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Review Article

The character of the Moho and lower crust within Archean cratons and the tectonic implications

Dallas H. Abbott [a,*], Walter D. Mooney [b], Jill A. VanTongeren [c]

[a] Lamont–Doherty Earth Observatory of Columbia University, Palisades, NY 10964
[b] US Geological Survey, Menlo Park, CA 94025
[c] Rutgers University, Piscataway, NJ 08854

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ABSTRACT

Undisturbed mid Archean crust (stabilized by 3.0–2.9 Ga) has several characteristics that distinguish it from post Archean crust. Undisturbed mid-Archean crust has a low proportion of internal seismic boundaries (as evidenced by converted phases in seismic receiver functions), lacks high seismic velocities in the lower crust and has a sharp, flat Moho. Most of the seismic data on mid-Archean crust comes from the undisturbed portions of the Kaapvaal and Zimbabwe (Tokwe segment) cratons. Around 67–74% of younger Archean crust (stabilized by 2.8–2.5 Ga) has a sharp, flat Moho. Much of the crust with a sharp, flat Moho also lacks strong internal seismic boundaries, but there is not a one to one correspondence. In cases where its age is known, basaltic lower crust in Archean terranes is often but not always the result of post Archean underplating. Undisturbed mid-Archean cratons are also characterized by lower crustal thicknesses (Archean median range = 32–39 km vs. post-Archean average = 41 km) and lower crustal seismic velocities. These observations are shown to be distinct from those observed in any modern-day tectonic environment. The data presented here are most consistent with a model in which Archean crust undergoes delamination of dense lithologies at the garnet-in isograd resulting in a flat, sharp Moho reflector and a thinner and more felsic-intermediate crust. We discuss the implications of this model for several outstanding paradoxes of Archean geology.

Contents

* Corresponding author.
E-mail address: dallashabbott@gmail.com (D.H. Abbott).

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1. Introduction

There is continuing controversy about the tectonic processes that produced Archean continental crust (Helmstaedt, 2009; Herzberg and Rudnick, 2013; Miller and Eaton, 2010; Rollinson, 2010; Wyman and Kerrich, 2009). Based on geochemical indices, modern continental crust seems to be largely of arc affinity (Taylor and McLennan, 1985, 1995), or at least extensively contaminated by arc-like processes (Condie, 1999, 2005; Jagoutz and Schmidt, 2012; Rudnick and Gao, 2003). However, the crust is differentiated, with a large component of silicic material that could not have originated from a single stage of mantle melting either in an arc or in a mantle plume. In contrast, the low Fe olivine (Mg# 93) [Mg# = Mg^{2+} / (Mg^{2+} + Fe^{Total}) × 100] in the Archean-age mantle roots of continental cratons seems to represent the residue from high degrees of partial melting—a possible Archean analog for mantle plume processes (Afonso et al., 2008). In this paper, we focus on tabulations of the characteristics of the lower crust and Moho within undisturbed Archean cratons and use this data set to constrain their genesis.

We consider the physical properties of the lower crust and the Moho. Our goal is to see how the properties of the lower crust and the sharpness of the Moho transition varies as a function of geological age and tectonic history, and how this may relate to the origin of the crust and underlying lithospheric mantle. In particular, we ask if the physical characteristics of the Moho relate in some fundamental way to the changes in lithospheric evolution since Archean time. This study has been preceded by numerous related studies that address more broadly the composition and physical properties of the lower crust (Christensen and Mooney, 1995; Fountain and Christensen, 1989; Griffin and O'Reilly, 1987; Holbrook et al., 1992; Mooney and Meissner, 1992; Rudnick and Fountain, 1995; Rudnick and Gao, 2003; Wedepohl, 1995).

2. Petrological and geophysical data sources

Moho depth has been determined on a global scale (Mooney et al., 1998). We define a sharp Moho as one where the crust/mantle transition occurs over a vertical distance of less than 2 km, e.g. (James et al., 2003). In areas with a more diffuse Moho, the crust/mantle transition commonly occurs over a minimum distance of 3 to 5 km. Previous studies of the Moho have primarily focused on its characteristics within different tectonic provinces (Cook, 2002; Cook et al., 2010; Hale and Thompson, 1982; Jarchow and Thompson, 1989; Mooney and Meissner, 1992). The study of Jarchow and Thompson (1989) provides a valuable historical perspective on the seismic Moho, and Cook et al. (2010) provides a detailed review of seismic reflection observations in different geological and age settings within Canada.

While there has been much discussion of the petrology of the Archean crust and sub-crustal lithosphere, the physical properties of the crust–mantle boundary (the Moho) also provide constraints on the processes by which the crust and lithospheric mantle were formed. The modern-day seismic Moho is defined as the depth at which the P-wave seismic velocity reaches values ≥7.6 km/s (Jarchow and Thompson, 1989; Steinhart, 1967). This depth typically coincides with the seismic reflection Moho, which is the boundary between the reflector rich crust and the reflector poor uppermost mantle (Cook, 2002; Cook et al., 2010; Mooney and Brocher, 1987). In addition to seismic refraction/wide-angle reflection profiles and vertical-incidence seismic reflection profiles, Archean crust has recently been investigated by studies that employ seismic receiver functions. The latter have provided a new look at the crust. Significantly, these studies rarely find strong seismic discontinuities within Archean crust; the most prominent discontinuity is generally the Moho itself (Kumar et al., 2012; Nguuri et al., 2001). In refraction studies, Archean crust can be divided into layers, but the Moho is usually the strongest discontinuity, a finding that is consistent with receiver function studies. Thus, a consistent feature of seismic studies of Archean crust is a sharp Moho boundary.

2.1. Moho and crustal characteristics: Part 1—Western Australia

In western Australia, there are two Archean cratons, the Pilbara block (3.7–2.9 Ga) and the Yilgarn block (3.0–2.7 Ga)(Griffin et al., 2004; van Kranendonk et al., 2007). They are separated by the 1.84 Ga Capricorn orogen. The Moho beneath both cratons is sharp and thin with one exception near the southern edge of the Pilbara block (Fig. 1, Tables 1,2) (Reading et al., 2012). The Moho is visible as a pronounced increase in seismic velocity over a depth range of 2 km or less. In contrast, the Moho beneath the younger Capricorn Orogen is diffuse. Indeed, of the three seismic stations within the Capricorn Orogen (WS06, WS05, and WS04), the Moho is detectable only at WS05. The crustal cross section (Fig. 1) shows two salient features (1) thinner crust (30–34 km) in areas of older Archean crust (3.65–3.15 Ga) and (2) a sharp Moho boundary for Archean crust as compared with the Proterozoic Capricorn Orogen.

2.2. Moho and crustal characteristics: Part 2—Canadian Shield

As in Australia, we also see age related trends in the character of the Archean crust of the Canadian Shield. From west to east, the cratonic crust of the Superior Province becomes progressively younger, from ca. 3.5 Ga in the Winnipeg River subprovince, to ca. 2.8–2.9 Ga in the eastern Wabigoon subprovince (Fig. 2). Seismic refraction and wide-angle reflection results from the Superior Province of the Canadian shield (Fig. 2) show the thinnest crust (~32–36 km) in the 3.5 Ga Winnipeg River subprovince (Davis et al., 2005; Musacchio et al., 2004) whereas the 2.8 Ga Wabigoon has a crustal thickness between 38 and 42 km. While the translation of seismic P-wave velocity into crustal composition can be misleading (i.e. Behn and Kelemen, 2003), lower P-wave velocities generally correspond to more evolved, Si-rich crustal compositions and higher P-wave velocities are associated with more mafic compositions. Average lower crustal velocities in the 3.5 Ga Winnipeg River subprovince are approximately 6.7 to 6.8 km/s. The 3.2–3.0 Ga Central Wabigoon subprovince has average crustal velocities of 6.8 km/s (in the west) up to 6.9 km/s in the east, and the 2.8–2.9 Ga Eastern Wabigoon subprovince has a lower crustal seismic velocity of 7.1 km/s. The high velocity in the Eastern Wabigoon subprovince most likely represents mafic underplating from the 1.1 Ga Keweenawan rifting event (Boerboom, 1994; Hansen, 1975). In summary, the seismic cross section from the Canadian Shield illustrates the general trend of thinner crust in older undisturbed Archean cratons and a possibly intermediate composition lower crust in pre 3.0 Ga cratons, compared with their post-Archean counterparts. The cross section does not provide much information on the sharpness of the Moho transition.

2.3. Moho and crustal characteristics: Part 3—Southern Africa

The contrast in Moho character between Archean cratons and post-Archean crust is best seen from the Kaapvaal and Zimbabwe cratons in