Are Lithospheres Forever? Tracking Changes in Subcontinental Lithospheric Mantle Through Time

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ABSTRACT

The lithospheric mantle beneath continents is often the same age as the superjacent crust, but remains less well understood. Analysis based on a large database of xenoliths and xenocrysts shows that mantle domains that stabilized during different geologic eons have distinctly different mean compositions. There is a secular evolution from depleted Mg-rich low-density Archean mantle to more fertile, denser Phanerozoic mantle; the most significant differences are between the Archean and Proterozoic mantle. The compositional variations produce differences in the density and elastic properties of lithospheric mantle of different age. Archean and Proterozoic mantle roots are highly buoyant; they cannot be delaminated but require mechanical disaggregation (lithospheric thinning and/or rifting) and infiltration of upwelling fertile material to be destroyed or transformed. In contrast, Phanerozoic subcontinental lithospheric mantle is denser than the asthenosphere for observed thicknesses (~100 km) and can "delaminate" under stress. The contrasting properties of different mantle domains require lateral contrasts in composition, density, thickness, and seismic response in the present-day subcontinental lithospheric mantle. They 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.

LITHOSPHERE DOMAINS IN TIME AND SPACE

Knowledge of the architecture and evolution of the mantle portion of the continental plates—the subcontinental lithospheric mantle—is critical to understanding the large-scale processes responsible for the development of Earth's continents. Plate tectonicists use a mechanical definition (rigid plates) for the lithosphere, contrasting it with the less rigid asthenosphere. Geochemists consider the subcontinental lithospheric mantle to be a chemically depleted reservoir that is the residue of partial melting of Earth's asthenosphere. Seismologists define it using velocities and extrapolated densities and consider its base to coincide with the top of a low-velocity zone in tectonically young regions, and others use heat flow and magnetotelluric data to define it as a thermal boundary layer. These various definitions may coincide (or not) and give rise to a persistent and fascinating controversy over the physical nature of the lithosphere and asthenosphere and the boundary zone between them.

The subcontinental lithospheric mantle is isolated from the convecting mantle and thus tends to resist homogenization over time. At the lithosphere-asthenosphere boundary, the temperatures of the lithosphere and the uppermost asthenosphere coincide, and the greater buoyancy and viscosity of the lithosphere are important in maintaining its mechanical integrity. This emphasizes a thermal and rheological distinction between lithosphere and asthenosphere that also coincides well with seismic observations and with the geochemical signatures that are used in this paper to help define the location and character of the lithosphere-asthenosphere boundary.

Four-dimensional lithosphere mapping is a methodology that integrates petrological, geochemical, geophysical, and tectonic information to map the composition of the subcontinental lithospheric mantle (Fig. 1) and the location of its important boundaries through time (O'Reilly and Griffin, 1996). Volcanic rocks (basalts, lamproites, kimberlites) carry fragments of the subcontinental lithospheric mantle to the surface as xenoliths and xenocrysts (e.g., garnet, chromite, and diamond). Xenoliths can be used to recognize mantle rock types and processes, and to measure physical properties (e.g., elastic, electric, magnetic properties, density, and heat production). Volcanic episodes of different ages in one region can provide this information for different time slices, corresponding to the age of the host volcanism. Geophysical data can be used to extend the geological information laterally by matching geophysical signatures with mapped subcontinental lithospheric mantle sections.

This methodology can provide some important constraints on fundamental questions about Earth's geological evolution. These include the compositional structure of subcontinental lithospheric mantle formed at different times, the lateral variability of subcontinental lithospheric mantle composition and its effects on tectonics, and the extent to which lithospheric mantle can be recycled into the convecting mantle or irreversibly differentiated from it.

TOOLS DEVELOPED FOR FOUR-DIMENSIONAL LITHOSPHERE MAPPING

Paleogeotherms

Heat drives all Earth processes and the thermal state of the lithosphere affects its thickness and density (Morgan, 1984; Lachenbruch and Morgan, 1990). Geotherms are a plot of temperature variation with depth at a given time and place. Empirical paleogeotherms can be constructed using temperatures and pressures calculated from mineral assemblages in mantle xenoliths and can provide a framework for mapping the geochemical structure of the subcontinental lithospheric mantle. Unfortunately, xenoliths from which pressures (depths) of origin can be calculated (e.g., with coexisting orthopyroxene and garnet) are limited in their geographic distribution. Nevertheless, single-element thermometers and barometers (e.g., Ni and Cr in garnet; Ryan et al., 1996) based on element partitioning between garnet and mantle olivine and pyroxene allow the derivation of paleogeotherms from the more abundant suites of garnet xenocrysts.

We have constructed, or compiled from published data, paleogeotherms for more than 300 localities worldwide. These paleogeotherms represent the temperature variation with depth at the time of volcanic eruption; they are typically low beneath cratonic areas with Archean crust, higher beneath Proterozoic cratons, and still higher beneath Phanerozoic mobile belts (Fig. 2). In areas of active basaltic volcanism, geotherms are generally high and strongly convex, consistent with advective heat transport by magmas and underplating of basaltic rocks in the upper part of the subcontinental lithospheric mantle (O'Reilly and Griffin, 1985; O'Reilly et al., 1997). These empirical geotherms are preferred over models for the thermal state of the lithosphere that are based on the downward extrapolation of surface heat flow (e.g., Pollack and Chapman, 1977) because input parameters such as thermal conductivity and heat production are poorly constrained and variable, both with depth and laterally, in the crust.

The Crust-Mantle Boundary and Lithosphere-Asthenosphere Boundary

Once a geotherm is inferred, the many xenolith samples for which temperature (*T*) can be calculated are projected to the geotherm to estimate their depth of origin. In the resulting sections, the minimum depth of abundant ultramafic rocks (mantle peridotite) commonly coincides with the maximum depth of mafic granulite xenoliths and can be used to estimate the depth of the crust-mantle boundary (O'Reilly and Griffin, 1996). We approximate the depth to the geochemical lithosphere-asthenosphere boundary by the maximum depth from which low-Y (<10 ppm) garnets, characteristic of depleted lithosphere (Griffin et al., 1999; references therein), are derived; it typically coincides with temperatures of 1250–1300 °C (Fig. 3). Deeper garnets have high Y + Ti + Zr, interpreted as the signature of asthenosphere-related metasomatism. The depth of the lithosphere-asthenosphere boundary

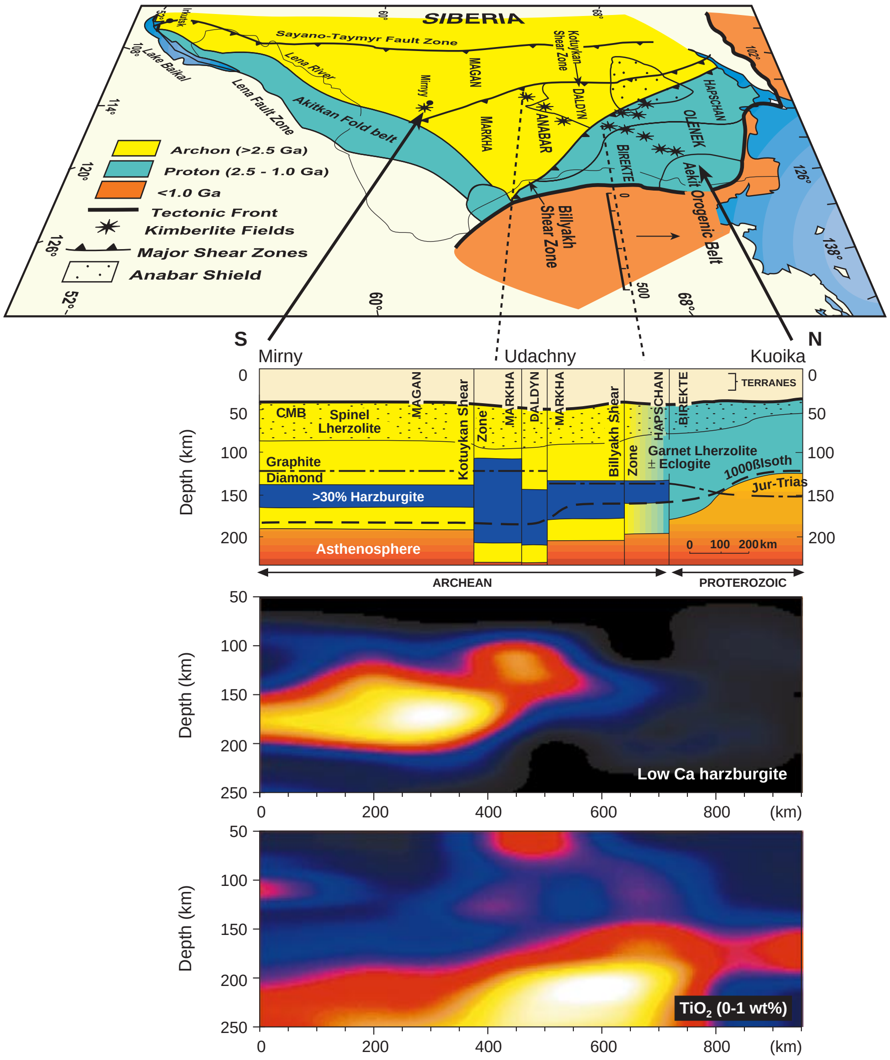

Figure 1. Example of lithosphere mapping across eastern Siberia, using xenoliths and xenocrysts (after Griffin et al., 1998a). Top view shows crustal terranes. Second view shows lithosphere sections mapped from xenoliths and xenocrysts in kimberlites (stars), delineating rock type distribution, the lithosphere-asthenosphere boundary and the 1000 °C isotherm (dashed). Next view shows distribution of low Ca-harzburgite, confined to Archean terranes. Lower view shows lithosphere-asthenosphere boundary reflected in Ti contents of garnets (higher in the asthenosphere). CMB—crust-mantle boundary.

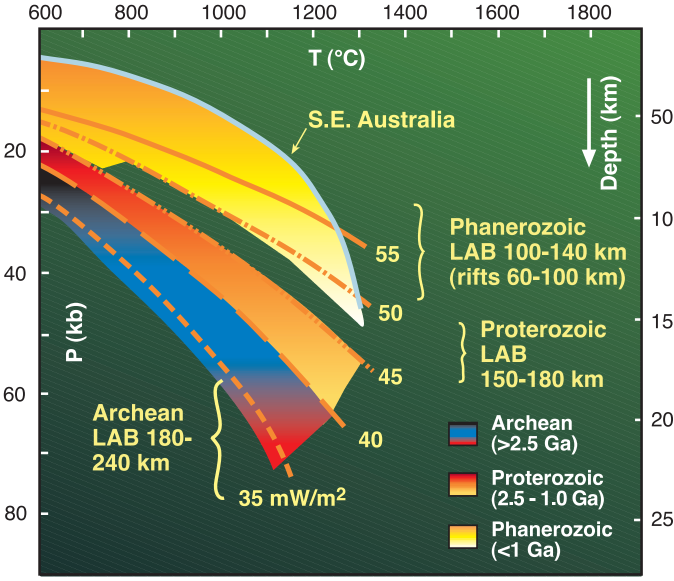

Figure 2. Range of *P-T* conditions and depths to lithosphere-asthenosphere boundary (LAB), commonly derived using xenolith and xenocryst suites entrained in volcanic rocks that penetrate crust of different tectonothermal age.

mapped in this way varies broadly with tectonic setting, being deepest (250–180 km) beneath undisturbed cratonic areas, and shallowest beneath Phanerozoic mobile belts or rifts (Fig. 2).

Chemical Tomography

Referring equilibration temperatures for xenoliths or xenocrysts to an inferred geotherm puts the geochemical information from each sample in a spatial context, so we can map the vertical distribution of rock types and styles of metasomatic alteration. The resulting lithological and/or geochemical columns (Fig. 4) provide one-dimensional maps, similar to drill-hole logs through individual subcontinental lithospheric mantle sections.

With multiple sampling points, mantle stratigraphy can be mapped and followed laterally, producing 2-dimensional and 3-dimensional images of the subcontinental lithospheric mantle that can be correlated with geophysical data and surface geology. On the Siberian Platform, Paleozoic to Mesozoic kimberlites (Fig. 1) provide mantle samples along a 1000 km traverse across Archean and Proterozoic terranes. Garnet data from more than 50 kimberlites along this trend define domains with distinctive mantle stratigraphy; these domains coincide with mapped crustal terranes (Griffin et al., 1998a; Fig. 1). This implies that the terrane boundaries are translithospheric and that each terrane carried its own lithospheric root during the assembly of the craton.

In the Slave craton of northern Canada, such mapping has revealed a distinctive two-layered lithospheric architecture beneath the Lac de Gras area (Fig. 4). The upper part of the subcontinental lithospheric mantle (to 140–150 km) consists of extremely depleted harzburgite, while the lower part (150–220 km) is significantly less depleted, though distinctively Archean in nature. The lateral extent of this structure (>14,000 km^2) has been mapped using concentrates from kimberlites and exploration samples (Griffin et al., 1998b), and is seen in magnetotelluric data (Jones et al., 2001). We have interpreted the lower layer as accreted plume material, consistent with the presence of abundant lower-mantle inclusions in diamonds from the region (Davies et al., 1999).

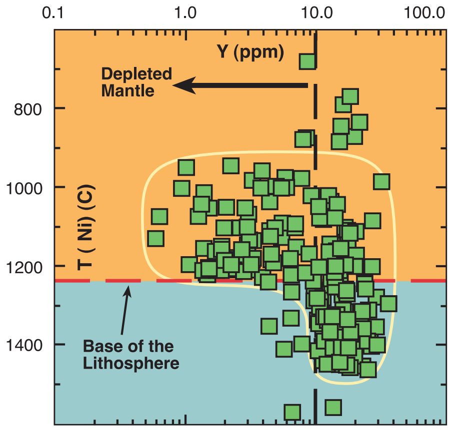

Figure 3. Geochemical definition of lithosphere-asthenosphere boundary beneath Shandong Province, China, using low-Y values characteristic of some garnets from depleted lithosphere, plotted against nickel temperature (T_{Ni}).

In the eastern Sino-Korean craton, volcanic eruptions separated by ca 400 Ma allow the lithospheric mapping to be extended to the fourth dimension (time). In Ordovician time, the mantle was thick, cool, diamondiferous, and typically Archean in composition (Fig. 5, A and B); it probably had survived for at least 2 Ga. Tertiary lamprophyres and basalts that erupted through the same terranes sampled only a thin (<120 km), hot and fertile lithosphere (Fig. 5; Griffin et al., 1998c).

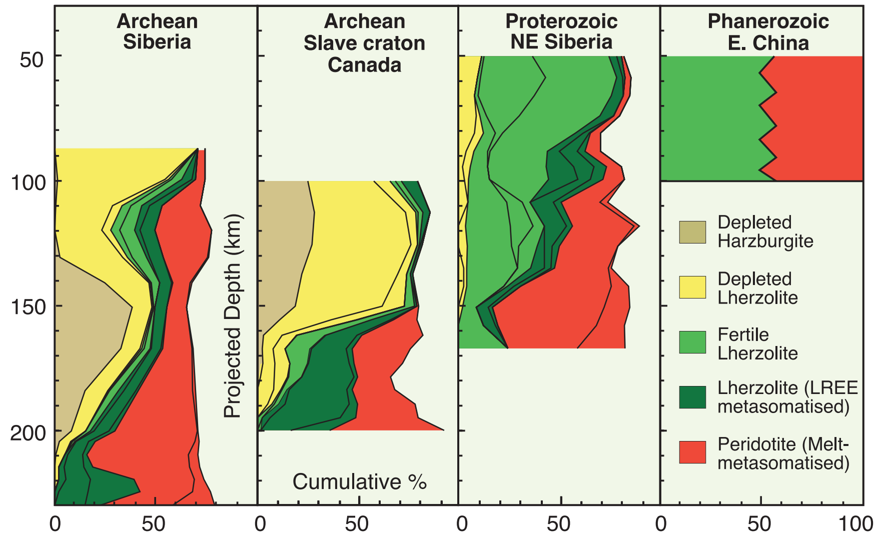

Figure 4. Chemical tomography sections showing relative abundances of different rock types in depth slices through lithospheric mantle. Sections are constructed by plotting data from garnet xenocrysts versus depth derived by projection of T_{Ni} for each grain to an inferred paleogeotherm (Griffin et al., 1999). Plotted garnet compositional types correspond only to xenolith types named in key, hence rock-type mix does not sum to 100% in each horizontal layer. LREE—light rare earth element.

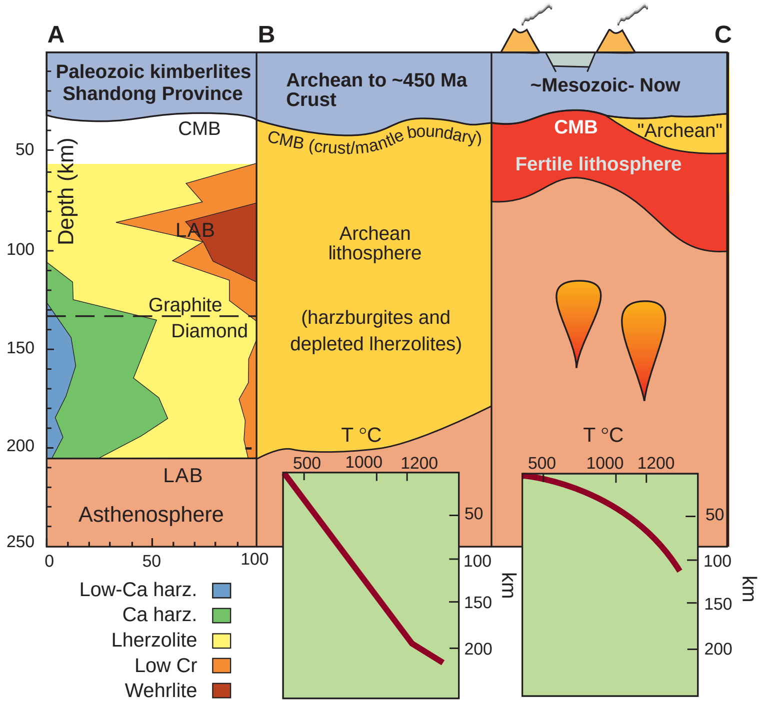

Figure 5. Lithosphere evolution in eastern part of Sino-Korean craton (after Griffin et al., 1998c). See text for discussion. A. Subcontinental lithospheric mantle stratigraphy derived from garnet data. B. Ordovician paleogeotherm derived from xenocrysts in kimberlites with Archean mantle thickness. C. Subcontinental lithospheric mantle section and geotherm derived from geophysical data and xenoliths in Tertiary basalts. CMB—crust-mantle boundary; LAB—lithosphere-asthenosphere boundary.

Secular Variation in Lithosphere Composition

Understanding the relationship of mantle lithosphere to its superjacent crust is important for understanding how continents are stabilized and whether plate tectonic and crustal growth processes have changed through time. The Cr_2O_3 content of xenolith garnets is a function of the Al_2O_3 content of their host rocks, which in turn is well correlated with other key major and minor elements (Griffin et al., 1998d, 1999). We have used these relationships to calculate the mean composition of the mantle from the Cr_2O_3 contents of more than 16,000 garnet xenocrysts from volcanic rocks worldwide. Figure 6 compares the calculated subcontinental lithospheric mantle compositions with the mean composition of xenolith suites for selected sections.

Average subcontinental lithospheric mantle composition is broadly correlated with the tectonothermal age of the crust penetrated by the volcanic rocks; younger continental crust is underlain by less depleted subcontinental lithospheric mantle (Griffin et al., 1998d, 1999). The data indicate that newly formed subcontinental lithospheric mantle has become progressively less depleted from Archean, through Proterozoic to Phanerozoic time, in terms of Al and Ca contents (and in Mg# and Fe/Al). Garnet peridotite xenoliths from young extensional areas (e.g., eastern China; Xu et al., 2000) are geochemically similar to primitive mantle, indicating very low degrees of melt depletion. Archean subcontinental lithospheric mantle also is distinctive in containing significant proportions of very depleted clinopyroxene-free peridotites (subcalcic harzburgites), emphasizing the marked compositional differences between Archean subcontinental lithospheric mantle and that beneath younger terranes (Figs. 1 and 4; Griffin et al., 1999). These observations expand Boyd's (1989, 1997) original recognition of a fundamental distinction between Archean cratonic subcontinental lithospheric mantle, represented by xenoliths in African and Siberian kimberlites, and Phanerozoic circumcratonic mantle, represented by xenoliths in intraplate basalts.

The broad correlation between subcontinental lithospheric mantle composition and crustal age is strong evidence that crustal volumes and their underlying lithospheric mantle formed at least quasi-contemporaneously, and can remain linked for periods of eons. The Archean-Proterozoic boundary represents a major change in the nature of lithosphere-forming processes, and a more gradual secular change has continued into the Phanerozoic. This secular evolution in process must be driven by global-scale secular changes in Earth; the most obvious of these is the secular cooling of Earth, which can produce gross changes in mantle convection styles (e.g., Davies, 1995).

The Density of Subcontinental Lithospheric Mantle Domains and Lithospheric Columns

Continents are long-lived records of geologic events in large part because of their long-term buoyancy, and it is important to understand the mantle contribution to this buoyancy structure. The relative proportions of olivine to garnet + clinopyroxene, and Mg#, are the main determinants of mantle

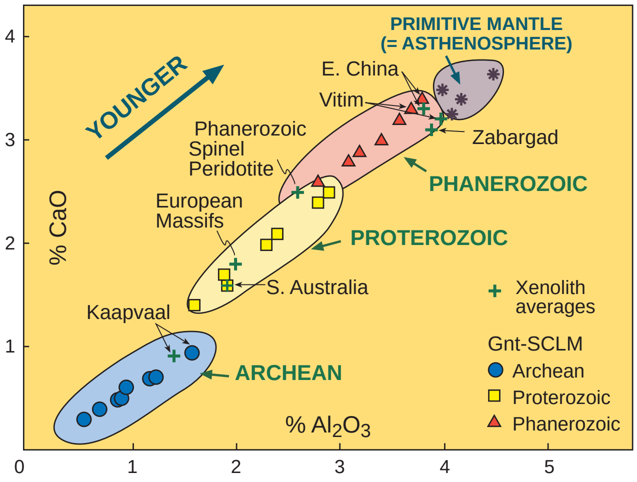

Figure 6. CaO-Al_2O_3 plot showing the range of mantle compositions for individual sections (matched with ages of the youngest tectonothermal events in the overlying crust) calculated using data from garnet xenocryst suites, with xenolith averages for comparison. SCLM—subcontinental lithospheric mantle; Gnt—garnet.

density. Mean mineral compositions for subcontinental lithospheric mantle of different ages have been derived from correlations between mineral and whole-rock compositions in xenoliths and then used, with interpolations of end-member mineral density data (Smyth and McCormick, 1995), to calculate the mean modes and densities of Archean, Proterozoic, and Phanerozoic subcontinental lithospheric mantle (Fig. 7; Poudjom Djomani et al., 2001). Mean density (at standard temperature and pressure) increases significantly from Archean (3.31 ± 0.016 Mg m^{-3}) to Proterozoic (3.34 ± 0.02 Mg m^{-3}) to Phanerozoic (3.36 ± 0.02 Mg m^{-3}) subcontinental lithospheric mantle.

Variations in mantle density with depth are controlled by the geotherm and the elastic behavior of the minerals at each temperature (T) and pressure (P). In Phanerozoic subcontinental lithospheric mantle, the change from spinel- to garnet-peridotite is also significant because of the higher geothermal regime and the T-dependence of the depth to the spinel-garnet transition. We used the range of geotherms characteristic of Archean, Proterozoic, and Phanerozoic subcontinental lithospheric mantle (Fig. 2) to estimate T at each depth; thermal expansion coefficients and bulk moduli for mineral end members were taken from Fei (1995) and Knittle (1995).

The cumulative density of different subcontinental lithospheric mantle sections was calculated as a function of their thickness and compared with the density of the asthenosphere (approximated as primitive mantle [McDonough and Sun, 1995] with a potential temperature of 1300 °C and an adiabat of 0.5 °C/km) at the lithosphere-asthenosphere boundary (Fig. 8). A typical Archean subcontinental lithospheric mantle section thicker than ~60 km is significantly buoyant; a 200 km section is 2.5% less dense than the asthenosphere at the lithosphere-asthenosphere boundary. Proterozoic subcontinental lithospheric mantle sections thicker than ~125 km are buoyant relative to the asthenosphere, while Phanerozoic subcontinental lithospheric mantle sections with advective geotherms decrease in density with depth and are very buoyant relative to the asthenosphere. However, Phanerozoic sections that have cooled to typical conductive geotherms are buoyant relative to the asthenosphere only if they are >110–120 km thick, which is unusual (Fig. 2).

Calculation of V_p and V_s

Our chemical tomography models of the subcontinental lithospheric mantle are compatible with observed seismic properties beneath different continents. Differences in density, coupled with the typical differences in geotherms between provinces of different tectonothermal age, result in different seismic velocities in different mantle volumes. At 25 °C, the compressional wave velocity (V_p) and shear wave velocity (V_s) of Archean subcontinental lithospheric mantle are higher than those of Phanerozoic subcontinental lithospheric mantle by about 0.4% and 1.4%, respectively (Fig. 7); the compositional differences account for ~25% of the worldwide range observed by seismic tomography. When typical geotherms (Fig. 2) are used to derive temperatures at 100 km depth for different tectonic settings, the calculated V_p and V_s beneath Archean cratons are higher by ~5% than those beneath Phanerozoic mobile belts (Fig. 7), corresponding to the ranges in velocity commonly seen by seismic tomography.

LITHOSPHERE PRESERVATION AND DESTRUCTION

The physical property data derived above provide important constraints on

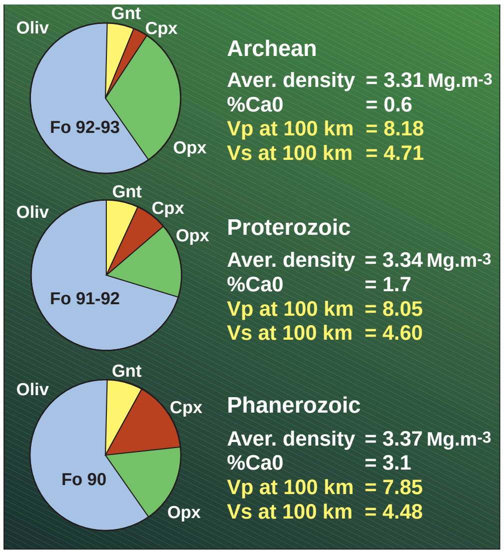

Figure 7. Modal and physical property data for lithospheric mantle of different ages (see text). Densities calculated at standard temperature and pressure, shear wave velocity (V_s) and compressional wave velocity (V_p) in km/s at 100 km (see text). Opx—orthopyroxene; Cpx—clinopyroxene; Gnt—garnet; Fo—forsterite; Oliv—olivine.

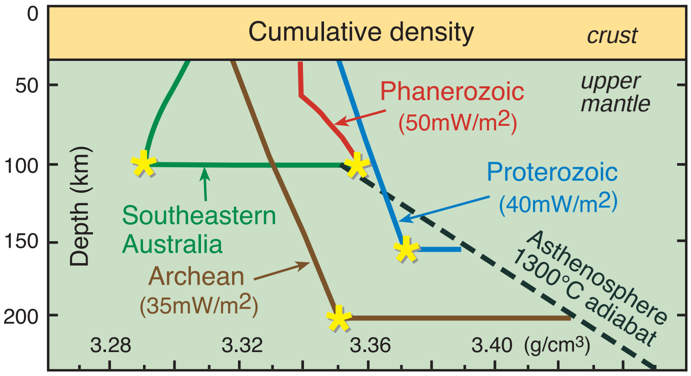

Figure 8. Cumulative density of typical subcontinental lithospheric mantle sections of different age. Dashed line shows asthenosphere density (potential T=1300 ºC). Yellow stars mark lithosphere-asthenosphere boundary on each lithosphere profile.

tectonic models that invoke the delamination and recycling of the subcontinental lithospheric mantle. Buoyant Archean lithosphere is unlikely to be delaminated through gravitational forces alone. Tectonic stacking, often invoked as a mechanism for delamination, will simply increase the relative buoyancy of the Archean subcontinental lithospheric mantle section, because the density of the asthenosphere increases faster (as the lithosphere-asthenosphere boundary is depressed) than that of the thickened subcontinental lithospheric mantle. This buoyancy, when combined with the refractory nature of Archean subcontinental lithospheric mantle, offers a simple explanation for the thickness and longevity of Archean lithospheric keels (Jordan, 1988). It also explains the common higher elevation of Archean terranes (e.g., Murray et al., 1997) although this is not seen in long-wavelength analyses of the geoid, probably due to the scale of data interpretation (Richards and Hager, 1988). The buoyancy of Archean subcontinental lithospheric mantle contributes significantly to the preservation of the overlying crust, protecting it from subduction and recycling (a "life-raft" model of craton formation). Conversely, crust formed in tectonic settings that did not involve the production of such keels would have been lost; this suggests that our record of Archean crustal processes may be significantly biased (also see Morgan, 1985).

If Archean subcontinental lithospheric mantle is too buoyant to be removed by gravitational forces and too depleted to be dispersed by melting, is it there forever? Changes tracked in the lithospheric mantle in several regions show that Archean mantle can be transformed. In the case of the eastern Sino-Korean craton (Fig. 5), detailed seismic tomography (Yuan, 1996) shows an upper mantle made up of vertically and laterally extensive blocks of high-velocity (probably Archean) mantle embedded in a matrix of lower velocity (presumably hot Phanerozoic) mantle, beneath a pronounced low-velocity zone. Yuan (1996) suggests that replacement of the Archean subcontinental lithospheric mantle has involved rifting, with contemporaneous upwelling of fertile asthenospheric material along breaks in the Archean root, leading to a dispersal and dilution of the Archean subcontinental lithospheric mantle, rather than its removal or delamination.

Any Proterozoic section more than ~150–180 km thick is moderately buoyant (Fig. 8), consistent with the preservation of lithosphere with Proterozoic Re-Os ages beneath Proterozoic cratons (e.g., Carlson et al., 1999; Handler et al., 1997) although a decrease in the geotherm below those modeled here might destabilize a section as thick as 150 km.

Typical Phanerozoic subcontinental lithospheric mantle sections (~110–120 km) are buoyant under conditions of high geothermal gradient (e.g., during their formation). However, they are at best neutrally buoyant after cooling to typical stable conductive geotherms and vulnerable to Rayleigh-Taylor instability (Houseman and Molnar, 1997) and will tend to delaminate and sink. Asthenospheric material welling up into the resulting "space" will cool to form a new, little-depleted subcontinental lithospheric mantle; this will raise geotherms and may cause melting in the overlying crust (Griffin et al., 1998d). As this new subcontinental lithospheric mantle cools down, it in turn will become unstable, and start the cycle again. This cyclic delamination may explain the ubiquitous presence of fertile xenolith suites in young basalts erupted through Paleozoic-Mesozoic orogenic belts (Griffin et al., 1999). If this model is correct, it suggests a fundamental difference between Phanerozoic and Archean tectonics, linked to differences in the processes involved in subcontinental lithospheric mantle production, and these processes ultimately must be reflected in changes in the production, preservation, and destruction of continental crust through time.

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DIALOGUE

Heard a Good Talk Lately?

Rob Van der Voo, *Chair, Annual Program Committee*

The answer is "yes," I hope. And chances are that one of those good talks was at a recent GSA meeting in Denver or Reno. Oh, you did not attend? You may be missing something. Let me explain some of the developments in programming of the national meetings.

There now are three ways in which sessions during the national meeting can be planned, programmed, and presented. We have had two years of experience with this new scheme, and it is apparent that members are generally pleased with the outcome. The three types of sessions are called Pardee Keynote Symposia, Topical Sessions, and Discipline Sessions. In addition, Associated Societies can organize a few symposia before the meeting (e.g., on Sunday), and there are short courses as well as lunchtime hot-topic sessions.

Only one Pardee Keynote Symposium is going on at any given time for a maximum of eight half-day Pardees during the meeting. All speakers are invited, and meeting organizers can request a budget of up to $2,000 from the Joseph T. Pardee Memorial Fund. Anyone can propose a Pardee Keynote Symposium. Given the limited number of Pardees and the inherent competition for their special status, it is important that proposals be carefully evaluated. This is done in early January by a panel of Joint Technical Program Committee (JTPC) members, rotating from year to year to represent seven of the Divisions and Associated Societies. I have attended a few Pardee Keynotes (regretting that I could not listen in on more). At one of them I was really excited about the science, and at the other I came away impressed with the stature of the speakers and their portrayal of important developments in their fields. Pardee proposals not selected can be modified to Topical Session proposals.

The Topical Session proposals (some 80–150 each year, typically) are also evaluated by the JTPC representatives. Most are approved, unless they seem to counter the mission of GSA. Unusual formats—such as those with more invited speakers than the automatically allowed number of four, those that combine oral and poster presentations, panel debates, and special ways of encouraging audience participation—must be specifically approved in advance.

Discipline sessions are filled with all the other papers not submitted to Pardees or Topical Sessions. These are grouped according to the categories that authors are asked to indicate on the abstract form. These sessions continue to be the main entrées on the menu of the meeting, but don't expect just meat and potatoes! You'll discover aubergines, paté de foie gras, mahi-mahi, and exquisite pastas. Oh well, you get the point.

So, what has really changed? Not the very important role of the Divisions and Associated Societies, who can (and do) propose as many topical sessions as they desire, although they no longer have a completely free hand in inviting unlimited numbers of speakers. Not the menu presented to the attendees, although it has become richer in content and strives to become more international. Not the audience profile, still ranging from the white-haired to undergraduates and from K–12 teachers to resource company researchers. No, what has changed is that all categories in the diverse membership have become more empowered. Everyone can (and should) send in proposals, while also participating in their Divisions and Associated Societies and helping to nominate or serve as JTPC representatives. As President Sharon Mosher wrote in this column in January: Participate, volunteer, and contribute suggestions—this is our society!