Middle Archean continent formation by crustal delamination

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ABSTRACT

The processes that created the first large cratonic areas such as the Pilbara and the Kaapvaal remain poorly understood. Models based on the uniformitarian extrapolation of present-day arc volcanic processes to a hotter early Earth have not adequately explained the observations in these terranes. Here we propose an alternative mechanism for the formation of the earliest continental crust. The formation of continental crust may be achieved by delamination of the lower eclogitic part of an oceanic plateau–like protocrust. Such delamination results in uplift, extension, and the production of tonalite, trondhjemite, and granodiorite (TTG) suites as recorded in Middle Archean cratons. The available geologic and geophysical observations in combination with model calculations permit this scenario as an alternative to subduction-based hypotheses.

Keywords: Pilbara craton, Archean, continental crust, eclogite, delamination, TTG suites.

INTRODUCTION

Despite extensive multidisciplinary research, the physical process responsible for the formation and stabilization of the first continental crust remains enigmatic. The essential step in the formation of felsic continental crust from the primordial mantle is the generation of Archean tonalite, trondhjemite, and granodiorite (TTG) suites. The geochemistry of these TTG suites is consistent with generation by partial melting of hydrated basaltic rocks under high-pressure and high-temperature conditions (Wyllie et al., 1997). TTG suites are often assumed to have formed by melting of subducting slabs (Martin, 1986). Such uniformitarian plate-tectonic models for the production of TTG suites seem to be consistent with observations in Late Archean (3.0–2.5 Ga) terranes, but older, Middle Archean (3.6–3.0 Ga) terranes lack most of the features that are typically associated with convergent plate boundaries, such as large-scale (100 km) linear trends, accreted terranes, and accretionary wedges or sutures with ophiolites and paired metamorphic belts (Condie, 1997). An additional argument against subduction in the Early Archean is that if Archean Earth was hotter, modern-style subduction is unlikely, due to the formation of a thicker basalt crust (Anderson, 1979; Vlaar et al., 1994). In this paper we present an alternative model, in which delamination of the lower, eclogitic protocrust results in the formation and stabilization of continental crust in Middle Archean cratons.

GEOLOGY OF MIDDLE ARCHEAN CRATONS

The oldest terranes in which original relationships between TTG suites and supracrustal rocks have been well preserved are the Pilbara (Fig. 1) and Kaapvaal granitoid-greenstone terranes (3.6–2.8 Ga). The volumetrically most important addition of new continental (felsic) crust occurred between 3.5 and 3.4 Ga (Fig. 2).

Seismic evidence from both cratons shows that they have an anomalously thick (~250 km) lithospheric mantle (Drummond, 1988; Vinnik et al., 1996), which has been in place since 3.5–3.1 Ga, as indicated by ages from diamond inclusions (Pearson, 1999). Peridotitic xenoliths from the Kaapvaal craton mantle show that the Archean mantle is depleted in Ca, Al, and Fe compared to fertile mantle (Boyd and McCallister, 1976), indicating that the subcratonic mantle is the residue of a high-volume melt extraction in the Archean. Eclogitic xenoliths are consistent with eclogites being residues of Archean TTG formation (Rudnick et al., 2000). The cratonic crust is thinner (35 km) than post-Archean continental crust and lacks the garnet-containing, basal high-velocity layer (Durrheim and Mooney, 1994).

The relationships among intrusion of TTG suites, deposition of volcanic rocks, deformation, and metamorphism for the 3.52–3.4 Ga period have recently been determined in detail in the Shaw area of the eastern Pilbara Craton (Zegers et al., 2001; Fig. 1). The stratigraphy of the Warrawoona Group (Fig. 3) consists of the mafic Talga Talga Subgroup, which is overlain unconformably by the felsic volcanic rocks and volcaniclastic sediments of the Duffer Formation and mafic Salgash Subgroup. The Talga Talga Subgroup consists of pillowed and massive high-MgO basalt, tholeiite, and komatiite, with oceanic geochemical affinities (Hickman, 1983). The Talga Talga Subgroup has not been directly dated, but it is likely to be similar in age to the 3520 Ma deep-water Coonterunah Succession (Buick et al., 1995; Green et al., 2000), which occupies the same stratigraphic position in the central Pilbara (Fig. 1).

Between 3.48 and 3.42 Ga, large volumes of TTG melt (Bickle et al., 1993; Barley, 1993) were produced; they can be classified as typical Archean TTG suites (Smithies, 2000). These melts intruded and were deformed to migmatitic gneisses in the middle crust, intruded as granitoids in the upper crust, and extruded as felsic volcanic rocks of the Duffer Formation. We estimate that the total volume of TTG melt produced during this episode amounts to that of a 5–10-km-thick layer. The Duffer Formation volcanic rocks and clastic sediments were deposited in shallow water (DiMarco and Lowe, 1989) and fill in fault scarps produced by extensional fault systems (Zegers et al., 1996). Granodiorites intruded as sheets along and above an extensional detachment in the Shaw batholith, and migmatitic gneisses were unroofed by the detachment in a metamorphic-core-complex geometry (Zegers et al., 2001). The Duffer Formation is conformably overlain by the 3450 Ma shallow-water (Buick et al., 1995; DiMarco and Lowe, 1989) Salgash Subgroup (Fig. 3), which consists largely of pillowed high-MgO and tholeiitic basalt and minor felsic volcanic and chert units. A remarkably similar and coeval stratigraphy (Onverwacht Group) exists in the Barberton belt of the Kaapvaal craton (Zegers et al., 1998).

MODEL FOR ARCHEAN TECTONICS

Radiogenic heat production in the Middle Archean was about three times higher than at present. It is generally assumed that this heat production resulted in a hotter mantle (Pollack, 1997), which is consistent with abundant high-MgO basalts in greenstone belts (Abbott et al., 1994). In such a hotter mantle, pressure-release melting starts deeper, causing formation of a significantly thicker basaltic crust that overlies a thick and stably stratified harzburgitic residue. The enhanced compositional stratification is such that gravitational instability, necessary for subduction, is not reached in geologically realistic time scales, rendering modern-day subduction processes unlikely. Recycling of eclogite formed in the deep parts of the basaltic crust has been proposed as an alternative (Anderson, 1979; Vlaar et al., 1994).

Combined with observations from the Kaapvaal and Pilbara cratons, this leads to a new model for the formation and stabilization of the early continental crust (Fig. 4). The first

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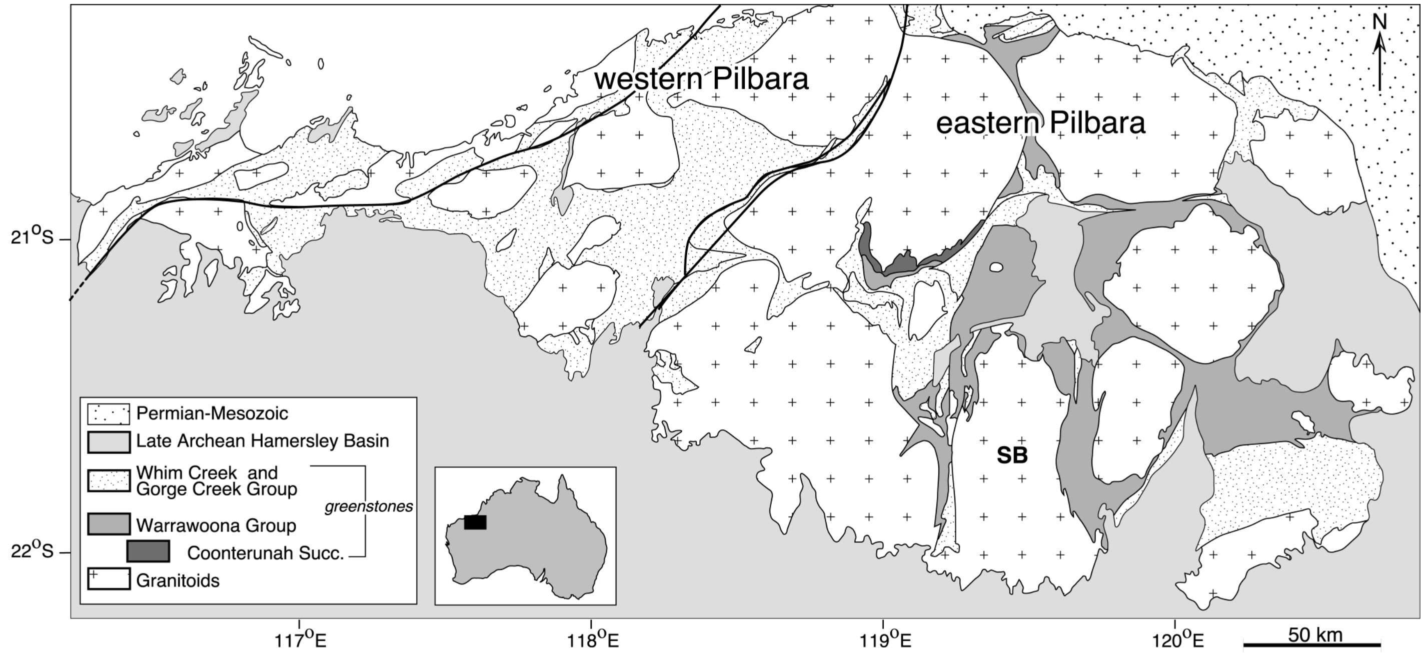

Figure 1. Geologic map of Pilbara granite-greenstone terrane. Eastern Pilbara shows typical ovoid outcrop pattern of granites surrounded by greenstone belts. Major addition of new felsic crust in eastern Pilbara occurred at 3.48–3.42 Ga, by intrusion of TTG (tonalite, trondhjemite, and granodiorite) suite granitoids and deposition of felsic volcanic rocks in Warrawoona Group. SB—Shaw batholith.

step is basalt formation by partial melting from the peridotitic mantle resulting in a thick mafic crust. In the Pilbara craton, this process corresponds to the 3520 Ma Coonterunah Succession and Talga Talga Subgroup. We assume here that the Archean mantle was hotter, but an equivalent model can be constructed by assuming that the mantle was wet (Parman et al., 1997), in which case the reduced solidus leads to a more voluminous melt production. The base of the depleted mantle from which melt was extracted is predicted to be at a depth of about 200 to 250 km in a 250 °C hotter Archean mantle, which is similar to the seismically inferred thickness of the Pilbara and Kaapvaal cratons (Drummond, 1988; Vinnik et al., 1996).

The structure of this protocrust is likely to have been similar to present-day oceanic plateaus: pillow basalts in the upper 10 km and a large volume of doleritic to gabbroic sills in the lower crust (Saunders et al., 1996). The upper brittle part is likely to be cooled efficiently by hydrothermal circulation. The lowest protocrust is in the eclogite stability field.

We assume that the lower mafic protocrust in the Pilbara and Kaapvaal cratons contained small amounts of water or CO_2, which allowed the reaction to eclogite to occur efficiently (Rubie, 1990). For MgO-rich amphibolite, this reaction may occur at 1.2 GPa (Green and Ringwood, 1967) (Fig. 4). Once a sufficiently thick eclogite layer at the base of the crust forms, it will delaminate owing to its high density compared to the underlying harzburgite and to the weakness of the middle crust (Hoffman and Ranalli, 1988). Model calculations show that the eclogite will not cause subduction of the entire basalt-harzburgite sequence, but will sink rapidly in the form of separate diapirs, with relatively little interaction with the underlying harzburgite (Vlaar et al., 1994). This scenario is consistent with the observation from diamond inclusions that the continental root and crust are of similar age. The removal of eclogite from the continental crust also helps explain the mass imbalance between the continental crust and depleted mantle, which requires an additional eclogite reservoir in the deep mantle (Rudnick et al., 2000).

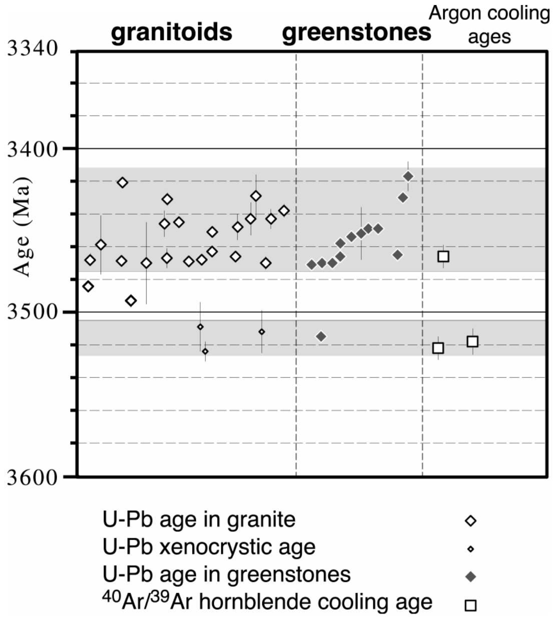

Figure 2. U-Pb zircon and $^{40}Ar/^{39}Ar$ cooling ages (for references, see Nelson et al., 1999) for earliest major continental-crust–forming events in eastern Pilbara craton.

OBSERVATIONAL CONSTRAINTS FROM THE PILBARA

The geological observations in the Pilbara craton are consistent with delamination occurring at ca. 3.49 Ga, just before the production of voluminous TTG melts between 3.48–3.42 Ga. Delamination typically results in rapid uplift, extension, and voluminous magmatism (Kay and Kay, 1993), which are all features of the 3.48–3.42 Ga event in the Pilbara craton. As the delaminated part is replaced by hot, depleted mantle, melts are produced by

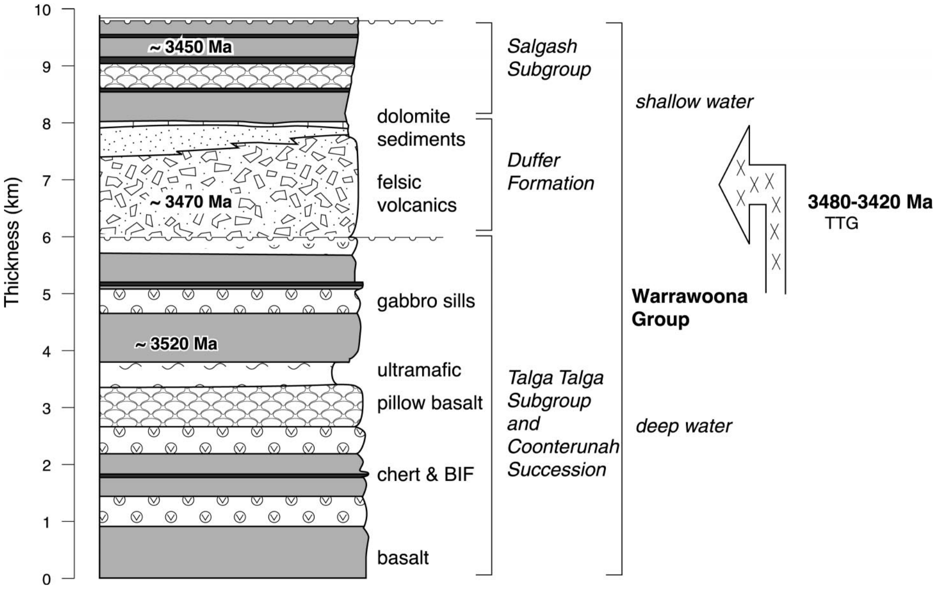

Figure 3. Generalized stratigraphy of Warrawoona Group (after Hickman, 1983; Barley, 1993; DiMarco and Lowe, 1989; Zegers et al., 1996). Talga Talga Subgroup and Coonterunah Succession were deposited in deep water; Duffer Formation and Salgash Subgroup were deposited in shallow water. Thus, rapid uplift is indicated before deposition of Duffer Formation. BIF—banded iron formation.

both decompression melting of the mantle, resulting in high-MgO basalts (Salgash Subgroup in the Pilbara craton), and melting of the gabbroic and amphibolitic lower crust, producing TTG melts. Partial melting of the protocrust to higher levels can be envisaged as a multistep process in which heat is conducted to higher levels and advection of heat occurs by intrusion of partial melts in subsequently higher levels (Fig. 4). TTG melt products that intrude are subsequently metamorphosed and possibly partially melted, as inferred from migmatitic gneisses. This multistep history can be the reason for the complex pattern of U-Pb zircon ages of gneisses and granodiorites found within one batholith (Fig. 2) and the range in geochemical compositions of the Pilbara TTG suite (Bickle et al., 1993). Simple mass- and heat-balance considerations suggest that delamination of a 10-km-thick eclogite layer would have led to 2 km of uplift and that the conducted and advected heat would allow mid-crustal melting and TTG production within 10–20 m.y. after delamination, which is consistent with the geologic evidence (Fig. 2). To produce 10 km of TTG melt from 30 km of mafic protocrust, an average of 30% partial melting is required. Melting contours in Figure 4 show that the 30% melt contour is exceeded with the high temperatures reached in the lower and middle crust.

Experiments on dehydration melting of amphibolite (Wolf and Wyllie, 1993; Wyllie et al., 1997) show that melting can take place over a wide range of pressure and temperature conditions (Fig. 4) and is facilitated by higher water content. The mineral composition of the residue depends on pressure and temperature conditions. Between 875 and 980 °C, garnet is formed in the residue after partial melting of amphibolite, and depending on the garnet content, the residue can have a density of 3.35–3.50 g/cm^3. This high density will lead

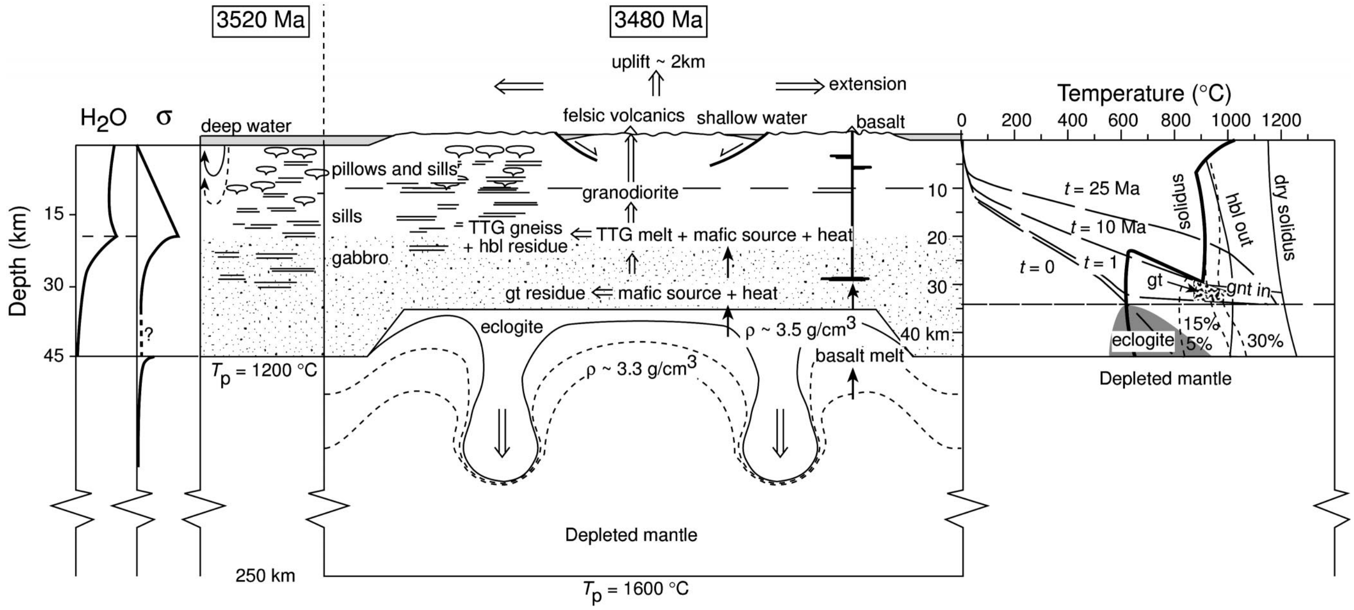

Figure 4. Model for delamination of thick oceanic crust. Partial melting in mantle with potential temperature (T_p) of 1600 °C leads to thick oceanic crust (45 km) and thick depleted mantle (200 km), shown on left. Oceanic crust, corresponding to 3520 Ma Coonterunah Succession in Pilbara craton, is hydrothermally altered by circulation of seawater. Qualitative water content is shown as a plot of H_2O. At ca. 3.49 Ga, lower oceanic crust, which has been metamorphosed to eclogite, delaminates from ductile middle crust (see strength, σ, profile for thick oceanic crust [Hoffman and Ranalli, 1988]). Eclogite is replaced by depleted mantle, forming basaltic melt by pressure-release melting. Overlying oceanic crust is intruded by these melts and conductively heated, resulting in melting of mafic protocrust to form TTG (tonalite, trondhjemite, and granodiorite) melts. Delamination of 10 km of eclogite results in ~2 km of uplift and associated extension in brittle upper crust. At right, solidus and melt contours are shown for dehydration-melting of amphibolite (hbl = hornblende; Wyllie et al., 1997; Rapp, 1997) in combination with estimated geotherms (based on conductive heating) in thick mafic protocrust before delamination, directly after delamination, and 10 and 25 m.y. after delamination. Garnet (gt) is formed in residue in patterned area of pressure-temperature conditions (Wolf and Wyllie, 1993).

to a renewed delamination event and subsequent uplift, extension, and magmatism. At lower depth, the residue will consist of hornblende, plagioclase, and clinopyroxene. TTG production will eventually cease when the heat effects of delamination have dissipated and when no new garnet residue is produced to cause delamination, because the crust is too thin (<30 km) to be in the garnet stability field.

In the Pilbara craton, the entire range of U-Pb ages (Fig. 2) of the TTG event spans from 3.49 to 3.42 Ga in the TTG suites and volcanic rocks, but two peaks at 3.47 and 3.45 Ga occur. We propose that the two peaks may each represent a delamination event, the second one of the garnet residue.

DISCUSSION AND CONCLUSIONS

Inferring tectonic processes from the few largely undisturbed products that remain from the Middle Archean is no easy task, and it is clear that there is no single observation that conclusively favors one tectonic process over another. The model presented here bears some similarities to two previously proposed models but differs in essential points. Glickson (1972) invoked megarippling of oceanic crust to form eclogite and deep melting of the oceanic crust. Hoffman and Ranalli (1988) proposed ''flake tectonics,'' in which delamination of the entire lithosphere (including the mantle part) takes place. But neither of these models satisfies the aforementioned constraints on the geophysical and geologic structure of the Pilbara or Kaapvaal cratons.

The eclogite-delamination model explains a wide range of observations that have been insufficiently explained by subduction models. These observations include (1) the compositional difference between subcratonic Archean and post-Archean lithospheric mantle and the spatial and temporal link between Middle Archean crust and depleted mantle, (2) the seismically inferred thinner continental crust and absence of the basal high-velocity layer in Middle Archean cratons, (3) coeval TTG melt over a large (20 000 km^2) area, (4) substantial uplift, extension, and core-complex formation during intrusion of TTG suites and juxtaposition of high-grade gneisses with low-grade greenstones, and (5) the nonlinear arrangement of volcanic rocks, structures, and metamorphism.

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