

Lower crustal flow kept Archean continental flood basalts at sea level

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ABSTRACT

Large basaltic provinces as much as 15 km thick are common in Archean cratons. Many of these flood basalts erupted through continental crust but remained at sea level. Although common in the Archean record, subaqueous continental flood basalts (CFBs) are rare to absent in the post-Archean. Here we show that gravity-driven lower crustal flow may have contributed to maintaining Archean CFBs close to sea level. Our numerical experiments reveal that the characteristic time to remove the thickness anomaly associated with a CFB decreases with increasing Moho temperature (T_M), from 500 m.y. for $T_M \approx 320$ °C to 1 m.y. for $T_M \approx 900$ °C. This strong dependency offers the opportunity to assess, from the subsidence history of CFBs, whether continental geotherms were significantly hotter in the Archean. In particular, we show that the subsidence history of the ca. 2.7 Ga upper Fortescue Group in the East Pilbara Craton, Western Australia, requires Moho temperatures $\gg 700$ °C. Applied to eight other unambiguous subaqueous Archean CFBs, our results indicate Moho temperatures $\gg 650$ °C at the time of eruption. We suggest that the decrease in the relative abundance of subaqueous CFBs over Earth's history could reflect the secular cooling of the continental lithosphere due to the decrease in radiogenic heat production.

INTRODUCTION

A salient feature of the Archean geological record is the abundance of subaqueous greenstone belts 5–15 km thick, dominated by mafic volcanics and covering areas $>100,000$ km² (de Wit and Ashwal, 1997; Arndt, 1999; Kump and Barley, 2007). Archean greenstone belts differ in composition, structure, and geological setting, including arc-like and mantle plume settings. We aim to explain why thick continental flood basalts (CFBs) failed to emerge and thus why subaqueous CFBs were relatively common in the Archean (Table 1; Arndt, 1999; Kump and Barley, 2007) but became rarer through geological time. The only two unambiguous post-Archean occurrences of subaqueous CFBs are the Paleoproterozoic komatiites

of the Gilmour Islands, Hudson Bay (Arndt, 1982), and the ca. 250 Ma Siberian flood basalts (Czamanske et al., 1998). We note that maintaining Archean CFBs as much as 10 km thick and emplaced in <70 m.y. (Table 1) below sea level would require a change in sea level of >1 km over a few tens of million years. Changes in eustatic sea level do not suffice to explain this observation because they have amplitudes of ~ 200 m in the Phanerozoic (Müller et al., 2008) and of <1 km over Earth's history (Flament et al., 2008). In this paper we focus on intraplate subaqueous Archean flood basalts that erupted away from continental rifting (Arndt, 1999; Tomlinson and Condie, 2001; Table 1); this allows us to characterize gravity-driven subsidence. Our generic

thermo-mechanical numerical experiments suggest that synemplacement to postemplacement lateral ductile flow of hot lower crust could have maintained Archean CFBs close to sea level. Comparing our modeling results to the eruption time of subaqueous Archean CFBs, we place broad constraints on the continental geotherm at the time of their eruption.

HYPOTHESIS AND MODEL

We hypothesize that the ductile lower continental crust can flow under the weight of a CFB to minimize the lateral pressure contrast in the lithosphere. To evaluate the time needed for the crust to reach mechanical equilibrium, we design a two-dimensional Cartesian model of a vertically stratified continental lithosphere on which a CFB has been emplaced and is in isostatic equilibrium (Fig. 1). The models are 800×100 km and they consist, from top to bottom, of a 20-km-thick compressible air-like layer, a volcanic plateau, a 40-km-thick continental crust, and the uppermost 40 km of the mantle (Fig. 1). We consider CFBs of 300 km width, and thicknesses of 3, 6, 9, and 12 km, and we use a conservative density of 2840 kg m⁻³, as CFBs consist of as much as 50% sediments. We adopt a viscoplastic rheological model, combining frictional flow (for methods, see the GSA Data Repository¹) and the temperature-dependent viscosity law (modified from Solomatov and Moresi, 1997):

$$\eta = \eta_0 \exp(-\gamma T), \quad (1)$$

TABLE 1. CHARACTERISTICS OF SELECTED SUBAQUEOUS ARCHEAN CONTINENTAL FLOOD BASALTS

Name	Craton	Events*	Thickness (km)	Age (Ma)	Duration (m.y.)	References
Lower Maddina Fm., Fortescue Gp.	Pilbara	1	~ 0.6	2718 ± 3 – 2713 ± 3	≤ 11	Blake et al. (2004)
Kylena Fm., Fortescue Gp.	Pilbara	1	≤ 1.4	2749–2735	14	Thorne and Trendall (2001)
Honman Fm., Lake Johnston gr. belt	Yilgarn	1	≤ 1.2	2921 ± 4 – 2903 ± 5	≤ 28	Wang et al. (1996)
Ngezi Gp., Bellingwe gr. belt	Zimbabwe	2	6.5	2692 ± 9	18?	Tomlinson and Condie (2001); Chauvel et al. (1993)
Upper Kam Gp., Yellowknife belt	Slave	3	~ 6	2722 ± 2 – 2701 ± 1	≤ 24	Isachsen and Bowring (1994)
Kambalda gr. belt	Yilgarn	4	~ 4	2726 ± 30 – 2690 ± 5	≤ 71	Tomlinson and Condie (2001)
Lower Warrawoona Gp., Marble Bar gr. belt	Pilbara	sequence	~ 3	3490–3469	> 21	van Kranendonk et al. (2004)
Balmer assemblage	Superior	sequence	< 10	2992–2964	> 28	Tomlinson and Condie (2001)
Lumby Lake gr. belt	Superior	sequence	≤ 7	< 2963 – 2898	< 70	Tomlinson and Condie (2001)
Kolar schist belt	Dharwar	sequence	~ 4	ca. 2700	N.D.	Krogstad et al. (1989)

Note: N.D.—no data; Fm.—Formation; Gp.—Group; gr.—greenstone.

*Number of distinct formations representing distinct magmatic events.

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¹GSA Data Repository item 2011343, extended methods, supplementary references, Figures DR1 and DR2, and Tables DR1 and DR2, is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

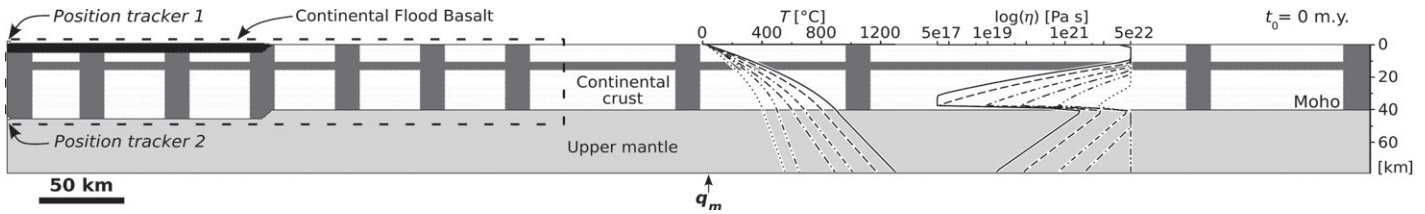


Figure 1. Setup to model crustal removal following eruption of continental flood basalt. Geometry, material densities, continental geotherms, viscosity profiles, and Lagrangian position trackers used in models. Thick, dark gray lines in continental crust are strain markers. Area within dashed frame is shown in Figure 2.

where T is the temperature, η_0 is the reference viscosity, and $\gamma = Q/RT_p^2$, Q being the activation enthalpy, R the gas constant, and T_p the temperature at the base of the lithosphere (parameter values are given in Table DR1 in the Data Repository). We limit the range of viscosities to 5×10^{17} – 5×10^{22} Pa s to optimize calculation time.

We use a thermal model in which the depth-independent crustal heat production is calculated back in time (see the Data Repository) from the present-day concentration of the bulk Archean continental crust (Taylor and McLennan, 1995; Tables DR1 and DR2). We allow the mantle heat flow to vary from a conservative present-day cratonic value of 12 mW m^{-2} (Jaupart and Mareschal, 1999) to 33.5 mW m^{-2} (Table DR2). Using the composition of present-day cratons is conservative because the most radiogenic uppermost 3–7 km of Archean continental crust have been eroded over time (Galer and Mezger, 1998). We compute an initial series of 6 geotherms with $400 \text{ °C} < T_M < 900 \text{ °C}$ (Fig. 1; Table DR2) that result in lithospheric rheological profiles in which the viscosity of the lower continental crust decreases from 5×10^{21} Pa s for $T_M \approx 400 \text{ °C}$ to 5×10^{18} Pa s for $T_M \approx 680 \text{ °C}$ (Fig. 1), in agreement with laboratory estimates of dislocation creep laws of quartzite (Gleason and Tullis, 1995).

RESULTS

For $T_M \geq 600 \text{ °C}$, we observe that the removal of the contrast in thickness of the continental crust due to the CFB occurs through lateral flow in a weak lower crustal channel (Fig. 2). The horizontal pressure gradient due to the final width of the CFB drives the flow. The channel is characterized by a Poiseuille-like velocity profile, and its thickness h increases from 10 to 15 km for increasingly hot geotherms. The removal of thickness contrast, determined from two Lagrangian position trackers (Fig. 1), follows an exponential evolution (Fig. DR1):

$$w(t) = w_0 \exp(-t/\tau_r), \quad (2)$$

where $w(t)$ is the cumulative thickness of the crust and CFB after a time t , w_0 is the initial cumulative thickness of the crust and CFB, and

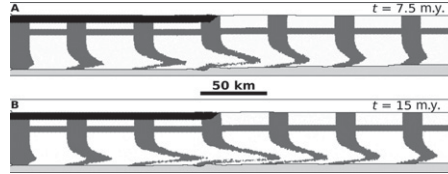


Figure 2. Thickness removal and subsidence of continental flood basalt (CFB) by lower crustal flow. Strain markers for numerical simulation with Moho temperature of $\sim 680 \text{ °C}$ and 6-km-thick CFB. **A:** After time, t , of 7.5 m.y. **B:** After 15 m.y.

τ_r is the characteristic relaxation time of thickness removal by lower crustal flow. We obtain τ_r for each model by fitting the calculated evolution of the thickness of the continental crust (Fig. DR1).

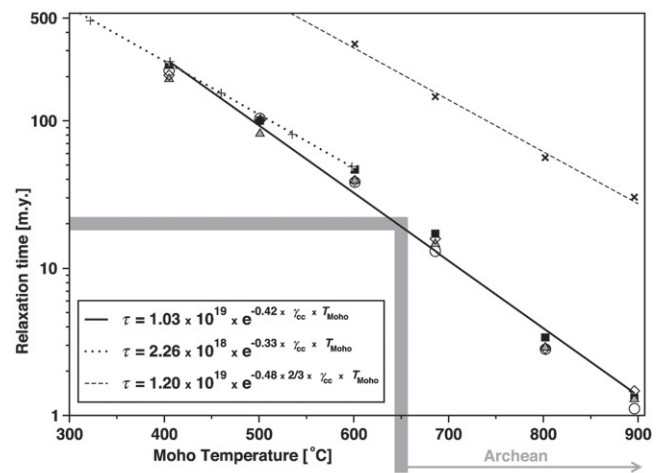
Two series of models with varying CFB density and increasing CFB half-width λ allow us to verify that τ_r is inversely proportional to CFB density and that τ_r increases with λ until it reaches a nearly constant value for $\lambda/h \geq 10$ (McKenzie and Jackson, 2002). In addition, τ_r is independent of the thickness of the CFB (Kruse et al., 1991; Fig. 3). Our key result is the exponential decrease of τ_r with increasing T_M , from ~ 500 m.y. for $T_M \approx 320 \text{ °C}$ to 1 m.y. for $T_M \approx 900 \text{ °C}$ (Fig. 3). This relationship is due to the

dependency of τ_r on viscosity (McKenzie and Jackson, 2002), which depends exponentially on temperature (Equation 1). Fitting the results for the series of six geotherms with various temperature dependence of the rheology gives a scaling law with an exponential constant of the order of $\gamma_{cc}/3$ (Fig. 3). This suggests that the effective viscosity of the modeled lithosphere during the relaxation of the topographic load is an average between the viscosity of the fast-flowing weak lower crust and the larger effective viscosity of the slow-deforming upper crust and upper mantle. In addition, the consistency of the fitted exponential constant for different rheological laws and continental geotherms suggests that the scaling laws we derived are robust.

CASE STUDY: SUBSIDENCE HISTORY OF THE UPPER FORTESCUE GROUP

The strong dependency of the relaxation time on Moho temperature offers the opportunity to constrain the geotherm at the time of eruption of a CFB from its subsidence history. In the following, we apply this concept to the Neoproterozoic upper Fortescue Group, Pilbara Craton, Western Australia. In the East Pilbara Craton, the 6.5-km-thick, 2775–2630 Ma Fortescue Group (Thorne and Trendall, 2001) is preferentially preserved in broad synclines and centroclines. While the

Figure 3. Scaling laws (black lines) for characteristic time of thickness removal (τ_r) as function of Moho temperature (T_{Moho}) (see text). Results are presented for three series of models. (1) Reference model for 12 km thickness of continental flood basalt (CFB) (circles), 9 km thickness (diamonds), 6 km thickness (gray triangles), and 3 km thickness (black squares). (2) 6 km thickness of CFB and $\gamma = 2/3 \gamma_{cc}$ in Equation 1 (see text; x symbols). (3) 6 km thickness of CFB, $\gamma = \gamma_{cc}$ in Equation 1, and continental crust 30 km thick (plus symbols). Thick gray lines show maximum relaxation time and minimum Moho temperature for subaqueous Archean CFBs (Table 1).



ca. 2772 Ma Mount Roe Basalt and the 2765–2752 Ma Hardey Formation were folded and faulted during their deposition, markers of syn-depositional extension are lacking in the upper (younger than 2752 Ma) Fortescue Group (Williams and Bagas, 2007). A paleostress analysis in the Meentheena centrocline reveals that a radially symmetric stress regime prevailed during its formation (Fig. DR2). This suggests that continental extension, which would be characterized by a unidirectional minimum horizontal stress, exerted little to no control on the emplacement and subsidence of the ≥ 2.5 -km-thick upper Fortescue Group (Fig. 4). In addition, there is abundant evidence for subaqueous sedimentation and volcanism throughout the Fortescue Group (Thorne and Trendall, 2001). Despite

being mostly subaerial in the East Pilbara Craton area, the effusive volcanics of the Kylena (2749–2735 Ma), Tumbiana (2729–2715 Ma), and Maddina (2718–2713 Ma) Formations alternate with stromatolite-bearing shallow-water sedimentary rocks of the Mopoke, Meentheena, and Kuruna Members (Thorne and Trendall, 2001; Williams and Bagas, 2007; Fig. 4). This alternation indicates that the erupting basalts were episodically brought back to sea level. In the absence of tectonic extension and of significant erosional features during the emplacement of the upper Fortescue Group, we suggest that the subsidence of these basalts is the surface expression of lower crustal flow. The Moho temperature at the time of emplacement of the upper Fortescue Group can be estimated from

its subsidence history and our modeling results. The ≤ 1400 -m-thick basalts of the Kylena Formation erupted in ~ 14 m.y. (Williams and Bagas, 2007; Fig. 4) and are stratigraphically bounded by the shallow-water sediments of the Mopoke and Mingah Members (Fig. 4). The lower ~ 600 -m-thick basalts of the Maddina Formation erupted in ≤ 11 m.y. (Blake et al., 2004; Fig. 4) and are stratigraphically bounded by the shallow-water sediments of the Meentheena and Kuruna Members (Fig. 4). For these formations that were episodically below sea level, the thickness removal time is necessarily much shorter than the eruption duration. Thus, assuming constant sea level, the subsidence of the Kylena Formation and Maddina Formation basalts requires Moho temperatures at the time of CFB emplacement much greater than 680 °C and 700 °C, respectively (Fig. 3). Given the uncertainty on the dependency between rheology and temperature, the uncertainty on these Moho temperatures is ± 100 °C.

DISCUSSION

The example of the upper Fortescue Group discussed here illustrates that subaqueous Archean CFBs as much as 10 km thick could have resulted from lower crustal flow during the repeated accumulation of kilometer-thick basaltic piles. Our model can be tested on at least eight other subaqueous Archean CFBs for which available high-precision geochronological data indicate that the eruption duration of individual basaltic events was ≤ 20 m.y. (Table 1). Because τ_f is necessarily $\ll 20$ m.y. for these subaqueous CFBs, our modeling results indicate Moho temperatures $\gg 650$ °C (Fig. 3) and viscosities of the lower crust $\ll 1.4 \times 10^{19}$ Pa s (Equation 1). This temperature estimate is ≥ 250 °C hotter than the present-day Moho temperature of Archean cratons of 400 ± 100 °C (Artemieva, 2009). The question arises whether the Moho temperatures that we derived for the time of emplacement of a CFB are representative of a steady-state geotherm, or of a geotherm transiently hot due to thermal anomaly at the origin of the CFB. Rey et al. (2003) showed that it takes >20 m.y. for a thermal anomaly at the base of the mechanical lithosphere (isotherm 900 °C) to heat up the Moho. Therefore, the Moho temperatures derived from the subsidence history of each of the basaltic events that constitute subaqueous CFBs represent steady-state geotherms rather than transient geotherms. The fact that Phanerozoic CFBs that erupted in <20 m.y., including the Deccan, Paraná-Etendeka, and Karoo basalts (Richards et al., 1989), are subaerial confirms that the lower crust remained cool during their eruption. The greater abundance of subaqueous CFBs in the Archean indicates that Archean continental geotherms were significantly hotter than their present-day counterparts.

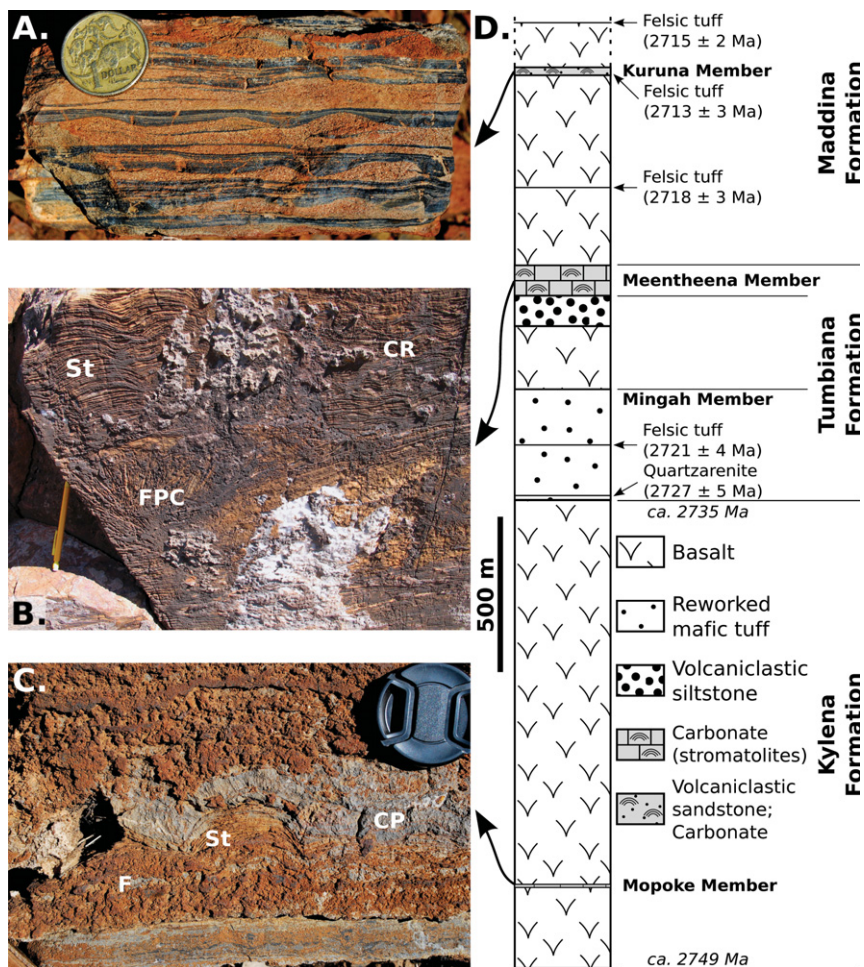


Figure 4. Sedimentology and stratigraphy of upper Fortescue Group in Meentheena centrocline. Three carbonate members display shallow-water facies. A: Wavy bedding (mudstone-sandstone interlayers) with laminated, rippled sand sheets indicates overbank and floodplain depositional environment (Kuruna Member). Diameter of coin is 25 mm. **B:** Laterally linked stromatolites (St) and their lateral sediments with climbing ripples (CR) overlying imbricate flat pebble conglomerate (FPC) indicate tidal-flat environment (Meentheena Member). Length of pen is 14 cm. **C:** Silicified carbonate precipitates (CP), stromatolites, and fenestrae (F) in restricted tidal-flat environments (Mopoke Member). Diameter of lens cap is 5 cm. **D:** Simplified stratigraphic column. Geochronological data are from Blake et al. (2004); ages for Kylena Formation and all thicknesses are from Williams and Bagas (2007). Dashed section of Maddina Formation does not crop out in Meentheena centrocline.

Our models suggest that the flow of hot, ductile lower crust was a key process that maintained CFBs at sea level. This is consistent with high-temperature shear fabrics described in Archean lower crust (Sandiford, 1989; Krogh, 1993). As the continental lithosphere became cooler over time, both CFBs and the underlying continental crust emerged, with major consequences for the composition of the atmosphere and of the oceans (Kump and Barley, 2007; Rey and Coltice, 2008; Flament et al., 2008).

Other processes have been put forward to explain the anomalous subsidence observed in some volcanic provinces. For example, Elkins Tanton and Hager (2000) attributed the anomalous subsidence of the Phanerozoic Siberian flood basalts to the freezing of rising melts into eclogite, triggering lithosphere removal via Rayleigh-Taylor instability. This model, which requires a very thin lithosphere, predicts an initial uplift due to the rising plume head followed by subsidence due to the delamination of the lithosphere throughout a short eruption (≤ 5 m.y.). Alternatively, Leng and Zhong (2010) proposed that the ponding of mantle plume head at the 660 km boundary could result in protracted, small-amplitude subsidence followed by rapid and important uplift prior to the eruption of a CFB. Neither of these processes reproduces the alternation between subaerial and subaqueous facies that is observed over >35 m.y. in the Fortescue Group (Fig. 4).

CONCLUSIONS

Our numerical experiments and the field examples discussed herein suggest that CFBs can remain at sea level if the lower crust can flow at a rate comparable to that of eruption. We show that the characteristic time to remove the thickness anomaly associated with a CFB by flow of the lower crust strongly depends on Moho temperature. This allows us to use the subsidence history of subaqueous Archean CFBs emplaced in an intraplate setting to place broad constraints on the continental geotherms at the time of their eruption. We show that the subsidence history of the upper Fortescue Group in the East Pilbara Craton and the subsidence histories of other subaqueous Archean CFBs are compatible with lower crustal flow. Together with our modeling results, this points to Archean Moho temperatures $\gg 650$ °C. For intraplate CFBs erupted over hot continental crust, our model predicts (1) alternating subaerial and subaqueous volcano-sedimentary facies during eruption, (2) shearing in the ductile lower continental crust upon loading, and (3) limited crustal thickness gradient. We speculate that subaqueous CFBs became less common over Earth's history because lower crustal flow became less efficient as the continental lithosphere cooled due to lesser radioactive heat production.

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