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Evolution of the Precambrian Lithosphere: Seismological and geochemical constraints

Raymond J. Durrheim[1]
Geophysics Department, Witwatersrand University, Johannesburg, South Africa

Walter D. Mooney
U.S. Geological Survey, Menlo Park, California

Abstract. Several recent models of crustal evolution are based on the belief that the thickness of the continental crust is proportional to its age, with ancient crust being the thickest. A worldwide review of seismic structure contradicts this belief and falsifies these models, at least for the Archean. Proterozoic crust has a thickness of 40-55 km and a substantial high-velocity (>7 km/s) layer at its base, while Archean crust is only 27-40 km thick (except at the site of younger rifts and collisional boundaries) and lacks the basal high-velocity layer. Seismology also provides evidence that the lithosphere is thickest beneath Archean cratons, while diamond ages show that this lithospheric keel must have already existed in the Archean. Geochemical data also indicate significant differences between Archean and Proterozoic lithosphere. Major and trace element studies of sediments show a change in upper crustal composition between the Archean and Proterozoic. Archean rocks are depleted in Si and K and enriched in Na, Ca, and Mg. There is also a marked change in the Eu/Eu^* ratio. Mantle xenoliths and continental flood basalts show that the mantle lithosphere beneath Archean crust is ultradepleted in FeO compared to that beneath post-Archean crust. The secular change in the crust-forming process is attributed to a decline in mantle temperature, leading to a change in the composition of the lithospheric mantle. The higher temperature of the Archean mantle led to the eruption of komatiitic lavas, producing a refractory lithospheric mantle which is ultradepleted in FeO and volatiles. The resultant lithospheric keel is intrinsically less dense than the surrounding mantle and thus not susceptible to delamination. It was sufficiently thick and cool for diamonds to form during the Archean. In contrast, Proterozoic crust developed above fertile mantle. The eruption of continental flood basalts and underplating of basaltic sills is attributed to subsequent heating and partial melting of the lithospheric mantle. Consequently, Proterozoic crust is thickened and has a high-velocity basal layer.

Introduction

It is widely believed that the thickness and mean velocity of the continental crust, with the exception of young orogens, are proportional to its age [e.g., *Meissner*, 1986; *Meissner and Wever*, 1989; *Mueller and Ansorge*, 1989; *Jarchow and Thompson*, 1989]. This belief has formed the basis for several recent models of lithospheric evolution. For example, *Nelson* [1991] suggests that any piece of continental crust, given long enough residence time on the surface of Earth, will be episodically underplated by basaltic magmas, establishing new deeper Mohos. The end result is a relatively thick shield-type crust with the lower one third to one half of the crust composed of a composite gabbro underplate exhibiting a P wave velocity greater than 7 km/s. *Pavlenkova* [1987] suggests crustal thickening by the transformation of mantle material during crustal cooling. The coldest crust (and usually the oldest) should thus be the thickest. *Meissner* [1986] notes that younger crust tends to be about 30 km thick, with a relatively low average velocity that is indicative of a high degree of crustal differentiation. His favored processes leading to thinner younger crust involve either multiple differentiation transferring light material from the lower crust upward, with the ultramafic cumulates becoming incorporated in the upper mantle, or steady depletion and modification of the original mantle by quasi-permanent extraction of material to create the crust, with the hotter and rather undepleted Archean mantle producing a greater volume of a more primitive (i.e., mafic) crustal composition.

In a worldwide review of seismic velocity-depth functions from Precambrian provinces, *Durrheim and Mooney* [1991, 1992] have shown that Archean crust (which has not been exposed to severe deformation or intrusion since cratonization) is significantly thinner than Proterozoic crust and lacks a high-velocity (>7 km/s) basal layer (Figure 1). These trends were noted previously for the Precambrian crust of Australia [*Drummond and Collins*, 1986; *Drummond*, 1988]. Two recent refraction studies of Archean provinces (the Nyanza Craton of East Africa and southwest Greenland) are consistent with these trends. Reflection profiles from the Abitibi province of Canada

[1]Now at Mining Technology Division, CSIR, Johannesburg, South Africa.

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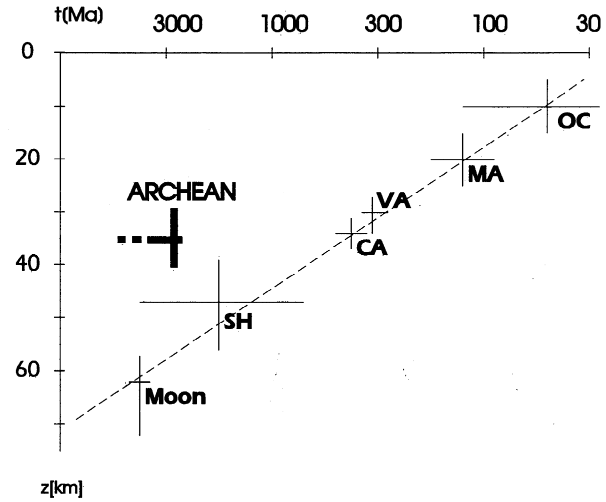

Figure 1. Crustal thickness versus age. Redrawn from *Meissner* [1986] together with worldwide compilation for Archean provinces from *Durrheim and Mooney* [1991, 1992]. OB, orogenic belts; OC, oceanic crust; MA, passive margins; VA, Variscan areas; CA, Caledonian areas; SH, shields. Bold lines indicate the thickness of Archean crust excluding areas affected by major Proterozoic tectonism. Note that the Archean crustal thicknesses are significantly different from the dashed line showing the thickness versus log(age) relationship proposed by *Meissner* [1986].

show a crustal thickness of 35-40 km [*Ludden et al.*, 1993], and profiles in the Archean greenstone terraines of Australia reveal a crustal thickness of only 30-32 km [*Goleby et al.*, 1992]. These observations are not in accord with the above models of crustal evolution, at least for the Archean. The view that Archean crust is thicker than Proterozoic crust is based largely on the Karelian Province of the Baltic Shield. It has a crustal thickness of 40-55 km, in contrast to the predominantly thin (about 30 km) Phanerozoic crust of western Europe (Figure 1). Although this part of the Baltic Shield yields Archean isotopic ages, it appears to have been thickened by Proterozoic tectonic events [*Gaál and Gorbatshev*, 1987; *BABEL Working Group*, 1991].

Geochemical analyses of sediments, mantle xenoliths and continental flood basalts have been interpreted to show a clear difference between Archean and Proterozoic lithosphere [*Taylor and McLennan*, 1985; *Hawkesworth et al.*, 1990; *Menzies*, 1990]. In this paper we use the seismological constraints together with heat flow, geochemical, and xenolith data to develop a consistent model of lithospheric evolution during the Precambrian.

Seismological Observations and Rock Type

Seismological investigations of the lithosphere provide measurements (averaged over large volumes of rock) of parameters such as the *P* and *S* wave velocity, anisotropy, and attenuation. Laboratory measurements at temperatures and pressures representative of the lower crust and upper mantle make it possible to interpret the in situ measurements in terms of rock composition, mineralogy, metamorphic grade, and fabric. This enables seismological observations to be synthesized with geochemical and xenolith data.

Crust

The relationship between compressional wave velocity *Vp* and rock type at temperatures and pressures representative of the crust and upper mantle is shown in Figure 2. Increases in temperature and pressure have opposite effects on the seismic velocity. At depths greater than 5 km and normal geothermal gradients, the effects are approximately equal. Two generalizations can be made: seismic velocity increases as silica content decreases; and seismic velocity increases as metamorphic grade increases, especially when garnets are formed. However, *Vp* does not uniquely define a rock type. For example, a layer with a velocity of 7 km/s (usually only found in the lower crust) could consist of gabbro, anorthosite, rocks of dioritic composition at granulite-grade metamorphic facies, or a mixture of different rock types. Other evidence must be considered in order to deduce the likely composition of the high-velocity layer (7.0-7.6 km/s) often found at the base of the crust: (1) lower crustal xenoliths are typically basic; (2) many exposed sections of the lower crust are dominated by basic granulite; (3) a silica-rich granulite lower crust (with a granodiorite upper crust) produces a bulk crustal composition with too much K, U, and Th to be consistent with the heat flow data; and (4) the lower crustal layer often has a steep velocity gradient which sometimes grades smoothly into the upper mantle [*Meissner*, 1986; *Fountain and Christensen*, 1989; *Taylor and McLennan*, 1985]. It is concluded that the high-velocity layer at the base of the crust, in most cases, consists of high-grade metamorphic rocks with intermediate to mafic compositions.

Coincident measurement of the shear wave velocity *Vs* can be used to reduce the ambiguity regarding mineralogical composition, as the ratio *Vp*/*Vs* is an indicator of SiO_2 content independent of the metamorphic grade. However, interpretation of *Vp*/*Vs* is not straightforward because *Vp*/*Vs* is also sensitive to variations in crack density, pore fluid pressure, and

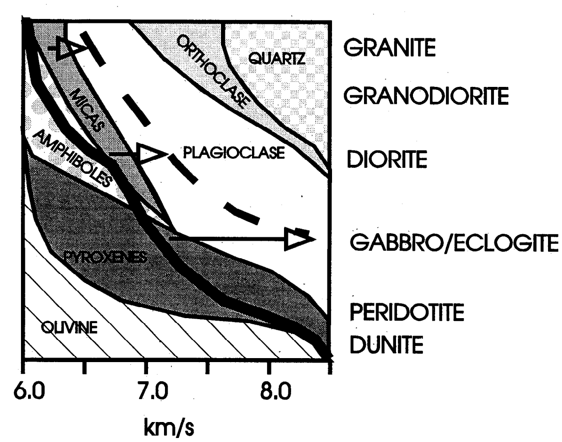

Figure 2. *P* wave velocity versus rock type. The solid curve indicates the generalized relationship between compressional wave velocity and crustal and upper mantle rock type in unmetamorphosed rocks at depths exceeding 5 km [*Christensen*, 1965]. The arrows indicate the increase in velocity due to increasing metamorphic grade, largely due to the formation of garnets [*Green*, 1970; *Green and Lambert*, 1965; *Ringwood and Green*, 1966]. The tips of the arrows indicate the velocity expected when the amount of garnet is the maximum amount expected.

temperature [*Alekseev et al.*, 1988]. Calculations of Vp/Vs may also be inappropriate in the presence of significant anisotropy [*Fountain and Christensen*, 1989].

Upper Mantle

The compressional wave velocity Vp in the upper mantle ranges from 7.6-8.6 km/s. The observed upper mantle velocity is a better mineralogical than chemical discriminant. For example, the velocities of olivine, garnet, and pyroxene show little variation in velocity for reasonable changes in FeO/MgO ratios, but olivine and garnet have higher velocities than pyroxenes [*Anderson*, 1990]. Variations in velocity in the upper mantle may also be caused by changes in melt content, crystal orientation, and dislocation density [*Anderson*, 1990].

Eclogite and peridotite have similar values of Vp, in spite of chemical differences. However, Vp/Vs increases with the garnet, clinopyroxene, or FeO content, enabling eclogitic rocks to be distinguished from peridotitic rocks [*Anderson*, 1990]. The olivine in peridotite is also strongly anisotropic. There is now abundant evidence that the upper 200 km of the mantle are markedly anisotropic and that this is primarily due to the preferred alignment of the olivine crystals, thereby favoring a peridotitic upper mantle composition [*Morris et al.*, 1969; *Montagner and Tanimoto*, 1991].

Apart from the seismic velocity a few kilometers below the Moho (P_n), relatively few detailed seismic velocity-depth functions for the upper mantle beneath Precambrian crust have been published, with the exception of the territory of the former USSR [e.g., *Pavlenkova and Yegorkin*, 1983]. The refraction method requires ultralong profiles (>2000 km) and very powerful sources (earthquakes, or nuclear or large chemical explosions) to penetrate to these depths, and the derived velocity models have poor lateral resolution, making it difficult to resolve the deep structure of adjacent Archean and Proterozoic provinces. Single-station methods (e.g., travel time residuals, receiver functions) offer superior lateral resolution, but the vertical resolution of the velocity-depth function is not as well constrained. However, recent determinations of the upper mantle structure of Precambrian mantle using a two-station method indicate greater lithospheric thickness beneath Archean provinces (240 km to more than 300 km) than Proterozoic provinces (180-240 km) [*Beghoul and Mereu*, 1992].

Seismological Studies of the Precambrian Lithosphere

Global trends in the seismological structure of the lithosphere provide vital constraints on evolutionary models. A world map of geologic age provinces is shown in Figure 3, together with the locations of the deep seismic soundings used in the search for a secular change in crustal structure. In order to compare the seismic velocity structure from different provinces

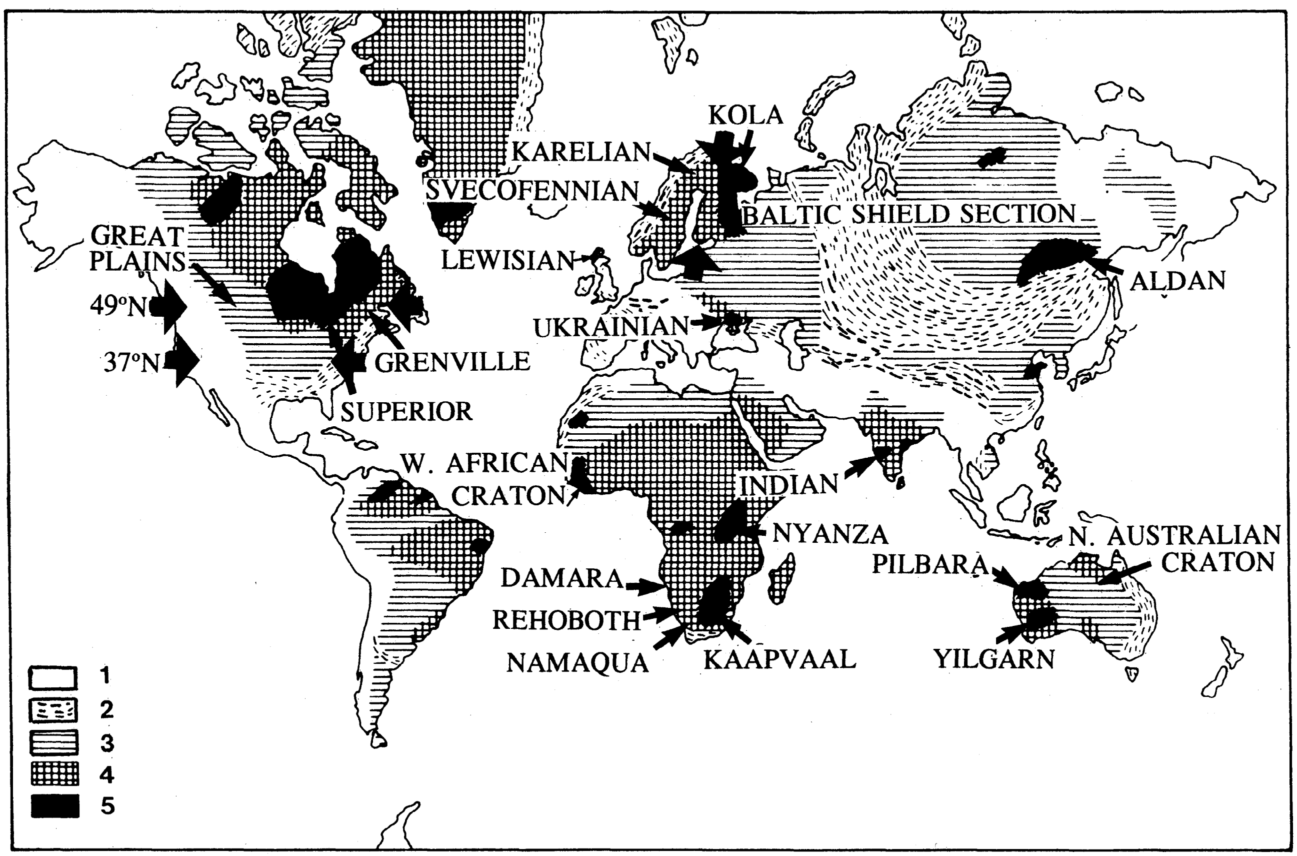

Figure 3. World map showing geological age provinces [after *Miyashiro et al.*, 1982] and the localities of Archean and Proterozoic provinces whose seismic structure is discussed in the text. The position of the sections across the midcontinent of North America (Figure 4) and the Baltic Shield (Figure 7) are indicated by large arrows. Key for age provinces: (1) Mesozoic and Cenozoic orogenic belts, (2) Paleozoic orogenic belts, (3) Proterozoic platforms, (4) Proterozoic shields, and (5) Archean shields.

worldwide, we have selected two parameters: crustal thickness and thickness of the basal high-velocity (7.0-7.6 km/s) layer. We take the base of the crust to be the point where the seismic velocity exceeds 7.6 km/s. The velocity gradient at the base of Archean crust (i.e., at the crust/mantle transition) has been estimated to be about 0.4 ±0.2 s^{-1} in several recent experiments, while the gradient beneath Proterozoic crust is generally smaller [e.g., *Drummond*, 1988]. Thus the definition of Moho at a velocity of 8.0 km/s rather than 7.6 km/s corresponds to a depth difference of about 1 km for Archean crust, which will not materially affect our conclusions.

North America and Greenland

The Superior Province of North America is probably the Archean craton that has been subjected to the most intensive seismic investigation. A representative velocity-depth function, which is the average of 11 Superior Province models, places Moho at a depth of 36 km [*Braile*, 1989]. The crustal structure across the midcontinent of North America (Figure 4) clearly shows that the crust of Superior Province, with the exception of the Midcontinent rift, is thinner than the crust of adjacent Proterozoic provinces and lacks a high-velocity basal layer. The results of 450 km of seismic reflection profiling across the late Archean crust of the southwestern Superior Province show the crustal thickness to be relatively constant at 35-40 km, with the thinnest crust adjacent to the Grenville Front [*Ludden et al.*, 1993].

The generalization of relatively thin Archean crust in the Superior Province should be treated with some caution. For example, the crust beneath the Kapuskasing Structural Zone reaches a thickness of 53 km and has a lower crust with velocities exceeding 7 km/s [*Boland and Ellis*, 1989]. The zone is interpreted to be an upthrust cross section of upper and middle Archean crust [*Percival and Card*, 1985; *Fountain et al.*, 1990] and thus is not representative of stable Archean crust. The Minnesota River Gneiss Terrane on the southern margin of the Superior Province has also been found to have a large crustal thickness (49 km) and high average crustal velocity [*Boyd et al.*, 1992].

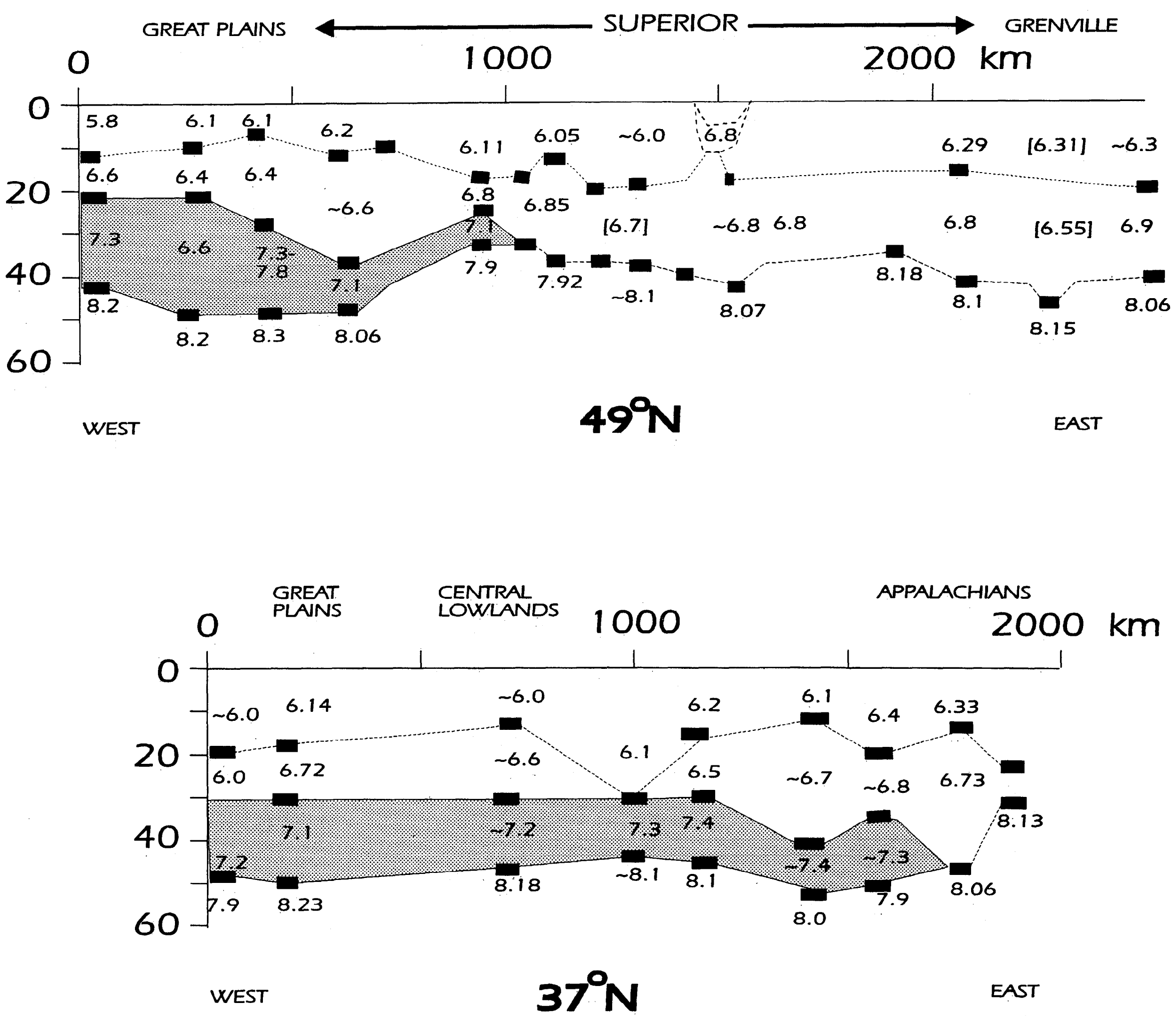

Figure 4. Sections through the midcontinent of North America along latitude 49°N and 37°N [after *Braile*, 1989]. Numbers in the crustal model are compressional wave velocities in kilometers per second. Values enclosed in brackets indicate averages where complicated velocity structure or gradients have been interpreted. Short, heavy lines indicate interpreted depths from seismic profiles that intersect the cross section. Dashed lines show interpreted correlations. The high-velocity ($Vp > 7$ km/s) lower crust has been shaded.

An extensive seismic wide-angle and vertical incidence experiment conducted over Archean crust in southwest Greenland [*Gohl et al.*, 1991] found that the velocities exceed 6 km/s at depths below 4-6 km, followed by a low gradient to the bottom of the crust. The results are strongly affected by the complicated three-dimensional structures of an Archean crust in proximity to the passive continental margin. The Moho depth is found to be 30-40 km, with the greatest depths in the north and some evidence for shoreward thickening of the crust. On two (of the five) velocity-depth functions a major discontinuity appears between 6 and 8 km above the Moho. High seismic velocities found below this discontinuity are attributed to mafic material, possibly accreted during the opening of the Labrador Sea. A similar study some 40 km to the south straddles the Archean/Proterozoic boundary and finds the crust to be 30-35 km thick but without evidence for a high-velocity lower crustal layer [*Chian and Louden*, 1992].

The Wyoming Province has a crustal thickness of 45-50 km [*Mooney and Braile*, 1989]. Although some Archean ages are obtained, the Wyoming Province was involved in three Proterozoic orogenies [*Hoffman*, 1989]. *Silver and Chan* [1988, p. 38] comment that the Wyoming craton "is primarily Proterozoic in age, or at least has been subject to extensive reworking in the Proterozoic".

Representative velocity-depth functions for the Proterozoic provinces adjacent to the Superior Province have been compiled by *Mooney and Braile* [1989]. The Proterozoic provinces generally have a thickness in excess of 40 km with a well-developed basal high-velocity layer (Figure 4). The seismic observation of thinner Archean crust has also been substantiated by gravity modeling across the boundaries between structural provinces. Gravity profiles across the Superior-Grenville and Slave-Churchill boundaries both show the Proterozoic crust to be consistently thicker and slightly denser than the crust of the adjacent Archean province [*Gibb and Thomas*, 1976].

Several seismic studies have investigated the upper mantle of North America. A set of 42 *S* wave station anomalies show a progressive increase in vertical travel time outward from the Canadian Shield [*Wickens and Buchbinder*, 1980]. The travel time anomaly is in accord with a relatively thick and cold high-velocity lithospheric root beneath the Archean craton. A high-resolution study of the *S* wave velocity structure of the upper mantle of the North American Shield has been carried out using waveforms and travel times of *S* and *SS* phases [*Grand and Helmberger*, 1984]. The derived model (designated SNA) does not distinguish between the Archean and Proterozoic provinces, although comparison with the Basin and Range Province (model TNA) shows that *S* wave velocities within the shield are relatively high to depths of 165 km, with the velocity-depth profiles converging at a depth of 400 km. *Grand* [1987] inverted the *S* and *SS* travel times, and found that anomalously fast *S* wave velocities in the depth range 100-300 km coincide with the surface extent of the Archean Superior and Churchill provinces. The major features of the *P* wave velocity structure of the Canadian Shield (model designated S25 [*LeFevre and Helmberger*, 1989]) are similar to the *S* wave model, displaying a high-velocity lid about 180 km in thickness above a low-velocity zone. The thickness of the lithosphere has also been determined by the analysis of *P* wave arrival times using a two-station method by *Beghoul and Mereu* [1992]. The thickness of the mantle lid for the Archean Canadian Shield is 240-300 km, while the Proterozoic Canadian Platform and the Grenville Province have thicknesses of 180-240 km and 180-220 km, respectively (Figure 8).

Measurements of shear wave splitting beneath the Superior and Slave Provinces of the Canadian Shield have been interpreted to indicate that the lithosphere is 200-250 km thick [*Silver and Chan*, 1988]. A close association has been found between the fast anisotropic direction and the dominant geological fabric, suggesting that the anisotropy is due to a fossil strain associated with the last major orogenic episode which occurred during the Archean [*Silver and Chan*, 1988, 1991]. The existence of a well-developed mantle root in the Archean argues against models that propose continued thermal evolution of the lithospheric mantle beneath Archean cratons or models that advocate significant crustal growth by underplating since the Archean; rather the data would suggest that the root was rapidly formed by orogenic episodes at the end of the Archean. *Silver and Chan* [1988] suggest that the orogenic episode may even have contributed to the strengthening of the lithosphere by the strain hardening of the relatively cold mantle.

Africa

The Kaapvaal Craton, Limpopo Belt, and Zimbabwe Craton form the Archean nucleus of southern Africa. The Kaapvaal Craton has a thickness of about 36 km (Figure 5a), as determined by several experiments which have used tremors induced by deep-level gold mining as the seismic energy source [*Durrheim and Green*, 1992]. The Limpopo Belt and Zimbabwe Craton lie to the north of the Kaapvaal Craton. The crustal thickness ranges from about 30 km in the center of the Limpopo Belt to 40 km within the Zimbabwe Craton. These

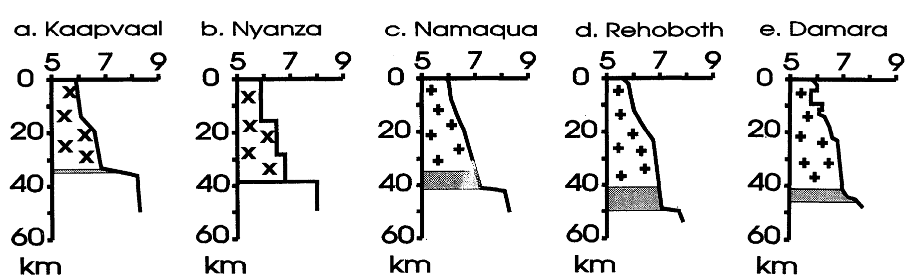

Figure 5. Representative velocity-depth functions for Precambrian provinces in Africa. Archean and Proterozoic crust is indicated by crosses and pluses, respectively. The high-velocity layer at the base of the crust (7.0-7.6 km/s) is shaded. (a) Kaapvaal Craton [*Durrheim and Green*, 1992], (b) Nyanza Craton [*Krisp Working Party*, 1991], (c) Namaqua Province [*Green and Durrheim*, 1990], (d) Rehoboth Province, and (e) Damara Province [*Green*, 1983].

estimates of crustal thickness have been derived from observations of tremors at regional distances, timed blasts from open pit mines, and gravity measurements [*Gwavava et al.*, 1992; *Durrheim et al.*, 1992]. No detailed velocity functions are available for the Limpopo Belt or Zimbabwe Craton.

The Kaapvaal Craton is rimmed to the south and southwest by the Proterozoic Namaqua Province. A seismic refraction investigation of the Namaqualand Metamorphic Complex [*Green and Durrheim*, 1990] found that the lower crust consists of a substantial proportion of intermediate velocity (6.6-6.9 km/s) rocks, with Moho at a depth of 42 km (Figure 5c). The basement rocks of the Rehoboth Province of Namibia are concealed by Late Proterozoic to Mesozoic platform cover but are thought to be Proterozoic in age [*Hartnady et al.*, 1985]. The seismic velocity reaches 7.6 km/s at a depth of 47 km (Figure 5d [*Green*, 1983]). The Namaqua and Rehoboth Provinces are rimmed by the Pan-African (670-530 Ma) Damara Province. In the central zone of the Damara Orogen in Namibia the crust-mantle boundary is found to be a transition zone of variable width at a depth of 47 km (Figure 5e [*Green*, 1983]). Gravity profiles across the boundary between the Archean Kaapvaal Craton and the Proterozoic Namaqua Province confirm that the crust of the Archean province is thinner and less dense [*De Beer and Meyer*, 1984].

Modeling of the P_{nl} phase (i.e., the long-period P_n and shear-coupled *P* (*PL*) mode body wave at regional ranges) of two Zambian earthquakes has yielded *P* wave velocity structures for the upper mantle of the Archean shield (Zimbabwe and Kaapvaal Craton and Limpopo Belt) and the Late Proterozoic Damara Belt [*Clouser and Langston*, 1990]. A positive velocity gradient is found to exist in the upper mantle. The upper mantle beneath the Proterozoic belt has a smaller velocity gradient and higher attenuation than beneath the Archean shield. The minimum depth of any low-velocity zone beneath the Archean and Proterozoic regions is 170 km and 150 km, respectively [*Clouser and Langston*, 1990]. Lithospheric thicknesses determined by teleseismic body wave delay times are in accord with these estimates [*Fairhead and Reeves*, 1977]. The seismic structure is interpreted to indicate that a thick and cool lithospheric root exists beneath the Archean cratons [*Clouser and Langston*, 1990].

Waveform inversion has been applied to *S* wave and surface wave data on a profile stretching across the Kaapvaal Craton/Namaqua Province boundary [*Cichowicz and Green*, 1992]. The study shows that there is a strong correspondence between tectonic province and upper mantle *S* wave velocity. The Kaapvaal Craton has relatively low velocities (mean of 4.3 km/s) for the crust and uppermost mantle down to 80 km depth. Beneath this a root of relatively high *S* wave velocity extends to a depth of 220 km, with a low-velocity zone below.

The eastern part of Archean Nyanza craton of East Africa was traversed by one profile of the Kenya Rift International Seismic Project (KRISP) [*KRISP Working Party*, 1991]. Interpretation shows a crustal thickness of 37 km and the absence of a high velocity (>7 km/s) layer at the base of the crust (Figure 5b). The West African Craton has been stable since 2000 Ma and is composed of both Archean and early Proterozoic provinces. It is surrounded by a Pan-African domain which resulted from collisional tectonic processes around 600 Ma. Teleseismic travel time residuals beneath the West African Craton are strongly negative (*Dorbath and Dorbath* [1984], cited by *Lesquer and Vasseur* [1992]; and *Briden et al.* [1981]). Gravity data show a positive isostatic anomaly over Archean provinces, a near zero anomaly over the early Proterozoic provinces and southern Pan-African domain, and a negative anomaly over the northern Pan-African domain. These long-wavelength isostatic anomalies are interpreted to indicate changes in mantle density due to temperature differences [*Lesquer and Vasseur*, 1992]. These observations are consistent with the West African craton having a thick and cold lithospheric keel.

Australia

The crust and upper mantle structure of the Precambrian areas of Australia has been reviewed by *Drummond* [1988]. The Archean cratons (Yilgarn and Pilbara Blocks) have a two-layered crust 25-35 km thick, with observed lower crustal velocities in the range 6.8-7.2 km/s (Figures 6a and 6b). The Proterozoic North Australian Craton has a 45-50 km thick crust, with velocities below 25 km usually greater than 7.0 km/s (Figure 6c). Recent reflection seismic profiling in the Archean greenstone terraines shows a crustal thickness of 30-32 km [*Goleby et al.*, 1992]. The area underlain by Precambrian rocks is characterized by negative teleseismic travel time residuals, indicating a thick, cold lithospheric keel [*Drummond et al.*, 1988].

The analysis of *P* wave arrivals at distances between 2° and 30° using a two-station method [*Beghoul and Mereu*, 1992] has shown that the thickness of the mantle lid beneath the Pilbara and Yilgarn Blocks is in excess of 300 km; while the Proterozoic NE Australian Craton has a thickness of 180-220 km (Figure 8). Recordings of earthquakes and large explosions at regional distances have been used to deduce the upper mantle *P* and *S* wave velocity structure of beneath the Precambrian regions of western and central Australia [*Bowman and Kennett*, 1990, 1993]. A 205-km-thick lid is found to lie over a low-velocity zone. As the rays mostly turn beneath the Proterozoic platform, this velocity model is consistent with the results of *Beghoul and Mereu* [1992]. The Phanerozoic regions of eastern Australia have a low-velocity zone for both *P* and *S* waves between 120 and 190 km depth [*Drummond*, 1988].

Eurasia

In Europe the crustal age decreases, broadly speaking, from Archean in the north to Cenozoic in the south. The Baltic Shield is composed of the Kola Nucleus and the Karelian and Svecofennian Provinces. The crustal thickness of the Archean Kola Nucleus ranges from 30 to 43 km with a mean value of 35 km [*Sollugub et al.*, 1973; *Luosto et al.*, 1990]. The Kola

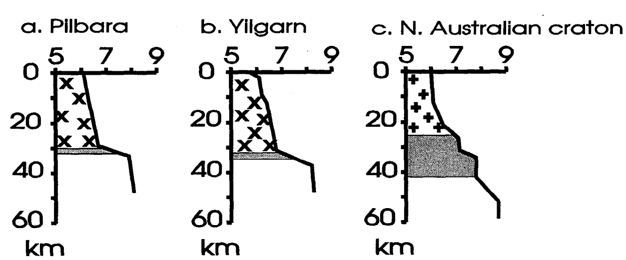

Figure 6. Representative velocity-depth functions for Precambrian provinces of Australia. Archean and Proterozoic crust is indicated by crosses and pluses, respectively. The high-velocity layer at the base of the crust (7.0-7.6 km/s) is shaded: (a) Pilbara Block, (b) Yilgarn Block, and (c) North Australian Craton [*Drummond*, 1988].

Nucleus is bounded to the south by the Karelian Province, which has a crustal thickness of 45-55 km and a substantial proportion (20-30%) of rocks with a velocity >7 km/s [*Lund*, 1987]. The Karelian Province has an Archean isotopic crustal age but was affected by Proterozoic tectonic events. Evidence for this is provided both by geological mapping, which has identified sutures and thrust planes of Proterozoic age within the Baltic Shield [*Gaál and Gorbatschev*, 1987]; the interpretation of high quality seismic refraction profiles which show a stack of crustal slices thrust from the south to the north [*Olsen and Lund*, 1986]; and reflection seismic profiles across the Baltic and Bothnian Seas [*BABEL Working Group*, 1991]. The Proterozoic Svecofennian Province ranges in thickness from 55 km in the north to 35 km in the south, and the Proterozoic East European Platform has crustal thicknesses in the range of 45-50 km [*Mueller and Ansorge*, 1989].

A crustal section from the Archean Kola Nucleus to the Proterozoic East European platform has been compiled by *Beloussov and Pavlenkova* [1991] using the results of several long-range refraction profiles. The section, reproduced in Figure 7, shows that the Archean crust is 30-40 km thick, while the Proterozoic crust is 40-50 km thick and has a basal high velocity layer.

A structural map of the Moho within the Archean Ukrainian Shield shows the crustal thickness to range from 30 to 55 km. Thick crust corresponds to early Proterozoic geosynclinal areas, while regions where the Moho depth is less than 40 km correspond to median massifs and ancient platform areas [*Sollugub et al.*, 1973]. A reinterpretation of one record section on the Ukrainian Shield confirms the crustal thickness of 36 km [*Jentsch*, 1979].

Refraction and reflection experiments show that the Archean Lewisian Province of northwest Scotland has a crustal thickness of about 30 km [*Snyder*, 1991]. While this thickness agrees with the pattern of thin Archean crust, it should be noted that this province is situated on a continental margin and has a small areal extent. It has also been demonstrated that the Lewisian Province has experienced substantial extension during the Phanerozoic [*Cheadle et al.*, 1987; *Reston*, 1990].

A representative velocity-depth model for the Archean Indian Shield was derived from near-refraction and wide-angle reflections along a 600-km profile and shows Moho at a depth of 40 km [*Kaila et al.*, 1979]. Inspection of the entire section shows that the depth of the reflections interpreted to be Moho range from 33 to 45 km, with an average depth of about 37 km.

The *P* wave velocity structure of the upper mantle beneath northwestern Eurasia has been determined from records of underground nuclear explosions in the former USSR [*Given and Helmberger*, 1980]. The travel paths for most of the sources lies largely beneath the stable continental region (Baltic Shield and continental shelf). The *P* wave velocity model (designated K8) shows a high-velocity lid, with a low-velocity zone at a depth of 150-200 km. The velocity model for central Eurasia (designated CE200) derived in a recent study using broadband three-component *P* waveforms from underground nuclear blasts [*Goldstein et al.*, 1992] is similar to model K8. The seismic velocity structure of the upper mantle of northwestern and central Eurasia resembles that of western North America (model TNA) of *Grand and Helmberger* [1984]. The thickness of the mantle lid of the Archean Aldan Shield of Siberia has been determined by *Beghoul and Mereu* [1992] to be 260-300 km (Figure 8).

Heat Flow Studies of Precambrian Provinces

Heat flow studies place an important constraint on lithospheric evolution models, particularly those models that maintain that crustal growth has occurred by a general cooling of the lithosphere, accompanied by a transformation of mantle rocks [*Pavlenkova*, 1987]. An excellent correlation has been found to exist between seismic velocities in the uppermost mantle (P_n) and the predicted Moho temperatures [*Black and Braile*, 1982]. In regions where the upper mantle temperature is high, the P_n velocity is typically 7.7-7.9 km/s, while in cold regions the P_n velocity may be as high as 8.3 km/s.

The mean heat flow in the Superior Province of North America is 41 mW/m^2, while the values in the adjacent Great Plains and Central Lowlands physiographic provinces are 66 and 59 mW/m^2, respectively [*Morgan and Gosnold*, 1989]. The mean heat flow in the Grenville Province is the same as that of the Superior Province [*Pinet et al.*, 1991].

The heat flow in the interior of the Kaapvaal-Limpopo-Zimbabwe craton is typically about 40 mW/m^2 but increases to about 60 mW/m^2 at the boundary between the Archean cratons and the surrounding Proterozoic mobile belts and reaches about 70 mW/m^2 within the mobile belts. *Ballard and Pollack* [1987] attribute this contrast in heat flow to the combined effects of differences in crustal heat production and the diversion of mantle heat flow by a cratonic root extending to a depth of 200-400 km. The heat flow in the Archean Nyanza craton and the adjacent Proterozoic Mozambique Belt is about 34 and 47 mW/m^2, respectively, showing increasing heat flow away from the center of the Archean cratons [*Nyblade et al.*, 1990]. The Archean and early Proterozoic provinces forming the West African Craton have a surface heat flow which ranges from 20 to 60 mW/m^2, with an average of about 40 mW/m^2. Heat flow in the adjacent Pan African domains varies widely: in the south it ranges from 30 to 90 mW/m^2, and in the north from 60 to 120 mW/m^2 [*Lesquer and Vasseur*, 1992].

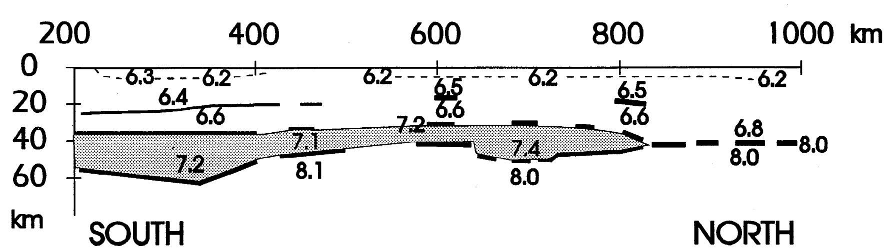

Figure 7. Section through the Baltic Shield and East European platform [after *Beloussov and Pavlenkova*, 1991]. Numbers in the crustal model are compressional wave velocities in kilometers per second. The high-velocity layer at the base of the crust (Vp > 7 km/s) is shaded.

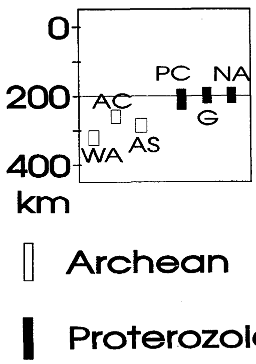

Figure 8. Range of measured thickness of the mantle lid for Archean and Proterozoic regions [*Beghoul and Mereu*, 1992]. WA, Pilbara and Yilgarn Blocks (western Australia); AC, Archean of Canada; AS, Aldan Shield (Russia); PC, Phanerozoic platform of Canada; G, Grenville Province (North America); NA, northeastern Australian craton.

Heat flow measurements for Australia and Eurasia are summarized by *Taylor and McLennan* [1985] and also show generally low values for the Archean provinces. The mean heat flow in the Archean provinces of western Australia is 39 mW/m^2, while it is 83 mW/m^2 in the Proterozoic provinces of central Australia. In the Archean Ukrainian Province the mean heat flow is 37 mW/m^2, and in the Archean-Proterozoic Baltic Shield it is 36 mW/m^2. The Archean province of the Indian Shield has somewhat higher heat flow (49 mW/m^2) than Archean provinces elsewhere, yet the heat flow is substantially lower than in the Proterozoic regions of the Indian Shield (71 mW/m^2).

These studies indicate that Archean provinces generally have lower mean surface heat flow than Proterozoic provinces, especially when adjacent provinces are compared.

Geochemistry and Petrology of the Precambrian Lithosphere

In this section we review geochemical and geological studies which will be synthesized with the seismological constraints to develop a model of lithospheric evolution. Specific examples from southern Africa are emphasized as this is a region endowed with a particularly well-preserved sequence of Archean and Proterozoic rocks and is also a region of concentrated kimberlite volcanism.

Crust

1. Several geological observations are commonly cited as distinguishing Archean provinces from Proterozoic provinces. In Archean provinces there is a general absence of characteristic features of convergent plate boundaries such as paired metamorphic belts, ophiolites and blueschist facies metamorphic rocks, and andesitic volcanism is rare [*Rutland*, 1976; *Etheridge et al.*, 1987; *Taylor and McLennan*, 1985].

2. Major element geochemistry of clastic sediments shows that the bulk composition of Archean sedimentary rocks differs from their post-Archean counterparts in being depleted in Si and K and enriched in Na, Ca, and Mg (Figures 9a-9e). No secular change in bulk major element composition is found to occur during the post-Archean [*Taylor and McLennan*, 1985]. These geochemical differences are consistent with an Archean upper crust that was significantly more mafic in average composition than post-Archean upper crust. Geochemical studies of the MgO content and Ni, Cr, U, and Th concentrations of shales and greywackes from southern Africa indicate that the source of the mafic component could have been komatiite [*Dia et al.*, 1990]. The MgO contents for South African shales are shown on Figure 9e (data from *Danchin* [1971], cited by *Dia et al.* [1990]). While the Archean data show considerable variation, the median values show the same general trend of relative enrichment in the Archean as found by *Taylor and McLennan* [1985].

3. Trace element geochemistry of clastic sediments also shows a marked change in concentrations at the Archean/Proterozoic boundary (Figures 9f-9i [*Taylor and McLennan*, 1985]). Trace element ratios of Precambrian pelites preserved on the Kaapvaal Craton of southern Africa [*Condie and Wronkiewicz*, 1990] are also shown on Figures 9f, 9h, and 9i. Most striking is the change in the Eu/Eu* ratio (which shows depletion or enrichment of Eu relative to neighbouring rare earth elements (REE), a value close to unity indicating that insignificant differentiation has taken place) at the Archean/Proterozoic boundary. The Eu/Eu* ratio is unity during the Archean, and decreases to about 0.7 in the post-Archean. This is interpreted by *Taylor and McLennan* [1985] to indicate that little internal crustal differentiation occurred during the Archean. However, some Archean rocks with low Eu/Eu* ratios have been discovered in southern Africa. These include early Archean clastic metasediments [*Kröner et al.*, 1991], pre-3.5 Ga granitoids [*Reimer et al.*, 1985], and late-Archean pelites [*Condie and Wronkiewicz*, 1990] (see Figure 9f). *Kröner and Layer* [1992] interpret the low Eu/Eu* ratios to indicate that these rocks were derived from erosion of differentiated crust and, as remelting is most likely in thickened crust, suggest that some crust of a similar thickness to the present day existed in the early Archean.

The ratios of Σ light REE/Σ heavy REE, Th/Sc, and La/Sc are indexes of bulk chemical composition. They all show an abrupt change at the Archean-Proterozoic boundary and remain constant in the post-Archean. The abundances of U and Th in fine-grained sediments increase at the Archean-Proterozoic boundary (Figures 9j and 9k). The Th/Sc and La/Sc ratios and U and Th contents of South African shales (*Hofmeyr*, [1971], cited by *Dia et al.* [1990]) are in accord with these trends (Figures 9j and 9k).

4. Lower crustal xenoliths provide information on the petrology of the lower crust. In southern Africa, large numbers of mafic to felsic garnet granulites, interpreted to originate from the lower crust, have been recovered from kimberlites in the Proterozoic Namaqua Province [*Dawson*, 1980]. In contrast, very few lower crustal xenoliths have been recovered from the numerous kimberlites within the Archean Kaapvaal craton. There are several possible explanations for the scarcity of lower crustal xenoliths: the lower crust was sparsely sampled by the kimberlites; fragments of lower crust have been altered or assimilated; or the lower crustal xenoliths are so undistinguished in appearance that they have been overlooked by petrologists [*Nixon*, 1987]. Our favored explanation is that the mineralogy of the lower crust of the Kaapvaal craton differs from the adjacent Namaqua Province, lacking a significant component of garnets, as xenoliths containing garnets have a distinctive appearance and are unlikely to have been overlooked.

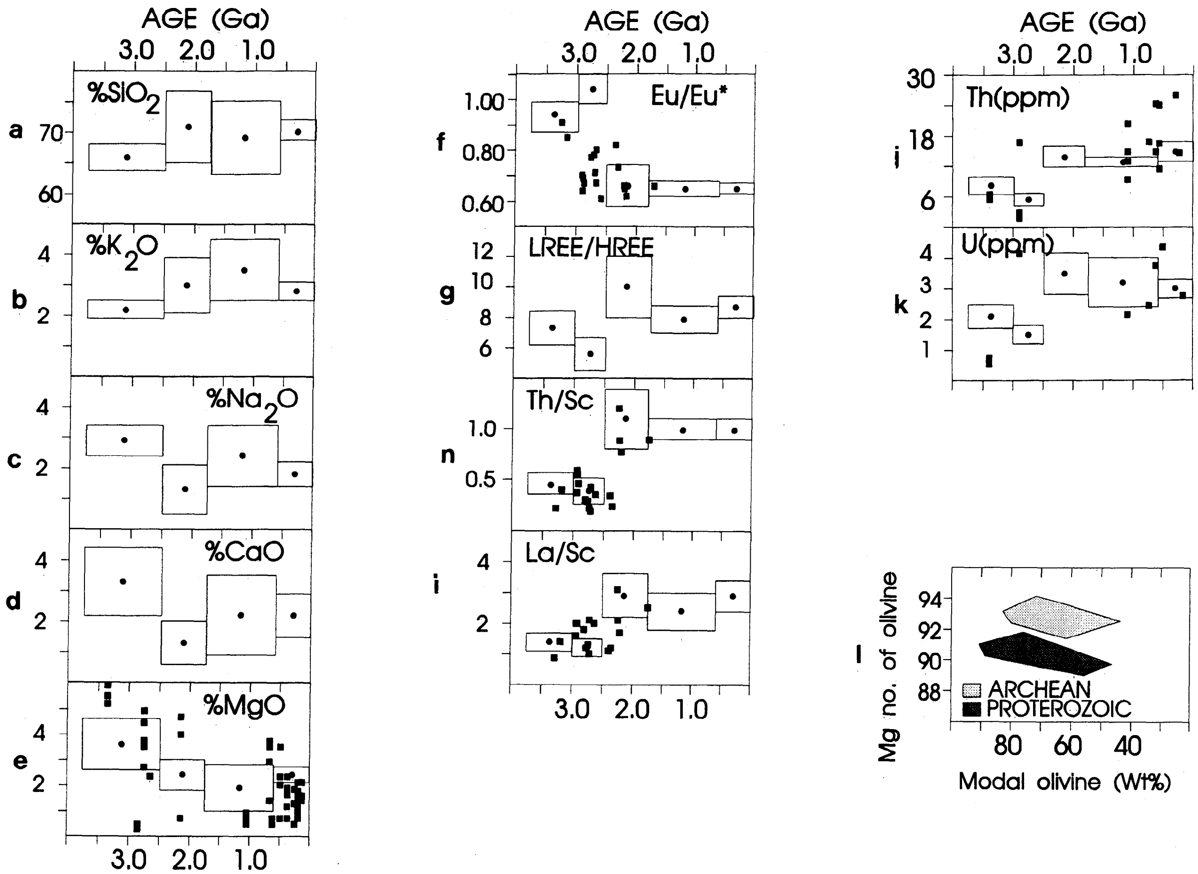

Figure 9. Geochemical data versus age: (a)-(e) Major element composition of sediments; (f)-(i) trace element ratios; (j)-(k) uranium and thorium content; (l) olivine chemistry of mantle xenoliths. The compilations of geochemical data by *Taylor and McLennan* [1985] are shown in Figures 9a-9k. The solid circle indicates the average value, and the rectangle represents 95% uncertainties. For comparison, analyses of southern African sediments [*Danchin*, 1970; *Hofmeyr*, 1971; *Condie and Wronkiewicz*, 1990] have been added (solid squares); these analyses are consistent with those of *Taylor and McLennan* [1985]. Figure 9l is after *Menzies* [1990].

5. Exhumed crustal sections provide direct information on the geology of the middle and lower crust. However, only a few exhumed Precambrian sections have been identified, and consequently, the observations cannot be generalized. Two examples of partial cross sections through the crust of the Archean Superior Province have been described. The Pikwitonei section from Manitoba shows the granite-greenstone terrain passing, with inferred increasing depth, into upper amphibolite- to granulite-facies tonalitic gneiss containing remnant greenstone belt lithologies. In contrast, deeper crustal levels in the Kapuskasing Structural Zone, thought to represent the middle crust, are characterized by various granulite-facies rocks (mafic gneiss, tonalite gneiss, metasedimentary gneiss, anorthosite) [*Fountain and Christensen*, 1989; *Percival and Card*, 1985; *Wu and Mereu*, 1990]. Strong geochemical gradients within the Vredefort structure are interpreted to indicate that the Archean crust of the Kaapvaal Craton has been "turned on edge". The upper crust consists of massive granite-gneisses, while in the center of the structure (10-15 km below the original cratonic surface), rocks of granitic composition, in granulite facies, predominate [*Hart et al.*, 1990]. The Fraser and Musgrave Range of Australia provide an insight into Proterozoic crust. The rocks in granulite facies include gneisses ranging in composition from felsic to mafic, as well as anorthosite and mafic plutons [*Fountain and Christensen*, 1989].

Upper Mantle

Kimberlite-borne xenoliths offer unique insights into the nature of the Archean lithospheric mantle since kimberlites are essentially restricted to Archean terranes with only minor occurrences in Proterozoic to Phanerozoic circum-cratonic mobile belts, while basalt-borne xenoliths constrain the nature of the post-Archean lithospheric mantle. Some major results of mantle xenolith studies are summarized below.

1. Major element chemistry of kimberlite- and basalt-borne xenoliths indicate a first-order difference between Archean and Proterozoic mantle lithosphere. Kimberlite-borne garnet lherzolite is richer in Si and poorer in Ca and Al than basalt-borne spinel lherzolite [*Menzies*, 1990]. *Maaloe and Aoki* [1977] considered and discarded the conventional explanation that these chemical differences are due to their derivation from different depths within the mantle and interpreted these chemical differences as evidence that the kimberlite-borne garnet lherzolite is more depleted and refractory than basalt-borne spinel lherzolite. *Jagoutz et al.* [1979] further demonstrate that several basalt-borne spinel lherzolites had a full complement of basaltic

elements and only highly incompatible elements were depleted. *Menzies* [1990] combines these observations to argue that the mantle beneath the stable, Archean craton of southern Africa is chemically different from that beneath the adjacent Proterozoic provinces.

Hawkesworth et al. [1990] note that the low Fe-O garnet peridotite xenoliths appear to be restricted to kimberlites which penetrate Archean crust and, as komatiite is essentially an Archean phenomenon, conclude that these xenoliths represent mantle lithosphere that is Archean in age. In southern Africa, most garnet peridotite xenoliths are from the Archean Kaapvaal craton, while most spinel peridotite xenoliths are from post-Archean regions. Furthermore, spinel peridotite xenoliths from the Kaapvaal craton are generally more depleted than spinel xenoliths from elsewhere [*Boyd and Mertzman*, 1987; *Nixon*, 1987]. More data are required from other areas to evaluate whether these compositional differences between spinel and garnet peridotites are a function of age, province or a combination of factors [*McDonough*, 1990].

2. Compositional variation of olivines in lithospheric peridotite has also been used to define first-order differences between Archean and Proterozoic lithosphere [*Boyd*, 1989; *Menzies*, 1990]. The low-temperature granular peridotites that constitute a major part of the Archean lithosphere of Africa are highly magnesian in character (Figure 9l). This ultradepleted character is attributed to either the extraction of komatiite in the production of early oceanic crust [*Boyd* 1987, 1989; *Boyd and Mertzman*, 1987; *Chase and Patchett*, 1988]; or hydrous melting above subduction zones during the accretion of Proterozoic and Phanerozoic lithosphere around the margins of the Archean nucleii [*Ashwal and Burke*, 1989]. In contrast, Proterozoic and Phanerozoic lithospheres are less magnesian in character and are compositionally similar to Phanerozoic oceanic lithosphere.

3. Trace element chemistry, especially the Nd isotopic composition of lithospheric peridotites, shows apparent differences between Archean and post-Archean lithospheres. Post-Archean lithospheric mantle is isotopically similar to oceanic lithosphere, while Archean lithospheric mantle has a much wider range of isotopic compositions ranging from values close to mid-ocean ridge basalts (MORB) to values typical of the lower crust, the least radiogenic Nd presumably reflecting Archean enrichment events as recorded in harzburgitic diamond inclusions [*Menzies*, 1990]. This diverse character is thought to be due to either recycling of oceanic lithosphere, or the mixing of depleted Archean lithosphere with fertile post-Archean mantle plumes.

The subcalcic, Cr-poor megacryst suite is one of the most abundant xenocryst types found in kimberlites and has been conventionally regarded as having an asthenospheric origin [*Nixon and Boyd*, 1973]. However, a recent study of the Nd, Sr, and Pb isotopic compositions of Cr-poor megacrysts from widely separated southern African localities suggests that they are derived from a single isotopic reservoir which differs from depleted asthenospheric reservoirs by having significantly more radiogenic Pb and less radiogenic Nd. This reservoir is interpreted to be resident in the deep subcontinental lithosphere [*Smith et al.*, 1992]. Re-Os systematics require that sheared, high-temperature peridotite xenoliths have had long isolation times from "normal" suboceanic mantle [*Walker et al.*, 1989]. These observations, together with the Archean ages of harzburgitic diamonds, are interpreted by *Smith et al.* [1992] to indicate that a lithospheric root possibly extending to a depth of 500 km has been intact since the Archean.

In summary, the major element chemistry and olivine composition of mantle xenoliths indicate a contrasting depletion of the Archean and Proterozoic-Phanerozoic lithosphere which may be explained by the extraction of some komatiitic melts during the Archean. Nd isotopic compositions suggest subsequent modification of the lithosphere by upward migration of small volume melts enriched in light rare earth elements and incompatible elements originating within the lithosphere or the asthenosphere. The wide range of Nd isotopic compositions within the Archean lithosphere is attributed to prolonged exposure to these small volume melts.

An important consequence of the depletion of the Archean lithosphere is the stabilisation of the refractory mantle by compositionally caused density changes in the range 0.03-0.08 g/cm^3 [*Bickle*, 1986]. The mantle experienced a major depletion in volatiles during the Archean, with several important consequences [*Pollack*, 1986]. The mantle became more refractory and less vulnerable to partial melting. It also became 1-2 orders of magnitude stiffer and much stronger, thereby inhibiting convection and reducing heat flow.

Diamond Chronology and Mantle Temperature

There are two main factors which indicate that mantle temperatures in the Archean were 100-500°C higher than at present: radiogenic heat production was 2-3 times greater than at present, thereby raising the average temperature, and the restriction of komatiitic volcanism, which requires eruption temperatures in excess of 1500°C, to the Archean [*Bickle*, 1986]. Diamonds are rare megacrysts, brought to the surface by kimberlite (and lamproite) pipes, which provide critical information on the temperature-depth profile of the upper mantle. Thermobarometry of peridotitic mineral inclusions in diamond indicates relatively cool crystallization temperatures (900°-1200°C) in the depth range 150-200 km [*Boyd et al.*, 1985]. In southern Africa, diamonds are restricted to kimberlites which intrude crust of Archean age, while kimberlites within the adjacent Proterozoic belt are barren [*Gurney*, 1990]. Thus the discovery that southern African diamonds have Sm-Nd model ages of 3.2-3.4 Ga, even within Phanerozoic kimberlites [*Richardson et al.*, 1984], was very surprising as it indicated that the Archean lithosphere must have had a relatively cool geotherm, similar to that found for the present-day Kaapvaal craton. The temperature gradient in the adjacent Proterozoic Namaqua Province is steeper and falls outside the diamond stability field [*Jones*, 1988].

A Model for Precambrian Lithospheric Evolution

The preceding sections have detailed a number of important constraints that should be considered in any model of lithosphere evolution. We summarize these constraints below and propose a model consistent with most available information on the properties of the lithosphere.

1. Geochemical studies of sediments and mantle xenoliths both differentiate between Archean and Proterozoic provinces. Sediments reveal a distinct change in major and trace element composition of the upper crust at the Archean-Proterozoic boundary. Xenoliths show that the lithospheric mantle beneath Archean provinces is relatively enriched in Mg and depleted in FeO when compared to post-Archean provinces.

2. Heat flow measurements indicate that the Archean provinces have lower mean surface heat flow (30-50 mW/m^2) than Proterozoic provinces (40-85 mW/m^2), especially when adjacent

provinces are compared. The confinement in South Africa of diamond-bearing kimberlites to the Archean craton, and especially the observation that some diamonds have Archean ages, provides critical evidence that the lithosphere was relatively thick and cool beneath stabilized Archean crust, even though the temperatures of the convecting mantle must have been substantially higher.

3. Seismic investigations of the crust show that crust which stabilized during the Archean ranges in thickness from 27 to 40 km, with an average of about 35 km. Crust that stabilized during the Proterozoic is substantially thicker (40-55 km). The layer at the base of the crust with a seismic velocity greater than 7 km/s (probably representing predominantly mafic rocks) is not well developed in Archean crust, but it comprises 20-30% of the Proterozoic crust. Modeling of the gravity field along profiles crossing the boundary between Archean and Proterozoic provinces confirms that the Proterozoic crust is thicker and denser. A thicker crust with a mafic basal layer can be produced in two basic ways. It can be formed by the shortening of an originally felsic crust, followed by igneous differentiation, uplift, and erosion. However, *Drummond and Collins* [1986] demonstrate that vast amounts of tectonic thickening and erosion are required and argue persuasively that basaltic underplating of the felsic crust is a more plausible process. Therefore a model of crustal evolution should explain why Proterozoic and not Archean crust is prone to basaltic underplating.

4. Seismic investigations of the upper mantle show that the Precambrian shields have deeper roots than adjacent Phanerozoic provinces. Where the deep structure of adjacent Archean and Proterozoic provinces is resolved, the lithosphere is thickest beneath the Archean terrain. The lithospheric mantle is seismically anisotropic, indicating a peridotitic composition. The anisotropy beneath the Superior and Slave Provinces of the Canadian Shield is interpreted to be the product of mantle deformation during the Archean and to indicate that the lithosphere has had a thickness of at least 200 km since then [*Silver and Chan*, 1988, 1991].

These observations enable us to evaluate previous models of crustal evolution which are based on the belief that crustal thickness is proportional to crustal age. The hypothesis that the crust thickens by cooling and transformation of mantle material [*Pavlenkova*, 1987] implies that the most ancient crust should have the lowest low heat flow and the thickest crust. While Archean provinces generally have lower heat flow than the adjacent Proterozoic province, the crust in the Archean crust is generally thinner than Proterozoic crust, contradicting the "growth by cooling" hypothesis. A modeling study of the lithospheric thermal structure of the Baltic Shield reveals that Moho depth is proportional to the Moho temperature, with the exception of southern Sweden [*Pasquale et al.*, 1991]. The oldest provinces generally have both the lowest Moho temperature and the thinnest crust.

Nelson [1991] proposes that the crust is thickened by repeated episodes of basaltic underplating. The absence of a high-velocity layer at the base of Archean crust, together with the observation that Archean crust is generally thinner than Proterozoic crust, indicates that this mechanism cannot be extended to the Archean.

Meissner [1986] and *Meissner and Wever* [1989] offer several possible mechanisms to explain the age dependence of Moho depth. Their favored processes involve either multiple differentiation with ultramafic cumulates becoming incorporated in the upper mantle or the quasi-permanent extraction of material from the mantle with the hotter and relatively undepleted mantle of Archean times producing a greater volume of more mafic crust. These mechanisms are based on the belief that crustal thickness is directly proportional to age, which is not valid for Archean crust. Furthermore, calculations by *Drummond and Collins* [1986] demonstrate that vast amounts of tectonic thickening and erosion are required to achieve a mafic lower crustal layer.

We propose an alternative model of lithospheric evolution that is consistent with the geophysical observations and that can be reconciled with models based on geochemical considerations [*Hawkesworth et al.*, 1990; *Menzies*, 1990]. The main features of this model are shown in Figure 10. We consider mantle temperature to be the critical variable that controlled the transition from the Archean to Proterozoic types of lithosphere. As Earth cooled, the decrease in mantle temperature by approximately 2.5 b.y. was sufficient to lead to a fundamental change in the lithosphere-forming process due to a change in the composition of magmatism and the upper mantle residuum. The high temperature of the convecting mantle during the Archean led to the eruption of komatiitic lavas at mid-ocean ridges or continental rifts, and the formation of a refractory lithosphere that was ultradepleted in FeO, enriched in MgO, depleted in volatiles, and intrinsically less dense than the surrounding asthenosphere [*Jordan*, 1988; *Richter*, 1988; *Hawkesworth et al.*, 1990; *Pollack*, 1986]. *De Wit et al.* [1992] emphasize the importance of hydration of the depleted ultramafic rocks, as this would result in their obduction rather than subduction and recycling. Intrinsic buoyancy of the lithospheric root is crucial to prevent delamination as the lithosphere cooled. Any underplated magma of komatiitic composition would be seismically indistinguishable from the mantle.

Although preserved komatiitic lavas are now quite rare, substantial amounts could have been removed by erosion. For example, studies of South African shales and greywackes indicate that the Archean crust was composed of granite (about 70%) and a mafic component (up to 30%) which probably was komatiite [*Condie and Wronkiewicz*, 1990; *Dia et al.*, 1990]. Gravity and geoelectrical studies of South African Archean greenstone belts show that they are shallow features which rarely exceed 7 km in depth [*De Beer and Stettler*, 1988], and present-day seismic velocities within the Archean crust are generally low to average, indicating a small mafic component.

The Archean lithospheric mantle, ultradepleted in FeO, was subsequently unable to produce significant amounts of basalt to intrude or underplate the Archean crust during thermal events, although some low volume melts (including kimberlites) metasomatised regions within the upper mantle, enriching it in incompatible elements. The Archean lithosphere stabilized and cooled, enabling diamonds to be formed at depths in excess of 150 km.

As the mantle temperature decreased, komatiitic volcanism ceased and Proterozoic crust formed above less depleted mantle. No major chemical distinction or intrinsic density contrast existed between the Proterozoic lithosphere and the asthenosphere. The Proterozoic lithosphere is thus prone to delamination and recycling into the asthenosphere [*Hawkesworth et al.*, 1990]. Partial melting of the mantle (instigated by modern-style plate subduction, rifting, or anorogenic heating) resulted in eruptions of continental flood basalts and magmatic underplating by basalt (rather than komatiite), thereby thickening the Proterozoic crust and forming

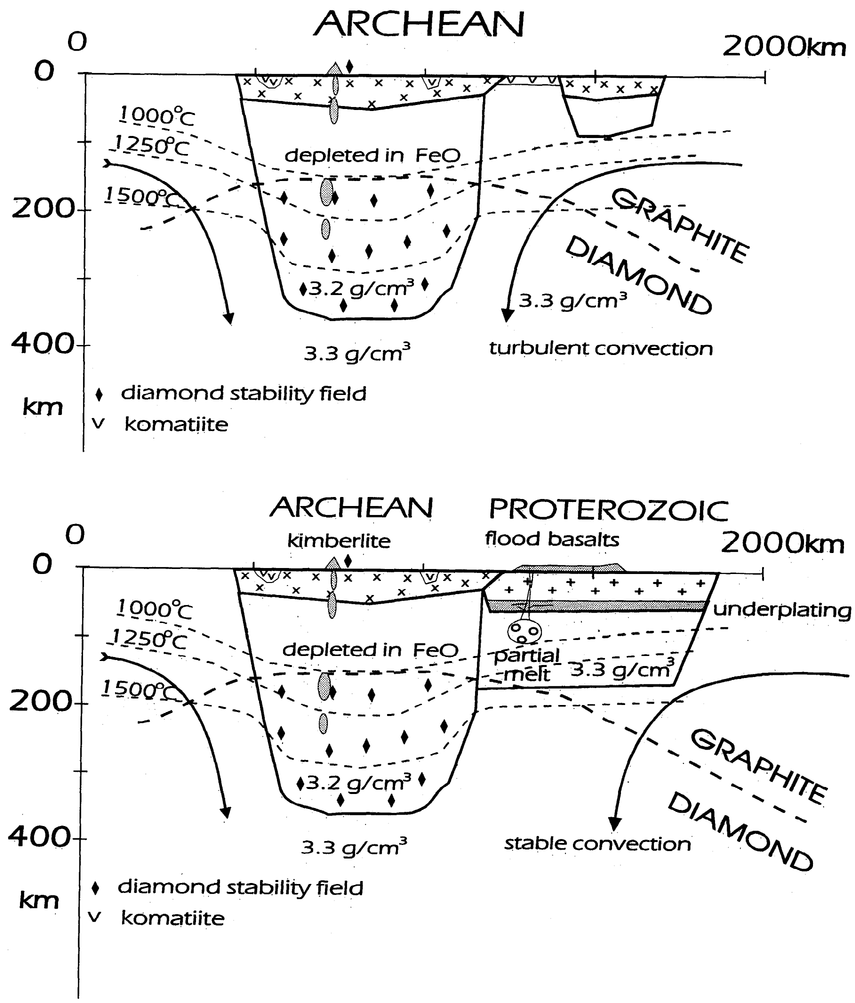

Figure 10. Model for Archean and Proterozoic lithospheric evolution (modified from *Hawkesworth et al.* [1990]; geotherms for southern Africa from *Jones* [1988]; diamond stability field from *Kennedy and Kennedy*, [1976]). Mantle temperatures during the Archean were 100°-500°C higher than at present, enabling komatiitic lavas to be produced. Archean crust develops above mantle lithosphere (garnet lherzolite) that is depleted in FeO and intrinsically buoyant. Diamonds with Archean ages indicate that the lithosphere must have been at least 150 km thick and relatively cool during the Archean. Proterozoic crust develops above fertile (normal FeO) mantle lithosphere (spinel lherzolite), which is the source of basaltic underplating leading to the formation of a high-velocity (>7 km/s) basal layer and crustal thickening.

a high-velocity basal layer. While there is much controversy regarding the genesis of komatiites [e.g., *Jochum et al.*, 1991] recent phase equilibrium experiments provide support for a model which depicts cratonic peridotites as residues of komatiitic liquid extraction [*Canil*, 1991, 1992].

The effect of mantle temperature on convection is more difficult to quantify, although attempts have been made [e.g., *Ogawa*, 1988]. The convection in the hotter Archean mantle was probably more turbulent and chaotic than at present [*Olson*, 1989], implying that the convection cells were of relatively small dimension and short-lived. It is argued by *McCulloch* [1993] that the steeper Archean geotherm produced partial melting of subducted slabs, a phenomenon which became relatively rare in the post-Archean as the Earth cooled, thereby accounting for the domination of trondhjemite-tonalite-granodiorite suites in early Archean granitic terrains. *McCulloch* [1993] suggests that Earth had cooled sufficiently by the early Proterozoic so that the slab no longer experienced substantial degrees of partial melting, acting rather as a catalyst for melting of the overlying mantle wedge by providing fluids via dehydration reactions.

A comparison of average Proterozoic crustal structure with highly evolved Phanerozoic crust that has undergone the full range of plate tectonic processes (from island arc accretion to continental-arc volcanism) reveals a remarkable similarity [*Mooney and Braile*, 1989]. We suggest that the mantle had cooled sufficiently by the Proterozoic for stable convection (similar to the present day) to take place, and substantial island and continental arcs formed. Basaltic underplating produced the high-velocity basal layer and thickened the crust.

We therefore hypothesize that actualistic plate tectonic processes can be extended back to the early Proterozoic but that these processes operated in a highly modified form during the Archean, due to the high mantle temperature.

Conclusion

It is a commonly held viewpoint among seismologists that crustal thickness is directly proportional to age, excepting young mountain belts, with Archean crust being the thickest. Several models of lithospheric evolution have been proposed to explain this purported trend. Crustal growth models propose mechanisms such as underplating [*Nelson*, 1991] or the transformation of the uppermost mantle into lower crust through cooling [*Pavlenkova*, 1987], while crustal "reduction" models suggest that younger crust, with the exception of recent orogens, is thinner because it has experienced repeated melting and recycling processes differentiating the crust, with ultramafic cumulates becoming part of the mantle [e.g., *Meissner*, 1986]. However, a worldwide review of velocity-depth functions shows that the Archean crust is generally thinner than Proterozoic crust and lacks a high-velocity basal layer. Seismological studies also show that the lithosphere is thickest beneath Archean cratons.

We have sought to synthesize the seismological observations with geological data, major and trace element geochemistry of clastic sediments, diamond chronology, xenolith, and heat flow studies. The result is a model for Precambrian lithospheric evolution that appears to be consistent with most available information on lithospheric properties. Hotter Archean mantle temperatures led to the eruption of komatiitic lavas and the formation of a lithosphere that is ultradepleted in FeO, intrinsically buoyant, and sufficiently cool for diamonds to form. As Earth cooled, the mantle temperature passed through a critical point at the end of the Archean and komatiitic volcanism ceased. The fertile Proterozoic mantle lithosphere had an FeO content similar to the asthenosphere and was prone to partial melting during heating events. Thickening of the Proterozoic crust occurred by the extrusion of flood basalts and underplating, the latter forming the high-velocity basal layer.

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R. J. Durrheim, Geophysics Department, Witwatersrand University, Private Bag 3, Wits, 2050, South Africa.

W. D. Mooney, U. S. Geological Survey, 345 Middlefield Road, MS 977, Menlo Park, CA 94025.

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