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The origin and evolution of Archean lithospheric mantle

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Abstract

The composition of the subcontinental lithospheric mantle (SCLM) varies in a systematic way with the age of the last major tectonothermal event in the overlying crust. This secular evolution in SCLM composition implies quasi-contemporaneous formation (or modification) of the crust and its underlying mantle root, and indicates that crust and mantle in many cases have remained linked through their subsequent history. Archean SCLM is distinctively different from younger mantle; it is highly depleted, commonly is strongly stratified, and contains rock types (especially subcalcic harzburgites) that are essentially absent in younger SCLM. Some, but not all, Archean SCLM also has higher Si/Mg than younger SCLM. Attempts to explain the formation of Archean SCLM by reference to Uniformitarian processes, such as the subduction of oceanic mantle ("lithospheric stacking"), founder on the marked differences in geochemical trends between Archean xenolith suites and Phanerozoic examples of highly depleted mantle, such as abyssal peridotites, island-arc xenolith suites and ophiolites. In Archean xenolith suites, positive correlations between Fe, Cr and Al imply that no Cr–Al phase (i.e. spinel or garnet) was present on the liquidus during the melting. This situation is in direct contrast to the geochemical patterns observed in highly depleted peridotites from modern environments, which are controlled by the presence of spinel during melting. It is more likely that Archean SCLM represents residues and/or cumulates from high-degree melting at significant depths, related to specifically Archean processes involving major mantle overturns or megaplumes. The preservation of island-arc like SCLM at shallow levels in some sections (e.g. Slave Craton, E. Greenland) suggests that this specifically Archean tectonic regime may have coexisted with a shallow regime more similar to modern plate tectonics. Preliminary data from in situ Re–Os dating of sulfide minerals in mantle-derived peridotites suggest that much Archean SCLM may have formed in a small number of such major events >3.0 Ga ago. The survival of Archean crust may have been critically determined by the availability of large plugs of very buoyant SCLM (a "life-raft model" of craton formation). Many Archean SCLM sections have been strongly affected by Proterozoic and Phanerozoic metasomatism, and much of the observed secular evolution in SCLM composition, at least through Proterozoic time, may reflect the progressive modification of relict, buoyant Archean lithosphere.

Keywords: Archean; Lithospheric mantle; Mantle xenoliths; Mantle overturns; Mantle plumes; Lithosphere secular evolution

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1. Introduction

Uniformitarianism is a driving force in modern geology; linked with the plate-tectonics paradigm, it has provided a powerful tool for the analysis of ancient tectonic regimes. However, many papers from this symposium reflect possible problems with extending the Uniformitarian model into Deep Time. To what extent can we assume that Archean tectonic processes were analogous to Phanerozoic ones? How far back in time can the plate-tectonic paradigm, derived from modern observations, be extended before it must finally break down?

In this discussion paper, we will argue that the processes that formed most of the Archean subcontinental lithospheric mantle (SCLM), as sampled in kimberlites and other volcanic rocks, have not operated in Phanerozoic time. We will argue that Archean SCLM (with rare exceptions) was not generated by subduction of oceanic/arc mantle, and discuss the implications of alternative models. We use new, in situ, Re–Os data to suggest that most typically Archean SCLM probably was generated more than 3 Ga ago, and argue that the late Archean represents a fundamental "break-point" in Earth's geodynamics, with important implications for the formation and destruction of continents.

2. Secular evolution of SCLM composition

The concept of a linkage between crust-forming and mantle-forming events has been the starting point for our investigations. We have tested this concept by a detailed examination of the composition of SCLM beneath areas of different tectonothermal age (the age of the last major thermal event) worldwide. If a correlation exists between SCLM composition and crustal tectonothermal age, the linkage must be a fact and relate to the time of formation of the SCLM. For convenience, we have adopted a modified version of the Archon–Proton–Tecton subdivision of Janse (1994). *Archons* have tectonothermal ages >2.5 Ga, *Protons* have ages 1.0–2.5 Ga, and *Tectons* have ages <1.0 Ga.

The major obstacle to a comprehensive study of SCLM composition is the patchy distribution of good xenolith suites, in both time and space. Xenolith data from Archean cratons are heavily biased by samples from a few kimberlite pipes in southern Africa and one pipe (Udachnaya) in Siberia. The other large body of data is on spinel peridotites from alkali basalts in Tectons. These two suites are markedly different in composition (Boyd, 1989; Griffin et al., 1999a), and neither can represent the composition of the SCLM in a meaningful way, though each has been used for that purpose (e.g. McDonough, 1990; Maaloe and Aoki, 1977).

A more widespread and more easily accessible source of data is available in the form of xenocryst minerals, derived by disaggregation of mantle wall-rocks, in volcanic rocks. While these mineral grains have lost much of their petrological context, they can be analysed in large numbers, to provide broad and statistically meaningful information on SCLM composition across a much wider range of localities. Griffin et al. (1998, 1999d) showed that there are strong correlations between the compositions of Cr-pyrope garnets and their peridotitic host rocks, and that these correlations allow the calculation of mean SCLM composition from a garnet (gnt) concentrate. The mantle compositions calculated in this way compare well with the mean compositions of some well-studied xenolith suites (Table 1).

This approach has been used to calculate the mean composition of the SCLM beneath >30 areas worldwide (Griffin et al., 1999d; Table 2). The most striking feature is the consistent decrease in the degree of depletion from Archon to Proton to Tecton (Fig. 1). Archon SCLM is highly depleted in Ca, Al and other magmaphile elements; Tecton SCLM (as represented by garnet peridotites) is only moderately depleted relative to most estimates of the Primitive Mantle composition; Proton SCLM is intermediate between the two.

This secular evolution in SCLM composition, correlated with the tectonothermal age of the overlying crust, implies that the formation (or modification) of crust and mantle are broadly contemporaneous, and that crust and mantle have in general remained linked through periods of eons. The differences in SCLM composition also imply a secular change in the mechanisms that have produced the SCLM; this implies, in turn, an evolution in the mechanisms by which continents have formed.

Table 1
Comparison of SCLM compositions, calculated from garnet concentrates, with xenolith medians

	Kaapvaal Craton (Archon)				Daldyn Field, Siberia (Archon)			
	Garnet Lherzolite calculated from garnets	Garnet Lherzolites median xenolith	Garnet Harzburgite calculated from garnets	Garnet Harzburgite median xenolith	Garnet Lherzolite calculated from garnets	Garnet Lherzolites median xenolith	Garnet Harzburgite calculated from garnets	Garnet Harzburgite median xenolith
SiO_2	46.0	46.6	45.7	45.9	45.8	44.3	45.4	42.2
TiO_2	0.07	0.06	0.04	0.05	0.05	0.04	0.02	0.09
Al_2O_3	1.7	1.4	0.9	1.2	1.2	1.0	0.4	0.6
Cr_2O_3	0.40	0.35	0.26	0.27	0.31	0.37	0.18	0.37
FeO	6.8	6.6	6.3	6.4	6.5	7.6[a]	6.1	7.4[a]
MnO	0.12	0.11	0.11	0.09	0.11	0.13	0.11	0.10
MgO	43.5	43.5	45.8	45.2	44.9	45.2	47.2	47.8
CaO	1.0	1.0	0.5	0.5	0.7	1.0	0.2	1.0
Na_2O	0.12	0.10	0.06	0.09	0.08	0.07	0.03	0.07
NiO	0.27	0.28	0.30	0.27	0.29	0.29	0.32	0.31
	Protons				Tectons			
	S. Australia calculated from garnets	Mt. Gambier (SA) median xenolith	Obnazhennaya calculated from garnets	Obnazhennaya median xenolith	E. China calculated from garnets	E. China median xenolith	Vitim calculated from garnets	Vitim median xenolith
SiO_2	44.4	44.2	44.9	42.6	44.5	45.5	44.5	44.5
TiO_2	0.07	0.04	0.09	0.00	0.15	0.16	0.15	0.16
Al_2O_3	1.9	1.9	2.4	1.8	3.8	3.8	3.7	4.0
Cr_2O_3	0.41	0.44	0.42	0.44	0.40	0.44	0.40	0.37
FeO	7.8	7.6	7.9	8.4	8.0	8.2	8.0	8.0
MnO	0.13	0.13	0.13	0.13	0.13	0.14	0.13	0.00
MgO	43.2	43.5	41.7	44.7	39.1	38.1	39.3	39.3
CaO	1.6	1.6	2.1	1.4	3.4	3.3	3.3	3.2
Na_2O	0.13	0.05	0.17	0.06	0.27	0.23	0.26	0.32
NiO	0.30	0.29	0.28	0.26	0.25	0.25	0.25	0.25

[a] Affected by late Fe introduction on grain boundaries (Boyd et al., 1997).

3. Archon SCLM is unique

Archean SCLM is not simply more depleted than younger SCLM. Boyd (1989) used a plot of olivine (ol) composition against modal composition (Fig. 2) to illustrate his observation that peridotite xenoliths from the classical Archean localities in South Africa and Siberia have higher Si/Mg (reflected in a higher orthopyroxene/olivine ratio and lower olivine content) than highly depleted rocks produced in oceanic and arc-related settings; the few available suites of xenoliths from Proton settings lie between the "Archean" and the "oceanic" fields on this plot. As well as higher Si/Mg, Archean xenolith suites also show lower Cr# (100 Cr/(Cr+Al)), Ca/Al and Fe/Al at any Mg# (100 Mg/(Mg+Fe)) than Tecton or Proton xenolith suites, or ocean and massif peridotites (Griffin et al., 1999d; Figs. 3 and 4).

Archean SCLM is unique in other ways as well. One distinctive difference, long recognised by diamond exploration companies (e.g. Gurney, 1984; Gurney and Zweistra, 1995), is the presence of strongly subcalcic garnets in mineral concentrates from Archon settings, and their rarity (amounting to virtual absence) from Proton and Tecton settings (Fig. 3). The depleted harzburgites that contain these distinctive subcalcic garnets are unique to Archon SCLM, and their uniqueness suggests the operation of a process that has not produced this type of SCLM since the end of Archean time.

Griffin et al. (1999c, 2002a) used a large database ($n \geq 18{,}000$) with major- and trace-element analyses

Table 2
Estimated mean SCLM compositions

	Archons (mean garnet SCLM)	Protons (mean garnet SCLM + massifs + xenoliths)	Tectons (mean garnet SCLM)	Tectons (mean Spinel peridotite)	Primitive Mantle, McDonough and Sun (1995)
SiO_2	45.7	44.6	44.5	44.4	45.0
TiO_2	0.04	0.07	0.14	0.09	0.20
Al_2O_3	0.99	1.9	3.5	2.6	4.5
Cr_2O_3	0.28	0.40	0.40	0.40	0.38
FeO	6.4	7.9	8.0	8.2	8.1
MnO	0.11	0.12	0.13	0.13	0.14
MgO	45.5	42.6	39.8	41.1	37.8
CaO	0.59	1.70	3.1	2.5	3.6
Na_2O	0.07	0.12	0.24	0.18	0.36
NiO	0.30	0.26	0.26	0.27	0.25
Zn	34	52	55	53	55
V	20	48	70	59	82
Co	93	107	110	110	105
Sc	7	10	14	12	16
Mg#	92.7	90.6	89.9	89.9	89.3
Mg/Si	1.49	1.43	1.33	1.38	1.25
Ca/Al	0.55	0.80	0.82	0.85	0.73
Cr/Cr+Al	0.16	0.12	0.07	0.09	0.05
Fe/Al	4.66	3.02	1.66	2.23	1.30
Olivine/orthopyroxene/ clinopyroxene/garnet	69/25/2/4	70/17/6/7	60/17/11/12	66/17/9/8	57/13/12/18
Density, g/cc	3.31	3.34	3.37	3.36	3.39
Vp, km/s (room temperature)	8.34	8.32	8.30	8.30	8.33
Vp, 100 km, 700 °C	8.18	8.05	7.85	7.85	
Vs, Km/s (room temperature)	4.88	4.84	4.82	4.82	4.81
Vs, 100 km, 700 °C	4.71	4.6	4.48	4.48	

of mantle-derived Cr-pyrope garnets to evaluate approaches to the definition of populations using multivariate statistics. One of these techniques, Cluster Analysis by Recursive Partitioning (CARP), recognised 15 individual populations, which can be correlated with specific petrological types of xenoliths found in kimberlites and other volcanic rocks. These CARP classes can be grouped into five major categories (Table 3). *Depleted harzburgites* contain subcalcic garnets depleted in Y, Ga, Zr, Ti and HREE; *depleted lherzolites* have garnets with Ca–Cr relationships indicating equilibration with clinopyroxene (cpx) (Griffin et al., 1999c), but depleted in HREE and HFSE. The garnets of *depleted/metasomatised* lherzolites are depleted in Y and HREE, but enriched in Zr and LREE, suggesting that they were subjected to depletion and subsequent refertilisation; xenoliths of this type commonly contain phlogopite ± amphibole. The garnets of *fertile lherzolites* have high contents of HREE and near-median contents of HFSE; they retain no evidence of a depletion event. The garnets of *melt-metasomatised peridotites* have a characteristic signature of enrichment in Zr, Ti, Y and Ga, and correspond to the high-*T* sheared lherzolite xenoliths found in many kimberlites.

The distribution of CARP classes in Archon, Tecton and Proton SCLM (Table 4) again illustrates both the secular evolution of the SCLM, and the uniqueness of Archean SCLM. Some classes (mainly those related to strong depletion) are restricted to Archon SCLM, and/or are absent in Tecton SCLM, which is dominated by a class of fertile peridotites (class L10B) that is absent in Archon SCLM.

The garnet data can be plotted as a function of depth; the equilibration temperature of each grain can be calculated from its Ni content (Ryan et al., 1996), and an estimate of its depth of origin is derived by referring this temperature to a local paleogeotherm,

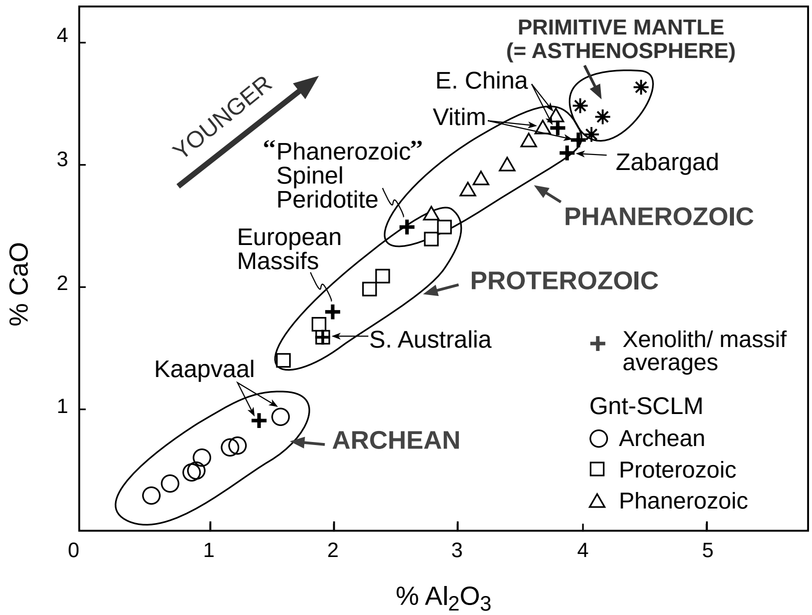

Fig. 1. CaO vs. Al_2O_3 for calculated SCLM compositions, showing the secular evolution in the composition of the SCLM (after Griffin et al., 1999d). Compositions are calculated from garnet concentrates (open symbols) or as means for xenolith suites and peridotite massifs (crosses). Several published estimates for the composition of the Primitive Upper Mantle (PUM) are shown by asterisks. Garnet lherzolite xenoliths from Tectons (E. China, Vitim) are only slightly depleted relative to PUM. All data from Griffin et al. (1999d).

derived either from xenolith data or from the garnet concentrate itself (Ryan et al., 1996). When the relative abundances of CARP classes (Table 4) in typical SCLM sections are plotted against depth (Fig. 4), they provide a picture of the vertical distribution of different rock types and metasomatic styles.

These sections illustrate the dominance of depleted harzburgites and lherzolites in the Archean SCLM, and their relative rarity in younger SCLM. The pervasive effects of metasomatism over time in the Archean SCLM are shown by the abundance of depleted/metasomatised lherzolites, and the increase in melt-related metasomatism downward in each section. Some sections, such as those from the Siberian and Slave cratons, show pronounced stratification (cf. Griffin et al., 1999a,e). The Slave section is unique in having an ultradepleted upper layer, separated from a more typically Archean lower layer by a sharp boundary (145 ± 5 km). Proterozoic sections contain a high proportion of fertile lherzolites; some of these lherzolites may represent metasomatic refertilisation of previously depleted rocks, while others may never have been through a melt-extraction event.

Typical Tecton SCLM (in the garnet peridotite facies) is compositionally simple, consisting of very fertile lherzolites with no evidence of strong depletion, and lherzolites showing a melt-metasomatism overprint.

4. Secular evolution by metasomatism?

As noted above, the garnet data illustrate extensive metasomatism of Archon and Proton SCLM, but the metasomatic effects observed in xenolith suites do not explain the high Si/Mg of Archon SCLM. Griffin et al. (1999d) suggested that olivine addition through melt infiltration has affected some Archean peridotite suites and was accompanied by a decrease in Mg#, as observed in abyssal peridotites (Niu, 1997). Phlogopite-related metasomatism, which is common in shallow garnet peridotites, has a similar effect, precipitating clinopyroxene and olivine at the expense of garnet (±orthopyroxene), and lowering Mg# (Fig. 5; Griffin et al., 1999f; van Achterbergh et al., 2001).

Numerous studies of mineral zoning show that the compositions of high-*T* sheared peridotite xenoliths

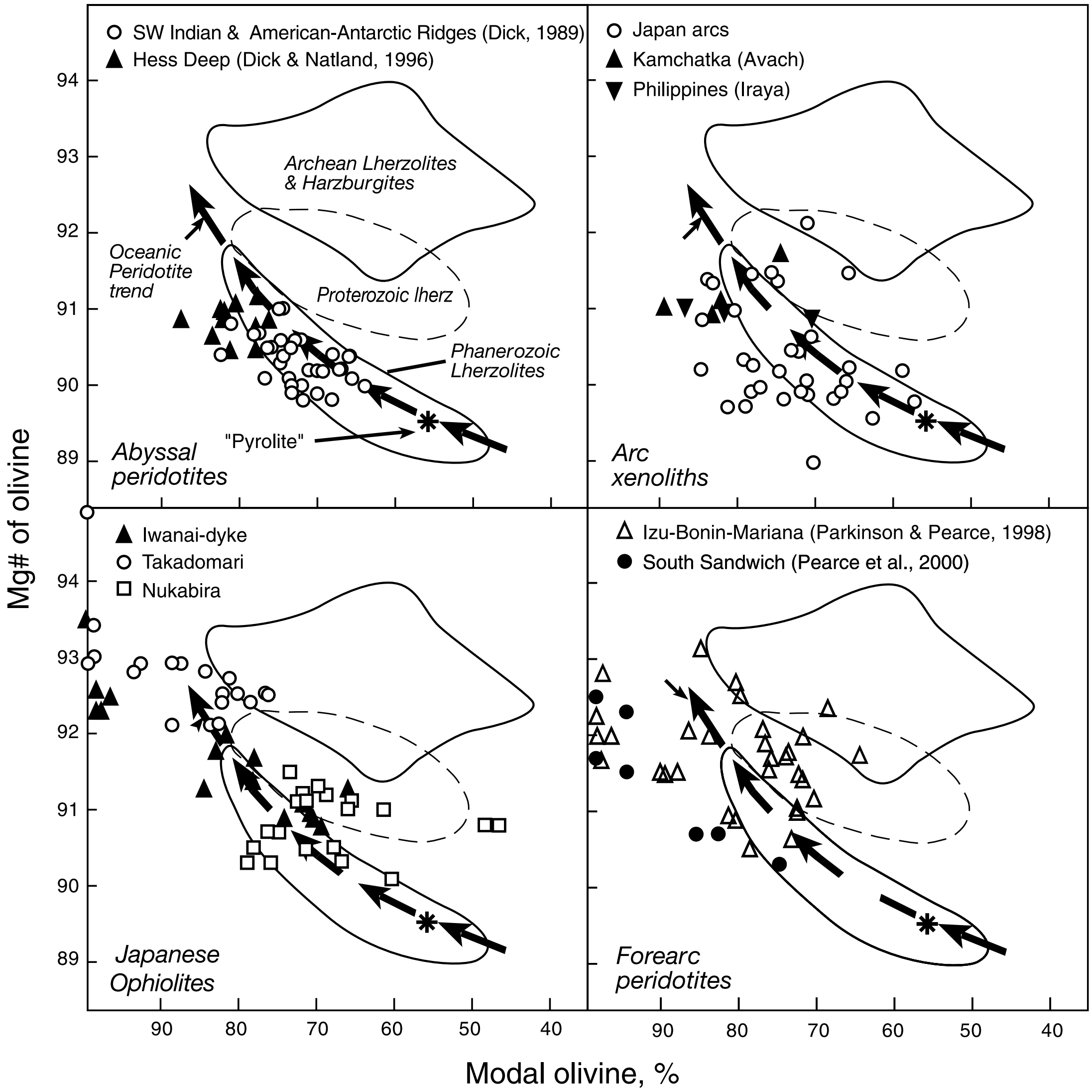

Fig. 2. Plot of modal olivine content vs. Mg# in peridotite xenoliths and abyssal and ophiolite peridotites, showing the low olivine content (related to high opx content) of Archean peridotite xenoliths from the Siberian and Kaapvaal cratons (after Boyd, 1987; field of Proterozoic lherzolite xenoliths from Griffin et al., 1998). The "oceanic trend" of Boyd (1987) is modelled from shallow melting of a "pyrolite" or PUM composition; most Phanerozoic lherzolite xenoliths, abyssal peridotites (Dick, 1989; Dick and Natland, 1996) and ophiolite peridotites lie along this trend. Xenoliths from subduction zones also follow this trend. Data for Japanese localities from Abe (1997), Abe et al. (1998), M. Makita, S. Arai (personal communication, 1997) and Tamura et al. (1999) (Parkinson and Pearce, 1998; Pearce et al., 2000).

found in many kimberlites reflect the infiltration of asthenosphere-derived melts on a short time scale before kimberlite eruption (Smith and Boyd, 1987; Smith et al., 1993; see review by Griffin et al., 1996). This style of metasomatism decreases both Mg# and the orthopyroxene/olivine (opx/ol) ratio, and increases the modal proportions of clinopyroxene and garnet. The effect is to drive Archean peridotites toward the compositions of younger ones.

There are no documented examples of metasomatism driving "Tecton" compositions toward "Archon" compositions. Instead, it would appear that

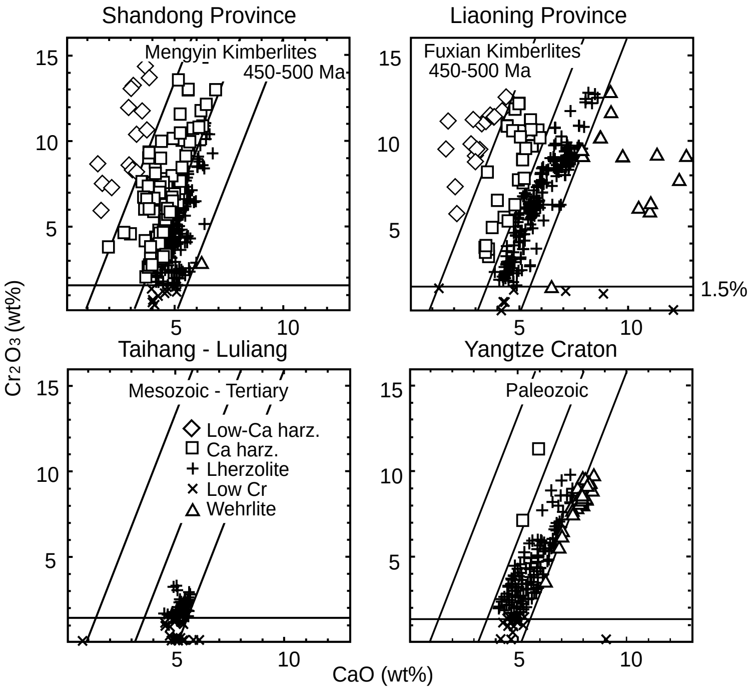

Fig. 3. Ca–Cr plots for garnets from Chinese kimberlites and lamproites. Devonian kimberlites in Shandong and Liaoning Provinces penetrate the Archean Sino–Korean Craton and contain high proportions of subcalcic pyropes derived from harzburgites (open squares and diamonds). These garnets are essentially absent in Paleozoic lamproites erupted through the Proterozoic Yangtze Craton, although high-Cr lherzolite garnets attest to a moderate degree of depletion. The Mesozoic-Tertiary Taihang-Luliang "kimberlites" have intruded rift zones bisecting the Sino–Korean Craton; the low-Cr garnets are typical of fertile Phanerozoic peridotites. Data from Zhou et al. (1994).

metasomatism of the Archean SCLM over time will tend to move it toward less depleted compositions with lower Si/Mg (Fig. 5). This observation suggests that metasomatic modification of Archean SCLM could be at least part of the cause of the observed secular evolution in the composition of the SCLM.

Secular evolution on a short time scale is demonstrated by a comparison of the SCLM sampled by the spatially associated Group 2 (largely older than 110 Ma) and Group 1 (largely younger than 95 Ma) kimberlites in the SW Kaapvaal Craton (Fig. 6). Over the short time span separating these two eruptive events, phlogopite-related metasomatism has substantially reduced the proportions of depleted harzburgites and lherzolites in the SCLM, and increased the proportion of fertile lherzolites. Melt-related metasomatism has severely affected the lower part of the section, effectively raising the base of the depleted lithosphere by 30 km; at the same time the geotherm has risen from near a 35 mW/m^2 conductive model geotherm to the 40 mW/m^2 conductive model familiar from many geothermobarometric studies of xenoliths from the Group 1 kimberlites (Finnerty and Boyd, 1987; Griffin et al., 2003). The mean forsterite content (% Fo, or Mg#) of olivine has decreased, at both the top and bottom of the section (Fig. 6). The different styles of metasomatism in the upper and lower parts of the section probably reflect the activity of different types of fluids, rising to different levels of the SCLM. The increase in SCLM density with depth (Fig. 7) provides a natural density filter, as fluids of different density rise to their depth of neutral buoyancy.

The section from northern Botswana (Fig. 6) represents SCLM beneath the Kheis Belt, which was the passive margin of the Kalahari Craton from ca. 2.3 to 2.0 Ga; deformation, volcanism and granitoid intrusion from 2.0 to 1.8 Ga define it as a typical Proton setting. Its SCLM section is typical of many Proton sections worldwide; it has few if any depleted harzburgites, depleted lherzolites are rare, and fertile

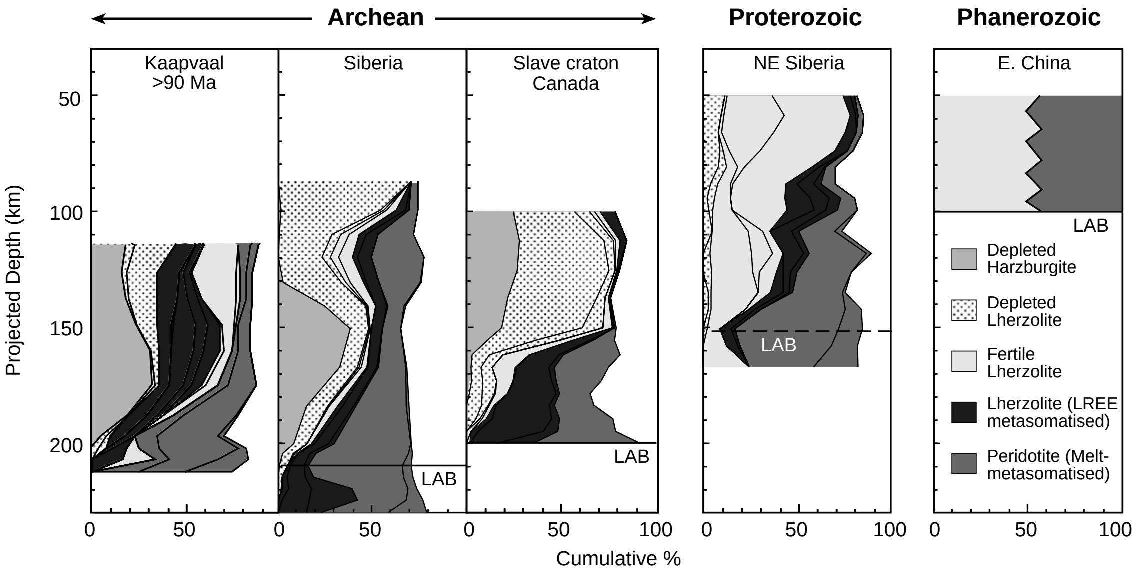

Fig. 4. Vertical distribution of CARP garnet classes (Table 3) in representative Archon, Proton and Tecton sections, showing the abundance and stratification of depleted rock types in Archon SCLM, and the more fertile nature of typical Proton SCLM. The Tecton sections in the garnet facies are short, shallow and very fertile relative to older SCLM. Data from Griffin et al. (2002a).

Table 3
Classes and major groups recognised by CARP analysis of Cr-pyrope garnets

	Mean % Fo in olivine[a]	Mean Y in garnet[b]	Mean Zr in garnet[b]	Mean TiO_2 in garnet[b]
Depleted harzburgites				
H2	93.7	2	21	345
Depleted lherzolites				
L3	91.8	2	6	250
L5	92.9	3	40	293
Depleted/metasomatised peridotites				
H3	93.1	24	126	250
L15	92.4	13	40	650
L18	92.8	15	67	930
L19	92.6	9	54	880
L21	92.0	47	123	980
Fertile lherzolites				
L9	87.5	21	23	570
L10A	92.1	16	38	510
L10B	89.6	40	40	1300
Melt-metasomatised peridotites				
L13	90.5	17	25	1265
L25	91.7	16	52	2100
L27	90.7	23	85	5300

Data from Griffin et al. (2001a).
[a] From classification of garnets in 200 peridotite xenoliths.
[b] Means from LAM-ICPMS database ($n = 5403$).

Table 4
Distribution of garnet populations identified by CARP analysis (Griffin et al., 2001a)

CARP	Archon ($n = 3082$)	Proton ($n = 1698$)	Tecton ($n = 623$)	Archon	Proton, normalised to 100% classified	Tecton
H2	9.0	0.8	0.0	10.4	0.9	0.0
L3	11.1	9.2	0.0	12.9	10.4	0.0
L5	10.8	6.2	0.0	12.5	7.0	0.0
Sum depleted peridotites	**30.9**	**16.2**	**0.0**	**35.8**	**18.3**	**0.0**
H3	2.0	0.3	0.0	2.3	0.3	0.0
L15	1.4	6.0	1.3	1.6	6.8	**1.4**
L18	2.8	0.5	0.0	3.2	0.6	0.0
L19	3.5	6.7	0.0	4.1	7.6	0.0
L21	1.0	1.2	0.0	1.2	1.4	0.0
Sum depleted/metasomatised	**8.7**	**14.4**	**1.3**	**10.1**	**16.3**	**1.4**
L9	2.7	4.6	5.8	3.1	5.2	6.3
L10A	15.0	12.7	16.2	17.4	14.4	17.7
L10B	2.9	6.2	44.5	3.4	7.0	48.5
Sum fertile lherzolites	**20.6**	**23.5**	**66.5**	**23.9**	**26.6**	**72.5**
L13	4.0	5.6	2.2	4.6	6.3	2.4
L25	11.0	13.4	18.6	12.7	15.2	20.3
L27	11.1	15.2	3.1	12.9	17.2	3.4
Sum melt-metasomatised	**26.1**	34.2	**23.9**	**30.2**	**38.7**	**26.1**
Total classified	**86.3**	**88.3**	**91.7**	100.0	100.0	100.0

Based on a database of 5403 Cr-pyrope garnets, analysed for major elements by electron microprobe and for trace elements by LAM-ICPMS (Griffin et al., 2001a).

lherzolites dominate the section. However, this composition could simply reflect the further progress of the type of metasomatic processes that modified the SCLM beneath the SW part of the craton around 100 Ma ago.

Re–Os analyses of 10 xenoliths from the Letlhakane kimberlite, which is included in the N. Botswana SCLM section, give a mean model age (T_{RD}) of 2.6 ± 0.2 Ga (Irvine et al., 2001), indicating that this SCLM was in fact originally generated in Archean time. It may originally have resembled the Group 2 SCLM (Fig. 6) but was modified to typical Proton composition by extensive metasomatism related to the Proterozoic rifting and compression (Griffin et al., 2003).

The density of typical Archean SCLM is significantly less than that of Proterozoic or Phanerozoic SCLM (Table 2), and sections of Archean SCLM more than ca. 60 km thick are significantly buoyant relative to the underlying asthenosphere (Fig. 8). This buoyancy persists even if the potential temperature of the asthenosphere is much higher, as probable in early Archean time (Poudjom Djomani et al., 2001). This buoyant Archean SCLM cannot be removed by gravitational forces alone, as proposed in many delamination models, and will tend to persist through most tectonic events. However, it can be progressively modified by addition of asthenosphere-derived material, especially in extensional settings (Fig. 7; O'Reilly et al., 2001), and its lower parts might ultimately become unstable as they approach the composition of the asthenosphere.

It therefore seems probable that many Proterozoic SCLM sections, like the one from northern Botswana, may be strongly modified Archean SCLM. However, this probably does not mean that Tecton lithosphere is simply more strongly modified Proterozoic or Archean SCLM. The analysis of garnet populations (Table 4) shows that Tecton SCLM is dominated by classes that are absent or very rare in Archon or Proton sections. If these compositions were the end result of metasomatic processes that have affected the older SCLM, we would expect to see more examples of these classes in

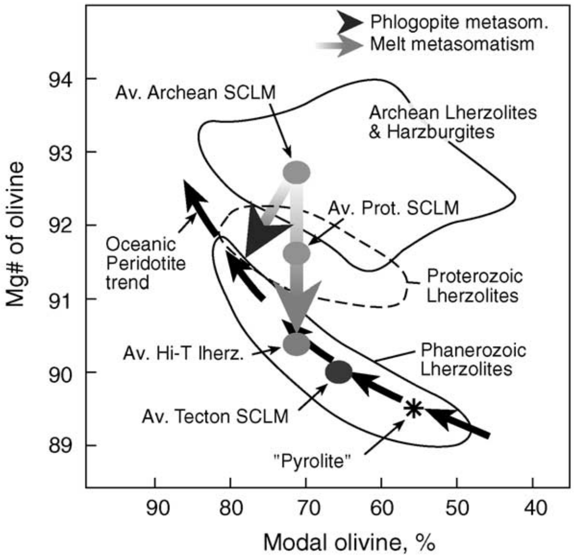

Fig. 5. Boyd plot (cf. Fig. 1) showing the compositions of mean Archon, Proton and Tecton SCLM (Table 2), and the mean composition of high-*T* sheared lherzolite xenoliths from kimberlites. Arrows illustrate the effects of shallow phlogopite-related metasomatism, and the melt-related metasomatism responsible for the composition of the sheared xenoliths (Smith et al., 1991). The observed metasomatism in Archean xenoliths results in refertilisation, and may be responsible for at least some of the observed secular change in SCLM composition between Archon and Proton sections.

the older sections. It appears on present evidence that Phanerozoic SCLM is produced by distinctly different processes from those that operated in the Archean.

5. SCLM by subduction?

So how was the unique Archean SCLM produced? One common model invokes the stacking of subducted slabs of oceanic or arc-related mantle beneath the continents. This approach probably is meant to be Uniformitarian; if so, it fails on two counts: (1) the proposed modern analogues are not compositionally similar to Archean SCLM; (2) there is little evidence that Phanerozoic SCLM is formed by the subduction of oceanic or arc-related mantle beneath continental margins.

As noted above, modern abyssal peridotites, even when highly depleted, do not have compositions similar to those of Archean SCLM. Uniformitarian models for SCLM formation therefore have tended to concentrate on processes in subduction-zone environments, where far fewer xenolith data are available. One common explanation for the high Si/Mg of Kaapvaal and Siberian SCLM invokes the infiltration of slab-derived silicic melts or fluids, usually in subduction settings (e.g. Kelemen et al., 1992). This model requires that while such processes occur beneath island arcs and active continental margins today, the subduction of such arc-related mantle to form SCLM was restricted to Archean time. However, both experimental and observational evidence suggests that this process is not a viable model for the generation of the unique composition of Archean SCLM.

Analyses of xenoliths from subduction-zone settings follow the same type of depletion trends observed in oceanic peridotites and many xenolith suites from Tectons (Fig. 2); although highly depleted rocks do occur, these are olivine-rich, rather than opx-rich, and have lower Mg# than most Archean suites (Fig. 2). Metasomatism has been described in xenolith suites from subduction settings (Kepezhinskas et al., 1995; Abe, 1997; Abe et al., 1998, 1999; McInnes et al., 2001; Gregoire et al., 2001), and in some cases this metasomatism has led to enrichment in orthopyroxene. However, this process does not produce an increase in Mg#, and it is accompanied by the introduction of amphibole, phlogopite and clinopyroxene (McInnes et al., 2001). It also involves strong enrichment in the LILE (Sr, Ba, Rb, Th, U) and LREE (Gregoire et al., 2001), and increases in Ca and Cr contents and Ca/Al, an effect opposite to those observed in Archean xenolith suites.

These observations on xenoliths are consistent with experimental studies (e.g. Prouteau et al., 1999, 2001), which show that the production of slab melts in subduction settings probably involves wet melting, and produces silicic, but strongly (per-)alkaline melts with low Mg# (15–30). These melts can precipitate orthopyroxene by reaction with peridotites, but also will deposit their alkali contents in the form of (sodic) phlogopite ± amphibole. It therefore seems unlikely that Archon SCLM attained its generally high Si/Mg through metasomatic processes analogous to those in modern subduction-zone environments.

Nor do the petrological data support the subduction model for Phanerozoic SCLM. A detailed analysis of most available data on Tecton xenolith suites (Griffin

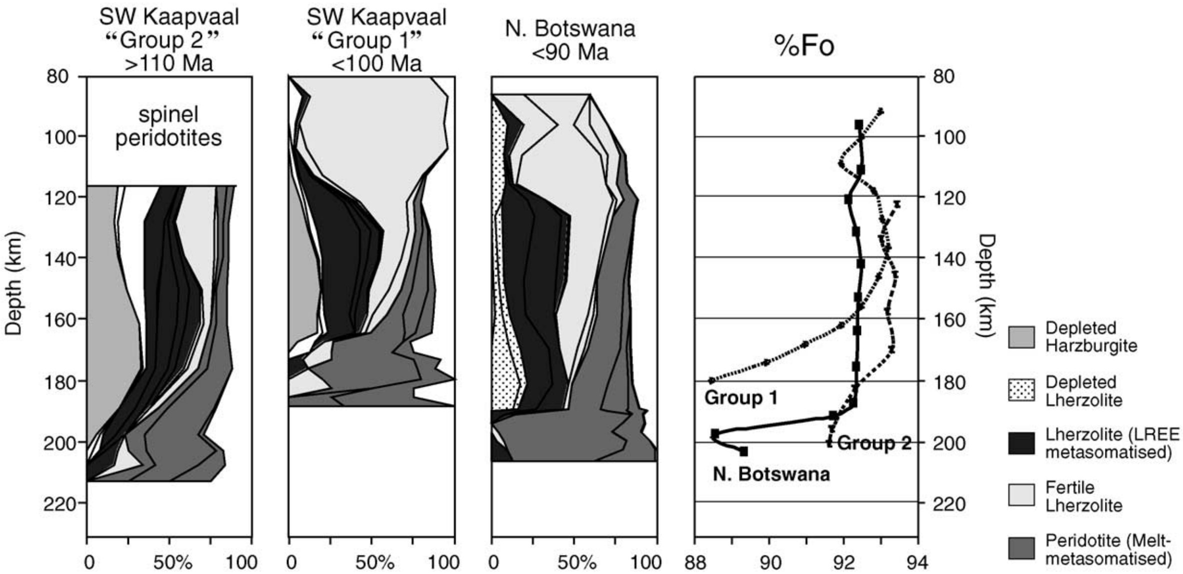

Fig. 6. CARP sections showing the vertical distribution of ultramafic rock types (derived from garnet classes) and $X_{Mg}^{Olivine}$ beneath the SW Kaapvaal Craton in two time slices, and beneath the Proterozoic craton margin in N. Botswana. Metasomatic activity ca. 100 Ma refertilised the SW Kaapvaal SCLM, leading to a decrease in the relative abundance of depleted rock types and mean $X_{Mg}^{Olivine}$, an increase in the proportion of fertile lherzolites, and a thinning of the depleted lithosphere by ca. 30 km. Similar metasomatic processes during Proterozoic rifting and compression may be responsible for the more fertile nature of the N. Botswana SCLM, which was originally formed in Archean time (Carlson et al., 1999).

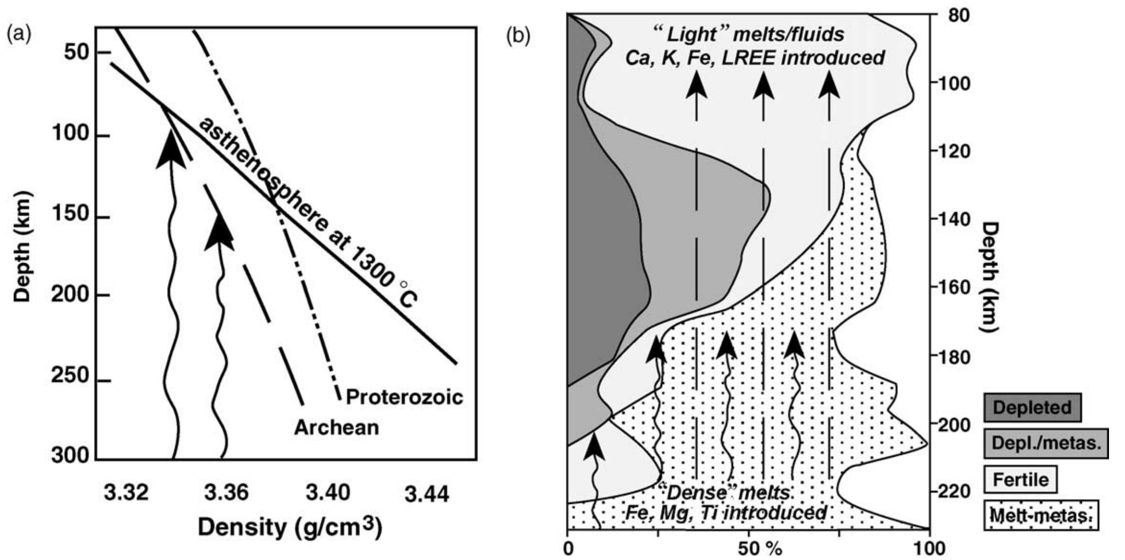

Fig. 7. (a) Change in density with depth for mean Archon and Proton SCLM; (b) cartoon illustrating typical depth distribution of different types of metasomatism in Archon SCLM sections, related to ascent of metasomatic fluids of different densities.

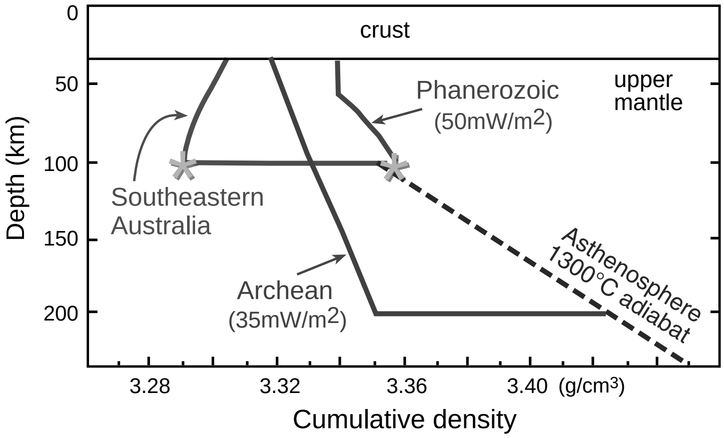

Fig. 8. Curves showing the density of mean Archean and Phanerozoic SCLM as a function of lithosphere thickness, compared with the density of the asthenosphere (taken as a Primitive Upper Mantle, or "pyrolite" composition). The difference between the SCLM curves and the density of the asthenosphere at any depth is a measure of the buoyancy of that section. The Southeastern Australia section represents young SCLM with a high advective geotherm; on cooling to a more typical conductive geotherm, it loses its buoyancy and becomes inherently unstable. Archon SCLM more than ca. 60 km thick is buoyant relative to the asthenosphere (Poudjom Djomani et al., 2001).

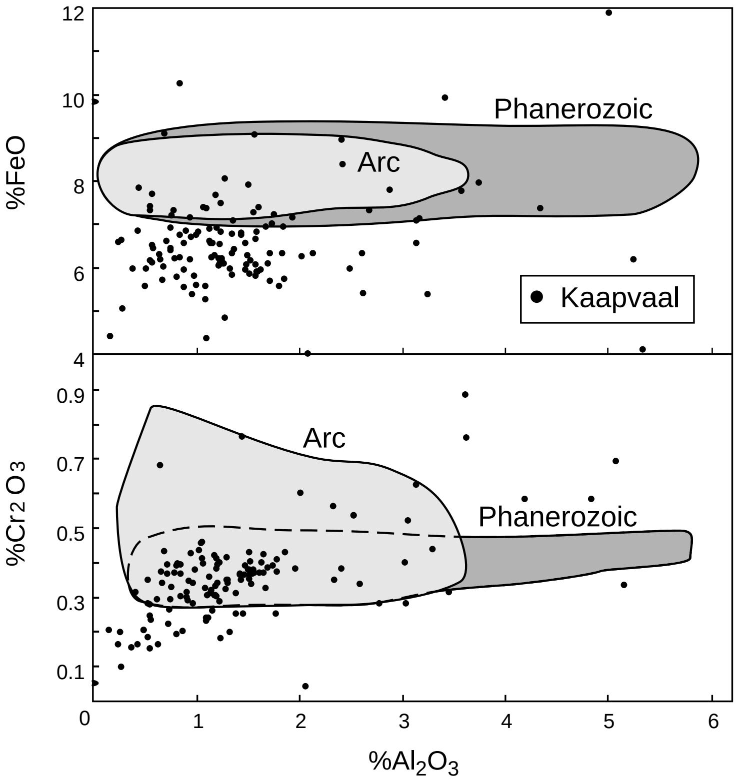

Fig. 9. FeO and Cr_2O_3 vs. Al_2O_3 for Phanerozoic xenolith suites and arc-related mantle (xenoliths, ophiolites), and Archean peridotite xenoliths from the Kaapvaal Craton. The incompatible behaviour of Fe and Cr at high degrees of melting (low Al contents) in the Archean suites is not obvious in the Phanerozoic suites, and implies significant differences in the style of depletion.

et al., 1999d) shows that these suites are dominated by relatively fertile peridotites (especially in the garnet facies; Table 2), and depleted rocks analogous to abyssal peridotites and arc-related harzburgites are rare. This observation is consistent with seismic tomography images, which show the subducting slabs plunging to the transition zone and lower mantle, rather than accumulating at lithospheric depths beneath the continents (van der Hilst et al., 1997; Gurnis et al., 1998; Fukao et al., 2001). If Phanerozoic SCLM is not formed by "lithospheric stacking" of oceanic mantle slabs, the modern plate-tectonic situation does not offer an analogue for the formation of Archon SCLM.

Archon SCLM also contains chemical evidence that argues against its formation at shallow levels of the Earth, and thus against subduction models. Fig. 9 shows a key difference between Tecton SCLM and highly depleted oceanic or arc-related mantle on the one hand, and Archon SCLM on the other (for more detailed data, see Griffin et al., 1999d). Even in the most depleted Phanerozoic peridotite suites, Fe and Cr remain constant or increase as Al decreases during progressive melt extraction, suggesting that melting was buffered by the presence of spinel ± garnet even at extreme degrees of depletion. The high degrees of depletion seen in some arc-related peridotites probably require melting under "wet" conditions, because of the rapid rise in liquidus temperature that occurs after clinopyroxene (cpx) is eliminated by progressive melt extraction during dry melting (Dick and Fisher, 1984; Kushiro, 2001). During wet melting, spinel remains on the liquidus even to high degrees of melt extraction (Kushiro, 2001), and the compatible behaviour of Cr illustrated in Fig. 9 therefore is a signature of melting under shallow, wet conditions.

In Archean peridotite suites, on the other hand, Fe and Cr decrease together with Al; that is, they behaved as incompatible elements during melt extraction. This implies that neither spinel nor garnet remained in the residue during the advanced stages of melting. These peridotites therefore are unlikely to be the residues of shallow melting processes and are unlikely to represent subducted Archean oceanic or arc mantle.

However, the Fe–Cr–Al relations of Archean peridotite xenoliths are consistent with high-degree melting under dry conditions at high pressure, where garnet is eliminated from the residue, while complex magmatic pyroxenes contain garnet and clinopyroxene in solid solution (Fig. 10). Mixtures of these residues and cumulates can give most of the range of compositions observed in Archean mantle. Archon xenoliths are extremely depleted in Sc (which resides primarily

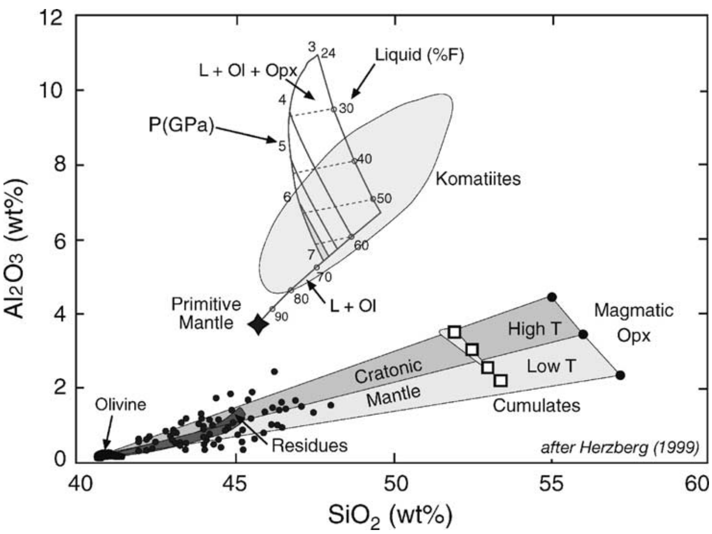

Fig. 10. Al–Si relationships during melting of Primitive Mantle compositions at high pressures, after Herzberg (1999). At high degrees of melting and pressures between 50 and 70 kb, garnet is removed from the residue, leaving only olivine ± orthopyroxene; magmatic opx has high contents of cpx and gnt in solid solution. Mixtures of residues and magmatic opx mimic the compositions of Archean peridotites (black dots).

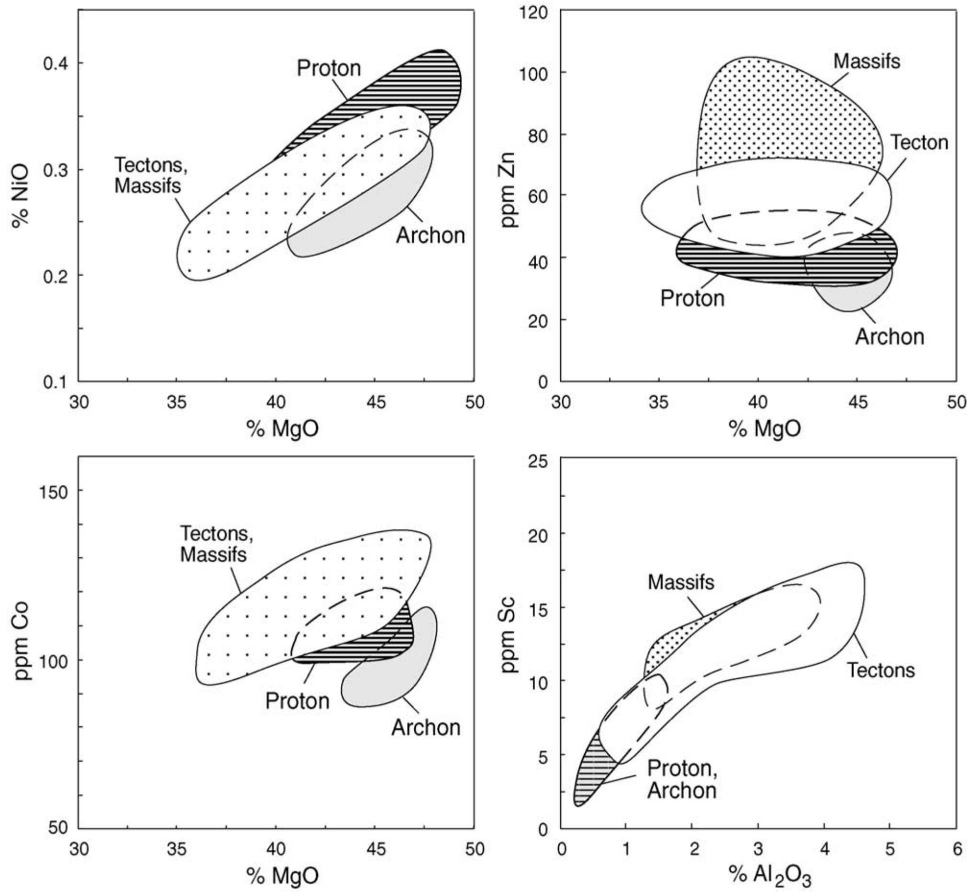

Fig. 11. Ni, Co, Zn and Sc contents of xenolith suites and peridotite massifs, relative to Mg and Al contents. The low Ni/Mg, Co/Mg and Zn/Mg of Archon xenolith suites are consistent with melting at high pressures, where the values of $D_i^{\text{olivine/melt}}$ decrease. The extreme depletion of Sc in Archon and Proton xenolith suites is consistent with melting under conditions where neither cpx nor gnt are present in the residue.

in clinopyroxene and garnet), compared to samples of Proton and Tecton SCLM (Fig. 11) and this is consistent with a lack of both phases in the residue during the melting of Archean SCLM.

Melting at high pressure is also suggested by the low Ni/Mg, Zn/Mg and Co/Mg of the Archon xenoliths, compared to those from Protons and Tectons (Fig. 11). Bickle et al. (1977) showed that the partition coefficient $D_{\text{Ni}}^{(\text{olivine/melt})}$ decreases with increasing pressure, so that high-P residues will be depleted in Ni relative to MgO, compared with residual peridotites generated at shallow levels. Suzuki and Akaogi (1995) confirmed this result for Ni and extended it to other divalent elements such as Co and Zn. The low Ni, Co and Zn contents of the Archon xenoliths are consistent with melting at high P, leaving a residue dominated by olivine $\pm$ orthopyroxene. Models based on high-pressure melt extraction, rather than analogues to modern subduction processes, are therefore more likely to provide explanations for the unique nature of Archean lithosphere.

Finally, it should be noted that Archean SCLM compositions are highly buoyant relative to the underlying asthenosphere. If Archean SCLM initially was formed at near-surface conditions (e.g. mid-ocean ridges) this buoyancy would make it difficult to subduct to depths of >200 km. Increasing the temperature of the Archean asthenosphere only aggravates the situation, by raising the temperature at the base of the (oceanic) lithosphere and further decreasing the density of the depleted material.

6. Timing of SCLM formation

Most of our present information on the timing of these mantle depletion events comes from the whole-rock Re–Os dating of xenoliths from kimberlites; these data show that some of these rocks were depleted of melt in the Archean, but (taken at face value) they also suggest that the process may have continued at least through the Proterozoic (Fig. 12a). However, the recent development of in situ analytical methods (Pearson et al., 2002) has shown that most of these whole-rock ages represent mixtures, because their Re–Os systematics are controlled by sulfide

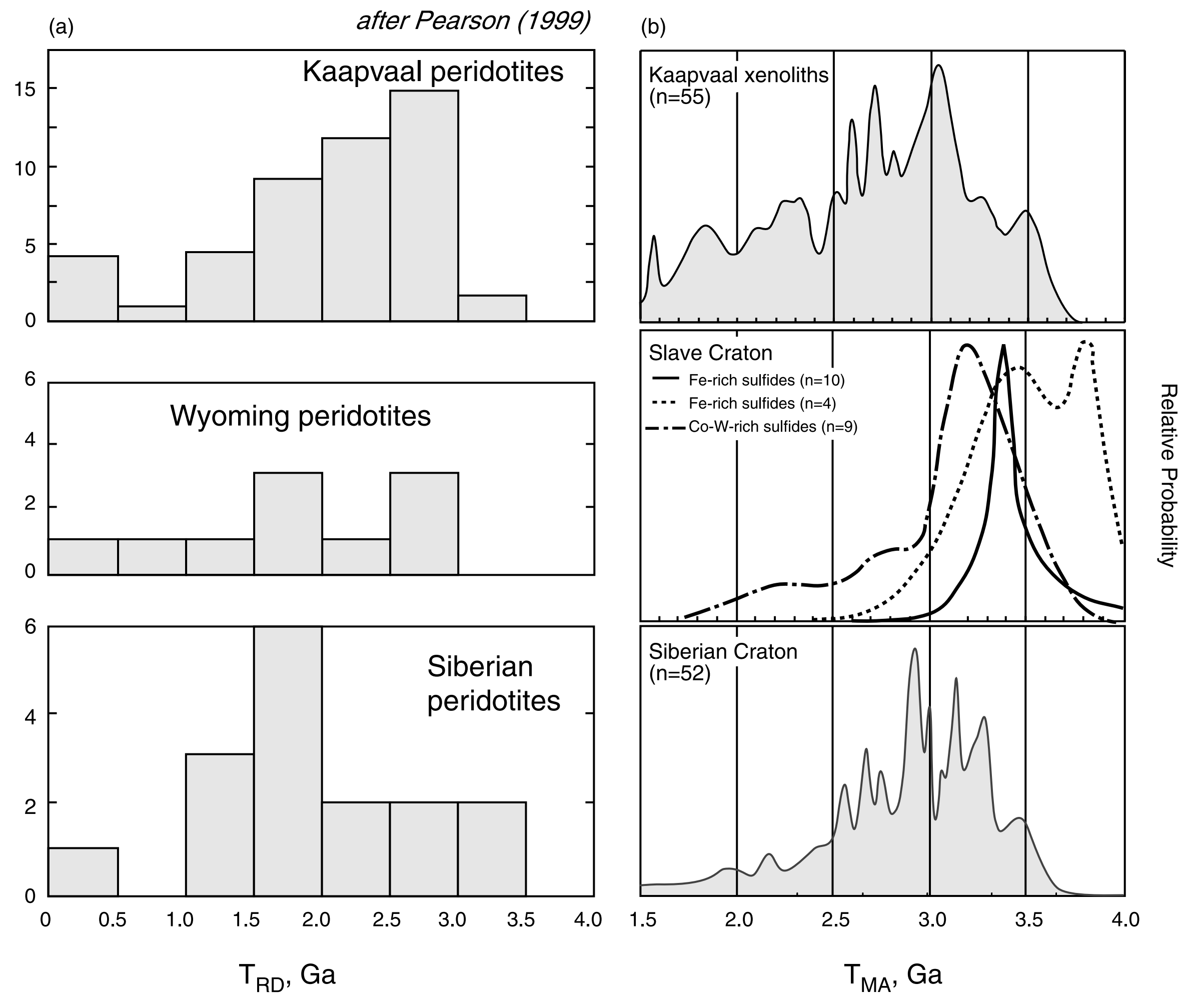

Fig. 12. (a) Histograms of whole-rock Re–Os model ages for three Archon peridotite xenolith suites, (Kaapvaal, Wyoming, Siberia) after Pearson (1999). (b) Cumulative-probability histograms of Re–Os model ages derived by in situ analysis of sulfide phases enclosed in primary silicates. Kaapvaal Craton data from Griffin et al. (unpublished data); Slave Craton data from Aulbach et al. (unpublished data); Siberian Craton data from Griffin et al. (2002a,b). The in situ data include only sulfides with $^{187}Re/^{188}Os \leq 0.07$, implying little disturbance by Re addition and giving little difference between T_{RD} and T_{MA} model ages.

phases, and these rocks generally contain >1 generation of sulfides (Burton et al., 1999; Alard et al., 2000).

In situ analyses of the Re–Os isotopic compositions of sulfides, enclosed in the primary silicate phases of peridotite xenoliths, show a narrower range of depletion ages, and the mean age is pushed back significantly in time (Fig. 12b) compared to the whole-rock data. These model ages probably represent minimum ages for the stabilisation of Archean cratonic mantle; the analysed sulfides may have been added to the depleted mantle after its formation. While a great deal of work remains to be done, the similarity of the data sets suggests that much Archean SCLM formed earlier than ca. 3 Ga. Griffin et al. (2002b) have suggested that beneath Siberia, SCLM formation ended with a major event at ca. 2.9 Ga, which involved the addition of crustal materials (eclogites) to the SCLM.

7. When did subduction begin?

If Archean SCLM had been made by stacking slabs of subducted oceanic crust and mantle, we would expect a significant proportion of eclogites, representing the crustal component of the subduction package, in the Archean SCLM. However, although they are locally abundant, eclogites make up only 2–3% of Archon xenolith suites (Schulze, 1989). It can be argued that the eclogites, because of their high density relative to depleted peridotite, have sunk through the SCLM and disappeared, but this is not a testable hypothesis. There is still controversy about the origin of eclogites in the Archean lithosphere; many are highly magnesian, and may represent the crystallisation of mafic to ultramafic magmas within the lithosphere, rather than the metamorphism of basalts (Milholland and Presnall, 1998; Snyder et al., 1997). A combination of low δ^{18}O in eclogitic phases, low δ^{13}C in diamonds of the eclogitic paragenesis, and a range of δ^{32}S in low-Ni sulfides included in diamonds (Chaussidon et al., 1987; Eldridge et al., 1991) commonly is regarded as evidence of the subduction of surficially altered components to lithospheric depths (but see a dissenting view by Cartigny et al., 1998).

Shirey et al. (2001) summarise Re–Os isotopic data for eclogites and eclogitic diamonds from the Kaapvaal Craton, and conclude that many were formed around 3 Ga, whereas a subsidiary group formed around 0.9–1 Ga. Similarly, Pearson et al. (1995) presented data suggesting that eclogites formed in the Siberian SCLM around 2.9 Ga.

However, eclogites and eclogite-paragenesis diamonds are much more abundant in Proton settings than in Archons (Fig. 13). The great majority of eclogitic diamonds with $\delta^{13}C < -10$ (Fig. 13b) are from Protons, or Archon-margin situations such as the Koffiefontein mine in South Africa or the Slave Craton, where Proterozoic subduction beneath the craton is suggested by seismic reflection studies (Cook et al., 1999). Eclogitic garnets and clinopyroxenes included in diamonds from Protons also show a narrower range of Ca/(Mg + Fe) than those in diamonds from Archons (Fig. 13c), suggesting that they formed over a narrower range of temperature. This might be evidence of metamorphic recrystallisation during subduction, rather than igneous crystallisation.

Shirey et al. (2001) have noted that the Re–Os ages of eclogites from the Kaapvaal Craton are significantly older than most Re–Os ages on the associated peridotites. They suggested that this anomaly may indicate problems with the models used to calculate depletion ages from the peridotites, or that lithospheric stabilisation actually occurred later than subduction. However, as noted above, in situ Re–Os analysis of sulfide inclusions suggests that the whole-rock Re–Os ages on peridotite xenoliths generally represent mixtures of several sulfide generations. In this case, as in the Siberian example (Fig. 12), the true depletion ages of the peridotites are significantly older than indicated by the whole-rock ages, and the eclogites become younger than most of the peridotites. The isotopic data and the change in the nature of eclogitic diamonds from Archon to Proton may indicate that subduction became important only near the end of the Archean, and perhaps contributed more to the construction of the SCLM during Proterozoic time than it did earlier.

8. A preferred model

The data reviewed here lead us to suggest that most Archean SCLM was generated in rising diapirs, with massive melting at 150–250 km depth (Fig. 10;

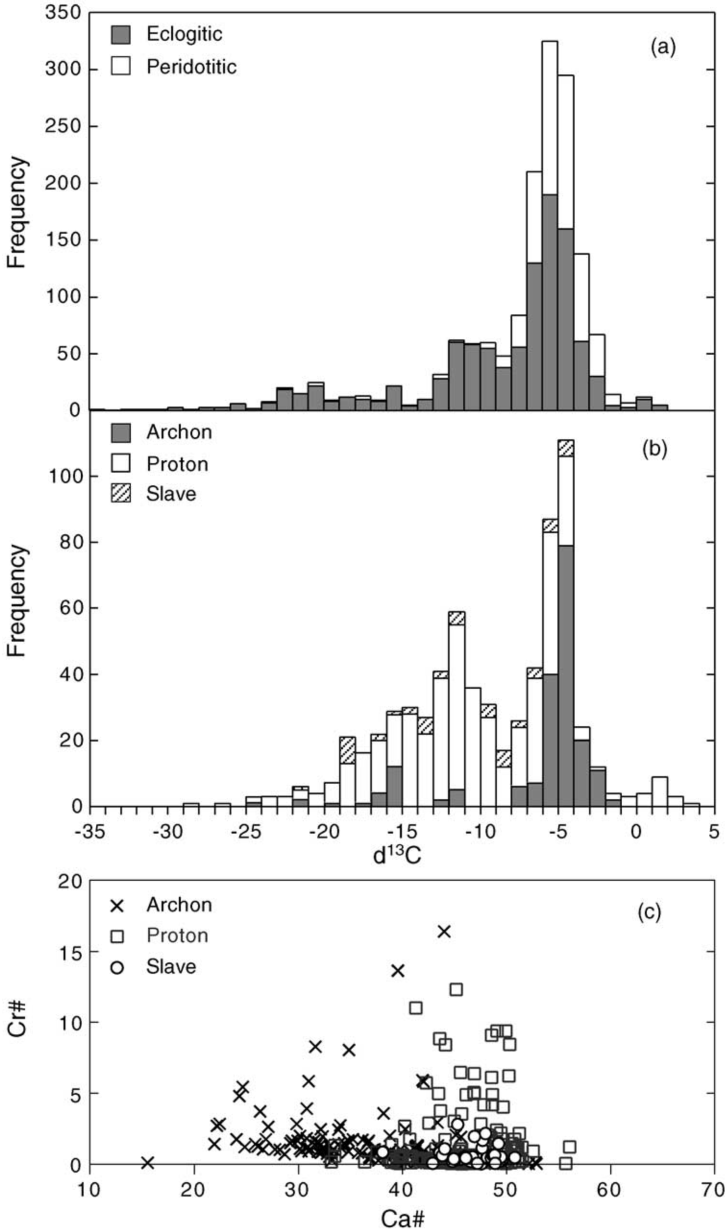

Fig. 13. Data on eclogitic diamonds. (a) Distribution of $\delta^{13}C$ in eclogite- and ultramafic-paragenesis diamonds; (b) distribution of $\delta^{13}C$ in eclogite-paragenesis diamonds from Archons and Protons; (c) Ca# vs. Cr# for eclogitic cpx inclusions in diamonds from Archons and Protons. Most eclogitic diamonds with low $\delta^{13}C$ are from Proton settings, and cpx inclusions in these diamonds reflect a narrower range of temperatures (Ca#) than eclogitic diamonds from Archons.

Herzberg, 1990, 1999; Herzberg and Zhang, 1996). The residues, mixed to some degree with cumulates, would be highly buoyant, and would rise further through the upper mantle to form potential continental nuclei. Although the available Re–Os data (including the in situ data) provide only minimum ages for SCLM formation, it may be significant that SCLM as old as the oldest crust has not yet been found. If major

SCLM formation took place from 3 to 3.5 Ga, as suggested by preliminary in situ Re–Os data (Fig. 12b), the scattered relics of pre-3.5 Ga crust may represent the fortunate bits that were picked up by rising plugs of younger SCLM before they could be recycled: a "life-raft" model of craton formation.

Archean-type SCLM apparently has not been produced since ca. 2.5 Ga; that observation alone suggests that its generation involved a process that no longer operates on any large scale in the Earth. This implies in turn a tectonic regime that was unique to the Archean. The major unidirectional factor in Earth's evolution is its secular cooling, as a consequence of the decay of short-lived radionuclides and the loss of accretional heat, and it is natural to examine the implications of this cooling in the search for behaviour unique to the Archean. Davies (1995) has modelled the behaviour of a two-layered Earth during secular cooling. Models based on a moderate level of heat transfer between lower and upper mantle predict periodic mantle overturns in the Archean, leading to massive melting as adiabatically rising lower mantle passed through the peridotite solidus (Fig. 14).

As Earth cools, this regime is superseded by one with lesser overturns, sparked by plate penetration into the lower mantle, and grades into present plate-tectonic regime with further cooling. The smaller overturns do not result in massive melting. These models provide a mechanism for generating early Archean SCLM through large-scale melting at depth, and predict that this mechanism would cease to operate as Earth cooled. They therefore are consistent with the observations reviewed here, which require

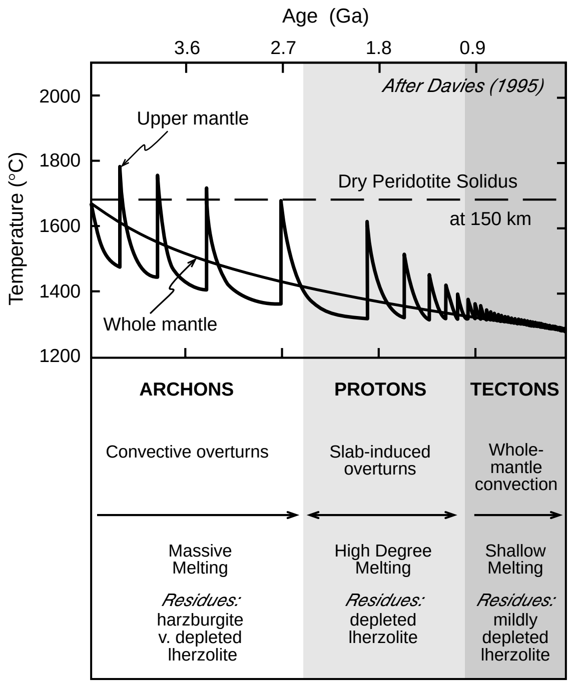

Fig. 14. Model for the thermal evolution of a two-layered Earth, after Davies (1995). This model is based on a moderate level of heat transfer between upper mantle and lower mantle. In an early hot Earth, heat builds up in the lower mantle faster than it can be lost from the upper mantle, leading to periodic convective overturns in which the rising lower mantle passes through the dry peridotite solidus and undergoes large-scale melting at depths ≥150 km. This provides a mechanism for the generation of Archean-type SCLM (cf. Fig. 10), and this mechanism would cease to operate after Archean time due to the secular cooling of Earth.

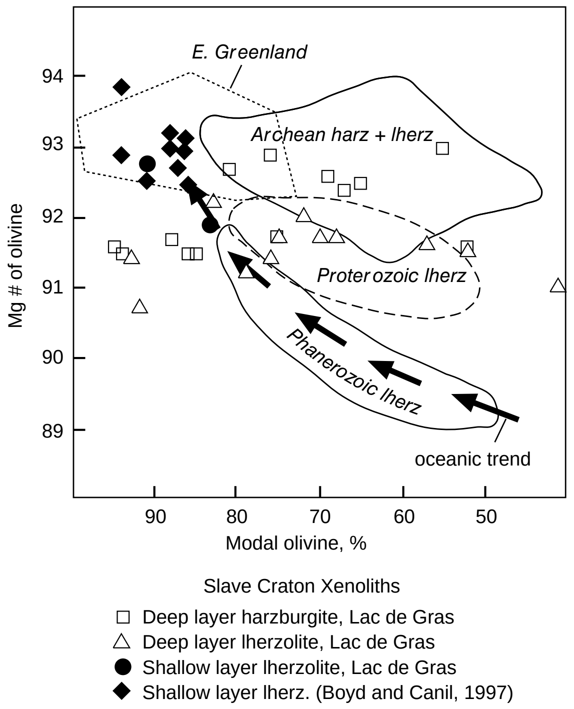

Fig. 15. "Boyd plot" (cf. Fig. 2) showing compositions of Archean xenoliths from the upper and lower layers of the lithosphere beneath the central Slave Craton (Boyd and Canil, 1997; Aulbach et al., unpublished data) and from East Greenland (Bernstein et al., 1998; Hanghøj et al., 2001). Most of these xenoliths are small and the modal analyses must be treated with caution, but it seems clear that the shallow levels of the SCLM in both localities contain rocks similar to the depleted members of some arc-related suites.

a uniquely Archean process involving high-degree melting at depth.

9. A second tectonic regime?

Although our preferred model involves a tectonic regime that was unique to the Archean, a form of plate tectonics may have operated in the Archean as well. Most of our data on Archean SCLM has come from the Kaapvaal and Siberian cratons. However, new data from the Slave Craton and East Greenland suggest that very depleted mantle with high Mg# but low orthopyroxene/olivine, similar to that found in modern arc settings, is present in the shallow parts of some cratons (Fig. 15). In the Slave Craton, ultradepleted garnet and spinel peridotites make up a distinct shallow layer, separated from the underlying more normal Archean SCLM by a sharp boundary at 145 ± 5 km. This more "modern" type of SCLM forms a body of limited areal extent that has been mapped by EM techniques and mantle-petrology studies (Griffin et al., 1999b; Jones et al., 2001). In East Greenland, T estimates (mean $T = 850\,^{\circ}\mathrm{C}$) combined with spinel–lherzolite mineralogy indicate that the depleted material, which has some Re–Os depletion ages as old as 2.6–3.7 Ga, resides at even shallower depths (<65 km; Bernstein et al., 1998; Hanghøj et al., 2001).

Griffin et al. (1999a) have suggested that the shallow ultradepleted layer of the Slave mantle was generated in a collisional setting, and that the deeper layer was added from below as a rising diapir of lower mantle material. The lower mantle origin of the deeper layer is supported by the high proportion of diamonds with lower mantle parageneses in Slave Craton kimberlites (Davies et al., 1999) and the minor-element systematics of sulfide inclusions in olivine and diamonds (Aulbach et al., 2002). The timing of its emplacement may be constrained by a 3.3 Ga Re–Os isochron derived from the sulfide inclusions (Aulbach et al., 2002).

If this scenario is correct, depleted mantle similar to that formed at modern mid-ocean ridges or collisional settings was being generated in Archean time. However, this material is unlikely to be preserved, except in rare cases. The problem is illustrated by a cumulative-density section for typical Phanerozoic mantle (Fig. 8). This sort of mantle, in which Fe is not depleted during melting, is buoyant while hot, but once it cools to a stable conductive geotherm, it is neutrally, or even negatively, buoyant relative to the asthenosphere. It can be delaminated through stress (Houseman and Molnar, 1996; Neil and Houseman,

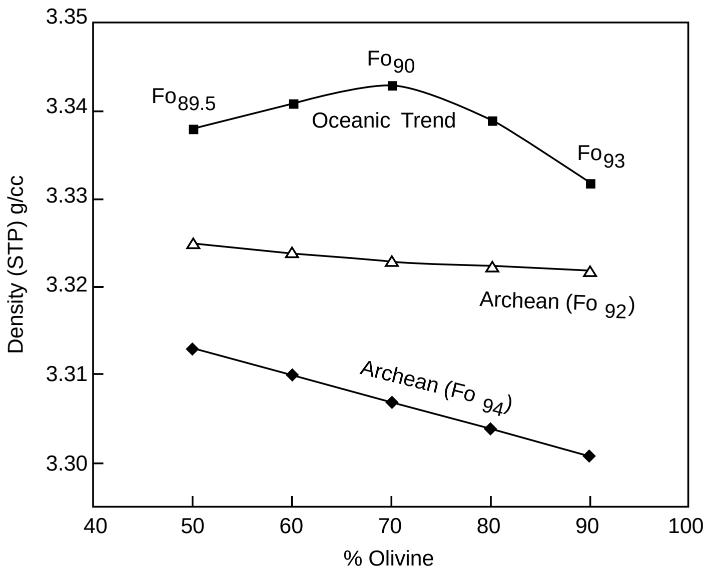

Fig. 16. Density as a function of % olivine, for two Archean SCLM compositions, and Phanerozoic compositions lying along the "oceanic trend" of Boyd (1987) (cf. Fig. 2). In each case the ratios of opx/cpx/gnt are held constant as % olivine increases.

1999) and will be replaced by upwelling of relatively fertile mantle, which will go through the same cycle of cooling, delamination and replacement. More extremely depleted mantle, like that described from East Greenland, will have a slightly lower density than typical Phanerozoic mantle (3.332 g/cm^3 versus 3.342 g/cm^3), but will not achieve the low density of Archean mantle of similar Mg# (3.301 g/cm^3) because olivine is denser than opx of similar Mg# (Fig. 16). This higher density suggests that Archean mantle that resembled modern oceanic or arc-related mantle rarely would survive to be picked up in the xenolith record.

Therefore it is probable that two tectonic regimes operated to produce SCLM in the Archean. One, involving high-degree melting in mantle overturns or massive plumes (Stein and Hofmann, 1994; Davies, 1995), produced most of what we see today as Archean SCLM and probably has not operated since at least 2.5 Ga ago. The other tectonic regime was more similar to the one we recognise from modern tectonic settings, but its products were only preserved where they were extremely depleted, or were picked up on buoyant “life-rafts” of more typically Archean mantle. The rest has been recycled and lost.

10. Conclusions

The unique nature of Archean SCLM implies that the Archean tectonic regime was very different from the modern one; SCLM was being generated by processes that have not operated for at least the last 2.5 Ga of Earth’s history. We suggest that these processes involved high-degree melting at sub-lithospheric depths, and that their products were preserved by their distinctive refractory compositions, buoyancy and rheology. This Archean SCLM has been progressively modified since its formation, and few mantle samples today, even beneath Archean cratons, may represent pristine samples of Archean material.

The observed secular evolution in the composition of the SCLM has been interpreted as reflecting a secular evolution in the processes that generate SCLM (Griffin et al., 1998, 1999d). However, if much Proterozoic SCLM is strongly modified Archean SCLM, preserved by its buoyancy despite metasomatic refertilisation, then Earth may only ever have had two tectonic regimes. One, which we recognise as uniquely “Archean” produced thick, highly depleted volumes of buoyant harzburgites, rising to form the roots of continents. The production of this kind of Archean SCLM probably ended as a result of the secular cooling of Earth. The other, operating concurrently, would be similar to the modern regime, with moderate depletion at spreading centres, subduction, and cyclic delamination and replacement. Evidence of the latter regime during Archean and Proterozoic time would rarely be preserved, as its products would not contribute to the construction of long-lived continental roots except in rare circumstances.

If this two-regime model is correct, the late Archean marks an even bigger change in Earth’s geodynamics than generally thought; it may be when the formation of stable SCLM ended and modern plate tectonics and lithosphere recycling became the dominant regime. The problem for Archean tectonics is to define the uniquely Archean process, to understand its implications for crustal tectonics, and to understand when and why it ceased to operate. It will require more detailed knowledge of the age structure and compositional evolution of SCLM beneath terrains of different tectonothermal age to test this model. New in situ methods of Re–Os analysis (Pearson et al., 2002; Griffin et al., 2002b) will play an important role in this work.

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