoic belts (e.g. SW Scandinavia) lack such roots. Re-Os isotopic data for sulfides in xenoliths from the mantle beneath some Proterozoic shields preserve Archean signatures. These observations suggest that much of the observed secular evolution in SCLM composition reflects progressive reworking of buoyant Archean SCLM, rather than secular changes in the mechanisms of SCLM production. Seismic tomography suggests that ≥50% of existing continental crust is underlain by relict Archean SCLM, modified to varying degrees. This implies a much larger volume of originally Archean crust than currently accepted, and hence very high early crustal growth rates.

Melt-modelling exercises that treat "typical" Archean peridotites as simple residues are invalid, and cannot be used to support "lithosphere stacking" models for SCLM formation. The "primitive" Archean dunites and harzburgites are best modelled as restites and cumulates from high-degree melting at 3-6 GPa, in ascending plumes or mantle upwellings and overturns. This uniquely Archean regime may have coexisted with a more modern plate-tectonic regime, which produced weakly depleted residues similar to Phanerozoic SCLM. This "modern-type" SCLM would be inherently unstable, easily recycled and lost to the modern record.

**Oceanic Archean mantle**

High-resolution global seismic tomography (Fig. 2; Deen at al, 2006) images high-velocity regions, persisting in some cases to over 300 km, beneath cratons and also beneath the oceans. In the Pacific Ocean, these regions are irregularly and densely distributed and probably reflect to a large extent the widespread subduction into the upper convecting mantle in that region. However, in the Atlantic Ocean (Fig. 2) these high-velocity regions show a more regular distribution. They extend significantly towards the mid-ocean ridge from the continental margins in the 1-100km depth slice. At deeper levels, many become discrete blobs that persist to depths of up to 300km, and some of these lie directly below oceanic basalt centres including Trinidade, Ascension and Crozet, and are adjacent to parts of others such as the Cape Verde Archipelago.

Old Re-Os ages for mantle sulfides in some depleted mantle rock types beneath rift zones (e.g. Brandon et al., 2000; Wang et al., 2003) and oceanic areas (e.g. Coltorti et al., 2008) suggest that these high-velocity (inferred high-Mg and therefore low-density) blobs represent relict original Archean to Proterozoic SCLM (now refertilised to varying degrees, during episodes of mantle fluid inflitration reflecting larger-scale tectonic events), that has been mechanically disrupted and thinned during the formation of the oceanic lithosphere. This implies that ocean basins do not form by clean breaks at now-observed continental boundaries, but that significant volumes of old mantle form buoyant volumes within the newly generated oceanic lithosphere.

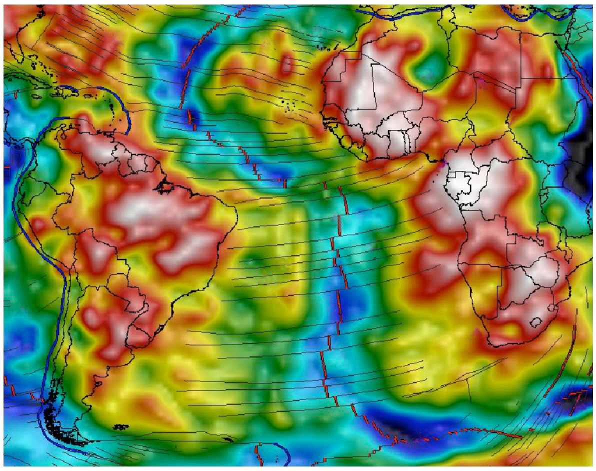

Fig. 2 Seismic tomography (Vs) slice for 0-100km for the Atlantic Ocean (from S. Grand, see Deen et al., 2006). Note the colour reversal with red spectrum for fast and blue for slow velocities.

If the higher-velocity coherent blobs observed to depths of up to 300 km below the Atlantic Ocean do represent remnant Archean mantle roots, this has important implications for the nature of global convection. Models involving large-scale horizontal components would be difficult to reconcile with these observations. Instead, convection may be dominantly in the form of upwelling vertical conduits with shallow horizontal flow (Fig. 3). The locus of these conduits may be controlled by the geometry of the margins and the coherence of the buoyant lithospheric blobs. The convective plate motions are “eddies” between these buoyant blobs and are preserved in some continental assembly configurations as the observed plate stress directions and anisotropy (e.g. Simons and van der Hilst). Mobile belts represent lithosphere accretion between the blobs.

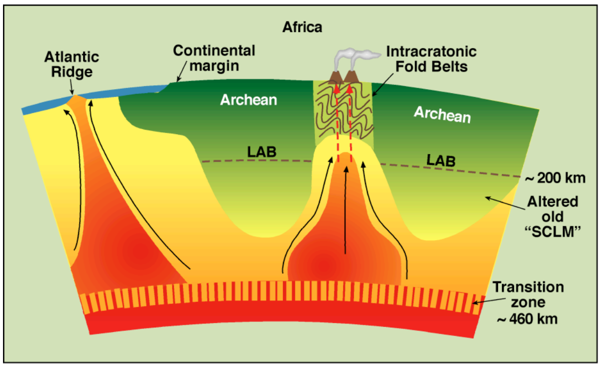


Fig. 3 Cartoon indicating how high-Vs (low-density), vertically coherent regions extending to up to > 250 km could control convection pathways.

The persistence of ancient SCLM beneath younger mobile belts and oceans also provides a logical explanation for the alphabet soup of mantle sources created by geochemists (EM1, EM2, HIMU, DMM (e.g. Hofman, 1997)). All of these geochemical fingerprints are found in lithospheric material and have been well characterised in mantle xenolith studies (e.g. Zhang et al., 2001, 2008). If lithospheric volumes persist to deep mantle levels (e.g. 250 - 300 km) then interaction with upwelling mantle can "contaminate" these plumes and fluids. The requirement for mysterious hidden source regions to provide the geochemical alphabet is removed. Magma interaction with deep ancient SCLM roots also provides a simple explanation for observations such as Archean Re-depletion model ages and old continental geochemical signatures in oceanic basalts.

**Conclusions**

* The primitive Archean SCLM appears to have been much more depleted than estimates from xenoliths.

* Seismic tomography images indicate that volumes of high-Vs ancient lithosphere (metasomatised and altered but identifiable as discrete higher velocity domains) have persisted through time and may extend to depths of at least 300 and 250 km beneath continental and oceanic regions respectively. The presence of disrupted ancient lithospheric roots in ocean basins provides new information on the mechanisms of continental breakup and mechanical disruption.

* Magma interaction with such deep lithospheric mantle roots can explain many geochemical signatures in asthenosphere-derived primitive magmas.

* Original Archean lithospheric mantle is apparently more extensive, both laterally and vertically, than previously considered and proposed processes for the formation of Archean lithosphere have to consider this.

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