Archean and Proterozoic crustal evolution: Evidence from crustal seismology

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ABSTRACT

Seismic-velocity models for Archean and Proterozoic provinces throughout the world are analyzed. The thickness of the crust in Archean provinces is generally found to be about 35 km (except at collisional boundaries), whereas Proterozoic crust has a significantly greater thickness of about 45 km and has a substantially thicker high-velocity (>7.0 km/s) layer at the base. We consider two models that may explain these differences. The first model attributes the difference to a change in the composition of the upper mantle. The higher temperatures in the Archean mantle led to the eruption of komatiitic lavas, resulting in an ultradepleted lithosphere unable to produce significant volumes of basaltic melt. Proterozoic crust developed above fertile mantle, and subsequent partial melting resulted in basaltic underplating and crustal inflation. In the second model, convection in the hot Archean mantle is considered to have been too turbulent to sustain stable long-lived subduction zones. By the Proterozoic the mantle had cooled sufficiently for substantial island and continental arcs to be constructed, and the high-velocity basal layer was formed by basaltic underplating.

INTRODUCTION

Many models describe the growth of the continental crust, ranging from roughly steady-state models involving early (ca. 4.5 Ga) crustal formation, to those involving continuous or episodic crustal growth with time (e.g., Ashwal, 1989, p. 144). The question of whether present-day processes of crustal formation (island-arc accretion, continental-rift and arc magmatism, continent-continent collision) were also the most important processes in the past is equally contentious. Some workers argue for a single dominant process throughout Earth history. For example, Turcotte (1989, p. 321) argued that continental crust has always formed as a result of basaltic volcanism at island arcs, continental rifts, and hotspots. Archean geology is also commonly interpreted in terms of modern plate-tectonic concepts. For example, Hoffman (1988) and Percival (1989) interpreted the granulite terranes of the Archean Superior province as representing magmatic arcs, accretionary wedges, and continental collisions. On the other hand, Kröner (1984) drew on isotopic and geologic evidence to argue that intracontinental rifting and magmatic underplating and overplating were the primary processes of crustal growth during the Archean and Early Proterozoic (i.e., vertical growth), whereas in the Late Proterozoic and Phanerozoic, collision and accretion (i.e., horizontal plate-margin processes) became dominant.

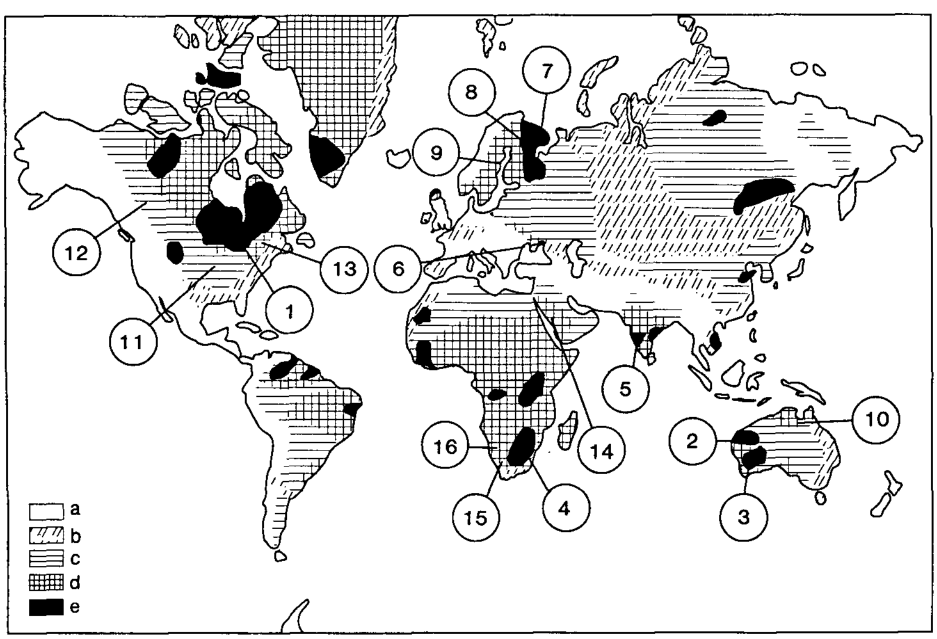

Figure 1. Map showing age provinces of continental crust and locations of deep seismic soundings used in this analysis. a: Mesozoic and Cenozoic orogenic belts. b: Paleozoic orogenic belts. c: Proterozoic platforms. d: Proterozoic shields. e: Archean shields (from Miyashiro et al., 1982). Numbers refer to Figure 2.

CRUSTAL STRUCTURE OF ARCHEAN AND PROTEROZOIC PROVINCES

The thickness and seismic velocity of the crust are important constraints on the process of crustal formation: if Archean crust formed by the same basic process as Proterozoic and Phanerozoic crust, the seismic characteristics of the crust (after discounting modifications by poststabilization tectonic processes) should be broadly similar over all geologic time. Conversely, if the process of crustal formation has changed significantly with time, these changes should be reflected by a secular change in the seismic character of the crust. A map of geologic age provinces and the locations of the deep seismic soundings used in this search for a secular change in crustal structure is shown in Figure 1.

In order to make global generalizations we have included velocity models from many parts of the world; these models are derived from studies that have used a variety of seismic survey configurations and interpretation methods (Table 1). Although the determination of subtle intracrustal features may be somewhat subjective, major features—such as the depth to Moho and average velocities in the crust and upper mantle—are reliably determined (e.g., Mooney et al., 1985, p. 235). For this reason we have characterized the velocity-depth functions in terms of two prominent parameters: total crustal thickness and thickness of the basal

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high-velocity layer. The base of the crust is defined as the depth at which the seismic velocity exceeds 7.6 km/s. The basal high-velocity layer is defined as the part of the crustal section that has seismic velocities in the range 7.0–7.6 km/s. Although these velocities may indicate anorthosite or rocks of intermediate average composition in high-grade metamorphic facies, probably the most common cause are rocks with a gabbro to olivine-gabbro bulk composition (Fountain and Christensen, 1989).

The results compiled in Figure 2 show that the crust in Archean provinces is relatively thin and lacks a substantial high-velocity basal layer when compared with Proterozoic provinces. It is important to note that our compilation excludes ancient collisional margins where the crust has been overthickened by thrusting (e.g., Kapuskasing structure, Canada; Boland and Ellis, 1989).

IMPLICATIONS FOR ARCHEAN AND PROTEROZOIC CRUSTAL EVOLUTION

Two important constraints have been identified in this study that should be taken into account in any model of continental evolution. First, crust that stabilized during the Archean ranges in thickness from 27 to 40 km and averages 35 km. Crust that stabilized during the Proterozoic is substantially thicker (40–55 km). Second, the layer at the base of the crust with a seismic velocity greater than 7.0 km/s (probably representing predominantly mafic rocks) com-

TABLE 1. SOURCES OF REPRESENTATIVE SEISMIC VELOCITY MODELS

Geologic province	Tectonothermal age	Reference*
Europe		
Baltic shield, Kola nucleus	Archean	Sollogub et al. (1973)
Baltic shield, Karelian province	Archean	Luosto et al. (1990)
Ukranian shield	Archean	Jentsch (1979)
Baltic shield, Svecofennian province	Proterozoic	Luosto et al. (1990)
India		
Indian shield	Archean	Kaila et al. (1978)
Arabian peninsula		
Arabian shield	Proterozoic	Mooney et al. (1985)
North America		
Superior province	Archean	Braile et al. (1989) and Mooney and Braile (1989)
Central province	Proterozoic	ibid.
Northwest Canadian platform	Proterozoic	ibid.
Grenville province	Proterozoic	ibid.
Australia		
Yilgarn block	Archean	Drummond (1988)
Pilbara block	Archean	Drummond and Collins (1986)
North Australian craton	Proterozoic	ibid.
Southern Africa		
Kaapvaal craton	Archean	Gane et al. (1956) and Durrheim (1989)
Zimbabwe craton	Archean	Stuart and Zengeni (1987)
Limpopo province	Archean	ibid.
Namaqua province, South Africa	Proterozoic	Green and Durrheim (1990)
Rehoboth province, Namibia	Proterozoic	Baier et al. (1983)

*Note: Regional reviews of the seismic velocity structure are cited; references to the original investigations are to be found in these reviews.

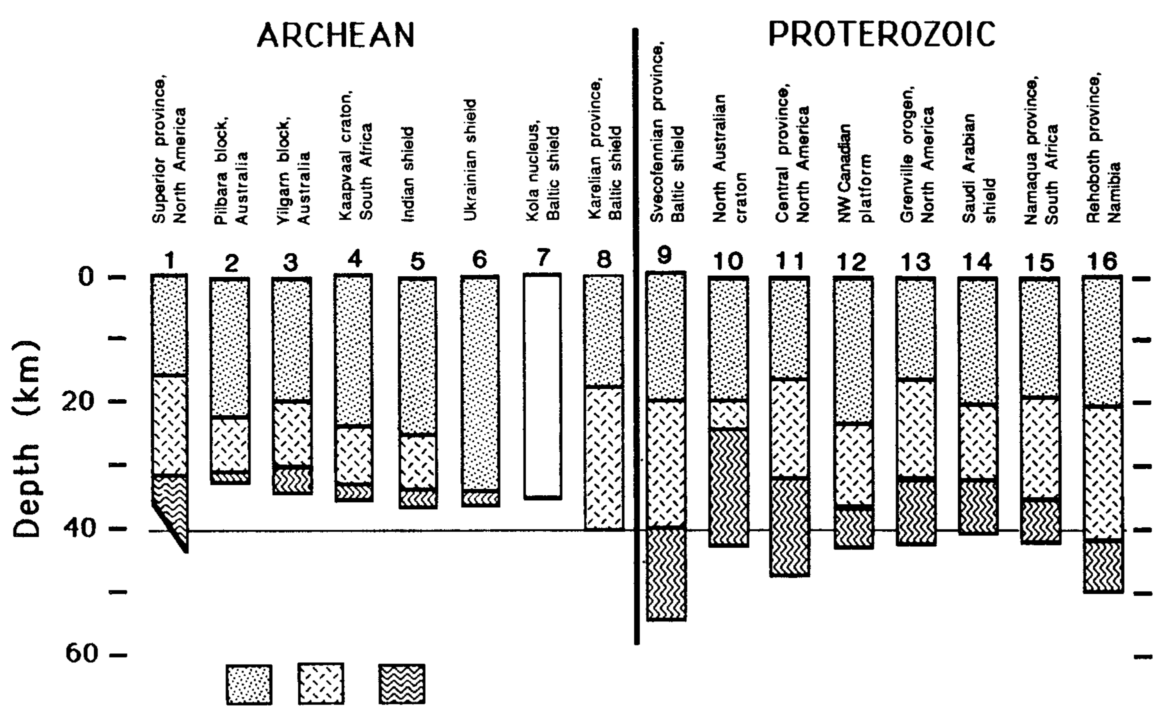

Figure 2. Representative seismic-velocity-depth functions for Archean and Proterozoic provinces. Archean crust is about 35 km thick, whereas Proterozoic crust is significantly thicker, about 45 km. Basal high-velocity layer, probably indicating rocks with mafic average composition, is substantially thicker in Proterozoic provinces.

poses only 5%–10% of the Archean crust, but it is typically 20%–30% of the Proterozoic crust. These trends were noted previously for the Precambrian crust of Australia (Drummond and Collins, 1986; Drummond, 1988), and we have extended the observation globally.

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, p. 368) demonstrated that vast amounts of tectonic thickening and erosion are required, and they argued persuasively that basaltic underplating of the felsic crust is a more likely process. Accepting this second process as a working hypothesis, we seek to explain why Proterozoic, and not Archean crust, is prone to basaltic underplating. Several geologic observations are commonly cited as distinguishing Archean cratons from Proterozoic cratons (Rutland, 1976; Etheridge et al., 1987). Characteristics of Archean cratons include (1) the virtual absence of ophiolites and blueschist facies metamorphic rocks, (2) the paucity of andesitic volcanism, (3) the occurrence of komatiitic lavas, and (4) the occurrence of diamonds within kimberlites. The first two observations are interpreted to indicate the absence (or the occurrence in a much modified form) of either sea-floor spreading or the subduction of oceanic lithosphere at island and continental arcs. The eruption of komatiitic lavas indicates higher mantle temperatures during the Archean. The occurrence of diamonds and especially the observation that diamonds may be Archean in age, even within Phanerozoic kimberlites, provide critical evidence that the lithosphere must have been relatively thick and cool beneath stabilized Archean crust (Richardson et al., 1984).

We consider mantle temperature to be the variable that controlled the transition from the Archean to Proterozoic type of crust. As the Earth cooled, the mantle-temperature decrease was sufficient to lead to a fundamental change in the crust-forming process. We consider two possible mechanisms: a change in magma composition and a change in mantle rheology. The first model (Jordan, 1978; Hawkesworth et al., 1990) proposes that hotter Archean mantle temperatures led to the eruption of komatiitic lavas and the formation of a refractory lithosphere depleted in FeO and intrinsically less dense than the surrounding asthenosphere (Fig. 3). Any underplated magma of komatiitic composition would be seismically indistinguishable from the mantle. The Archean lithosphere stabilized and thickened by conductive cooling, enabling diamonds to be formed at depths in excess of 150 km. The depleted lithosphere was unable to produce an amount of basaltic melt to significantly intrude or underplate the Archean crust during any subsequent heating event. As the mantle temperature decreased, komatiitic volcanism ceased and the Proterozoic crust formed above fertile mantle. Partial melting of the mantle (instigated by plate subduction, rifting, or anorogenic heating) resulted in magmatic underplating by basalt (rather than komatiite) and crustal inflation, thereby thickening the Proterozoic crust and forming a high-velocity basal layer. This model is permissive of actual plate-tectonic processes in the Archean, but the magmatic products would be komatiitic rather than basaltic.

The second model considers the crucial effect of decreasing mantle temperature to have been rheological. The difference over time in crust-forming processes is attributed to a change in the mode of mantle convection. During the Archean the convection in the hotter mantle was more turbulent and chaotic (Fig. 4; Olson, 1989). Consequently, the convection cells were of relatively small dimension, short-lived, and unable to sustain subduction. By the Proterozoic the mantle had cooled sufficiently for stable convection to take place, and substantial island and continental arcs formed. Basaltic underplating produced the high-velocity basal layer and thickened the crust. 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). In this model we hypothesize that actual plate-tectonic processes can be extended back to the Early Proterozoic but that these processes operated in a highly modified form during the Archean.

CONCLUSIONS

A comparison of the seismic-velocity structure of Archean and Proterozoic provinces shows that Proterozoic crust is both thicker and has a substantially greater proportion of material with seismic velocities higher than 7 km/s. This finding is attributed to basaltic underplating of Proterozoic crust. Two models that explain the absence of underplating of Archean crust are considered; in both cases the higher temperature of the mantle during the Archean is believed to be the primary cause of the secular change in crustal structure. The first model proposes that

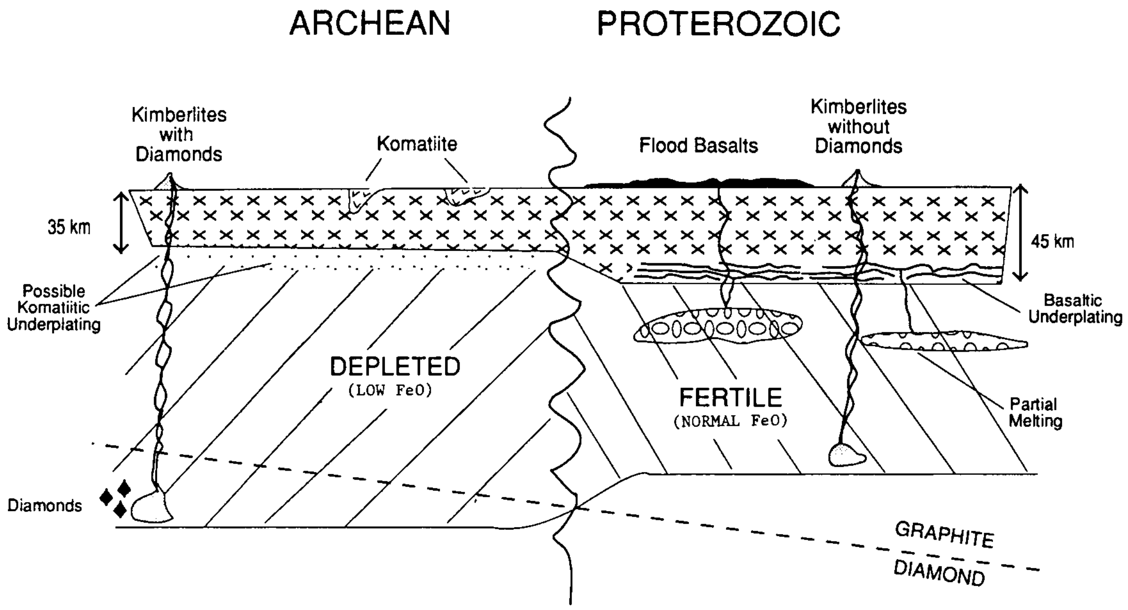

Figure 3. Model for Archean and Proterozoic crustal evolution emphasizing differences in chemical properties of uppermost mantle (modified from Hawkesworth et al., 1990). Proterozoic crust develops above fertile (normal FeO) mantle that is source of basaltic-composition crustal underplating, leading to development of thicker (45 km) crust. Archean crust develops above initially hotter mantle that is depleted in FeO through eruption of komatiitic lavas; magmatic underplating, if present, is ultramafic and is seismically indistinguishable from normal mantle. Presence of diamonds of Archean age within kimberlites indicates that lithosphere cooled and entered into diamond stability field during Archean. Cold lithospheric keel may also act as thermal boundary against crustal underplating by basaltic melts from asthenosphere.

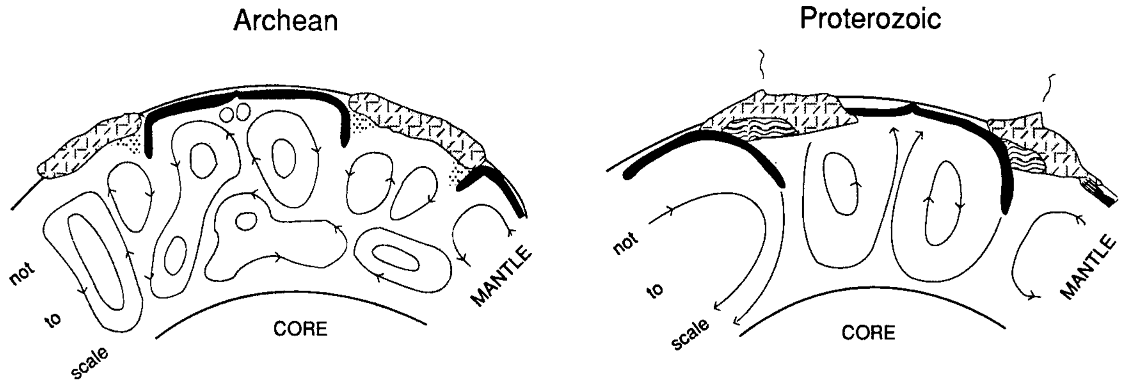

Figure 4. Model for Archean and Proterozoic crustal evolution emphasizing turbulent vs. stable convection patterns. Hotter Archean mantle lacks stable zones of upwelling and, particularly, downwelling that are needed to develop long-lived subduction zones and associated magmatic arcs. In contrast, Proterozoic subduction zones are long lived, and overriding crust is underplated (wavy pattern) and thickened (to 45 km) at seaward-migrating subduction zones. Consistent with concepts illustrated in Figure 3, Archean magmatic products (random dot pattern) may have been ultramafic and therefore seismically indistinguishable from normal upper mantle. Archean crust therefore remains thin (35 km).

the eruption of komatiitic lavas during the Archean led to the formation of an ultradepleted, refractory subcrustal lithosphere incapable of producing basaltic melt. In contrast, Proterozoic crust formed above fertile mantle, and partial melting resulted in magmatic underplating. The second model proposes that the Archean crust is a primary differentiation product of the primitive mantle and that mantle convection during the Archean was too vigorous to allow sustained subduction of oceanic lithosphere and continental-arc volcanism. These models are not, however, mutually exclusive.

An understanding of the processes that led to the formation of the crust during the Archean and Proterozoic requires a synthesis of geologic, geochemical, and geophysical results. The expanded coverage of Precambrian provinces by high-resolution seismic studies is crucial for unraveling the Earth's early history.

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