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# Thermal evolution of the Earth as recorded by komatiites

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## Abstract

Komatiites are rare ultramafic lavas that were produced most commonly during the Archean and Early Proterozoic and less frequently in the Phanerozoic. These magmas provide a record of the thermal and chemical characteristics of the upper mantle through time. The most widely cited interpretation is that komatiites were produced in a plume environment and record high mantle temperatures and deep melting pressures. The decline in their abundance from the Archean to the Phanerozoic has been interpreted as primary evidence for secular cooling (up to 500°C) of the mantle. In the last decade new evidence from petrology, geochemistry and field investigations has reopened the question of the conditions of mantle melting preserved by komatiites. An alternative proposal has been rekindled: that komatiites are produced by hydrous melting at shallow mantle depths in a subduction environment. This alternative interpretation predicts that the Archean mantle was only slightly ( $\sim 100^\circ\text{C}$ ) hotter than at present and implicates subduction as a process that operated in the Archean. Many thermal evolution and chemical differentiation models of the young Earth use the plume origin of komatiites as a central theme in their model. Therefore, this controversy over the mechanism of komatiite generation has the potential to modify widely accepted views of the Archean Earth and its subsequent evolution. This paper briefly reviews some of the pros and cons of the plume and subduction zone models and recounts other hypotheses that have been proposed for komatiites. We suggest critical tests that will improve our understanding of komatiites and allow us to better integrate the story recorded in komatiites into our view of early Earth evolution.

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## 1. Introduction

Many lines of evidence suggest that the early Earth was hotter than it is today. Increased heat-

ing from higher concentrations of radioactive isotopes, heat generated from the segregation of the core and from the initial accretion of the Earth (including a giant moon-forming impact) were likely large enough to have melted much or all of the silicate mantle [1]. While some aspects of the initial thermal state of the mantle seem relatively certain, the subsequent evolution is poorly constrained. An important unknown is the ratio of heat loss to heat production (Urey ratio).

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Higher mantle temperatures would have driven vigorous convection that would have rapidly cooled the mantle. Depending upon the temperature dependence of mantle viscosity chosen, the results of numerical models of secular cooling vary widely, from models that approach current mantle temperatures within the first 500 Myr to models that retain high temperatures into the Proterozoic [2]. The chemical compositions of mafic magmas record the temperature and depth of melt generation, and therefore provide important constraints on mantle conditions throughout Earth history. It is here that komatiites have played an important role, because their compositional characteristics have been used to trace mantle melting depths, temperatures and processes back into the Archean.

As a consequence of erosion, meteorite impacts, early plate tectonic processes or their equivalent there is imperfect preservation of the ancient record of igneous activity on the Earth. Today the basaltic crust formed at mid-ocean ridges and constituting ~70% of the Earth's surface preserves only the latest moments (~170 million years) of its 4.5 billion year magmatic history [3]. Arguably, most of this rock record has been lost and recycled back into the Earth's interior. The rock record that is preserved in the Earth's continental crust extends much further into the geologic past, but preservation deteriorates with increasing age. Detrital zircon crystals found in sandstones at Jack Hills in Australia came from rocks as old as 4.4 Ga [4]. The oldest crustal rocks currently known are the ~4.0 Ga Acasta gneisses [5], a series of granites, granodiorites and tonalites, and the oldest preserved mafic volcanic sequences are ~3.8 Ga [6,7].

Komatiite lavas were first recognized by the Viljoen brothers in the Barberton Mountainland of South Africa in 1965 [8,9]. These rocks represent some of the oldest ultramafic magmatic rocks preserved in the Earth's crust at 3.5 Ga [10]. Shortly after the recognition of these rocks as a record of submarine volcanic activity, komatiites were discovered in the late Archean (2.7 Ga) Abitibi Belt in Munro Township, Ontario, Canada [11]. In 1979 komatiites of Cretaceous age were discovered on Gorgona Island [12]; these repre-

sent the youngest example of komatiite volcanism. Further investigation of Archean terranes led to the recognition of komatiites that range from Archean to Cretaceous in age [13] with most occurring between 3.5 and 1.5 Ga and a peak in komatiite preservation occurring in the late Archean. Recent discoveries of komatiites include a Phanerozoic occurrence in Vietnam [14], and the new compositionally distinct 3.3 Ga komatiites from the Comondale Belt, South Africa [15,16].

Komatiites are distinguished as ultramafic volcanic rocks containing spinifex olivine textures with MgO contents > 18 wt% (Fig. 1). The maximum MgO content of komatiites is probably 25–30 wt% MgO, but this is a controversial issue, because all komatiites have been chemically modified by metamorphic processes. When high-MgO komatiites from Barberton were subjected to anhydrous melting experiments in the laboratory, they were found to possess very high liquidus temperatures (> 1600°C), a result that was initially interpreted to indicate deep melting conditions (150 km) at high temperatures [17,18] at 3.5 Ga. The progressive decline of komatiites in the Neoproterozoic and their near absence in the Phanerozoic (only three examples) has been used as evidence that conditions in the Earth's mantle had changed in some way through geologic time. The simplest explanation is that this change reflects secular cooling of the mantle.

Typically, komatiites are found interlayered with a variety of igneous lavas. These lower-MgO lavas (variously termed komatiitic basalt, basaltic komatiite or siliceous high-magnesium basalt) along with basalts and olivine cumulates generally form the bulk of the stratigraphy, with komatiites usually representing less than 20% of a sequence [13]. The interpretation of the lower-MgO magmas, especially the basaltic komatiites (Fig. 1), is a key question in the debate over the origin of komatiites. Are they related to komatiites by fractionation or crustal contamination? Were they produced by distinct melting conditions during the komatiite-producing event? Are they totally unrelated?

Archean komatiites are often found in the crust attached to depleted cratonic lithospheric mantle. The mantle beneath Archean cratons is distinct

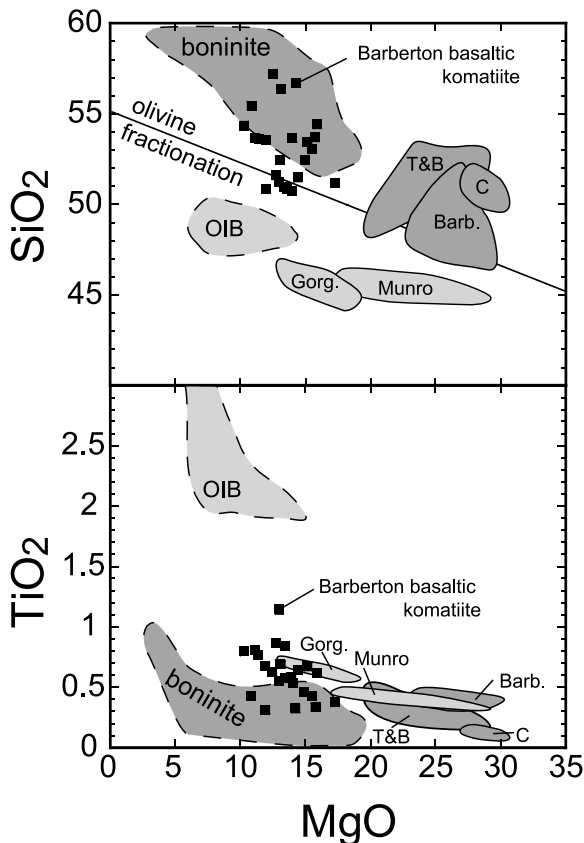


Fig. 1.  $\text{SiO}_2$  and  $\text{TiO}_2$  versus  $\text{MgO}$  in komatiites (fields with solid boundaries), basaltic komatiites (filled squares) and modern mafic magmas (fields with dashed boundaries). Solid line in top panel shows compositional effect that olivine fractionation would have on the most  $\text{MgO}$ -rich Barberton komatiite. The majority of the basaltic komatiites in Barberton cannot be made by olivine fractionation from a komatiite parent. Boninites (modern subduction-related magmas) show a large compositional overlap with Archean basaltic komatiites. Komatiites show a wide range of major and minor element composition. High- $\text{SiO}_2$  komatiites (dark fields) resemble modern boninite magmas that are produced by hydrous melting, while low- $\text{SiO}_2$  komatiites (light fields) more closely resemble modern basalts produced by anhydrous decompression melting. The low  $\text{TiO}_2$  content of komatiite magmas requires their source to have been depleted (i.e. already have had a melt extracted from it). Komatiites: Barb. (Barberton, South Africa, 3.5 Ga [68]), C (Comondale, South Africa, 3.3 Ga [16]), T (Tisdale, Canada, 2.7 Ga [46]), B (Ball, Canada, 2.9 Ga [48]), Munro (Munro, Canada, 2.7 Ga [46]) and Gorg. (Gorgona, South America, 0.088 Ga [93]). Modern magmas: OIB (ocean island basalt, GeoRoc online database), boninite (GeoRoc online database).

from all other mantle reservoirs and one of its distinguishing chemical characteristics is that it is highly depleted. Boyd [19] suggested a genetic link between komatiite and cratonic lithosphere. Age dating using Os isotopic techniques on the mantle xenoliths from the Kaapvaal craton [20] indicates that the melting event that depleted the mantle occurred during the time period that the South African komatiites were being produced (3.0–3.5 Ga). So there is permissive evidence that komatiites and cratonic mantle may somehow be linked in their origin. If cratonic mantle (or some part of it) is the residue of komatiite extraction, the pressure–temperature conditions recorded by cratonic xenoliths place additional constraints on komatiite melting conditions [21].

## 2. Historical overview

The first discussions concerning the existence of ultramafic magmas occurred in the first half of the 20th century, before there was any consensus that the chemical composition of the Earth's upper mantle was also ultramafic; specifically that it consisted of peridotite. One early interpretation of alpine peridotites was that they represented igneous intrusions of ultramafic magmas [22,23]. We know now that these rocks do not represent mantle melts, but are fragments of the Earth's upper mantle that have been tectonically emplaced into the crust. However, in the 1960s the question of the significance and/or existence of alpine peridotites as magmatic rocks was still very much an open topic [24]. Hess [25] was one of the proponents of the peridotitic magma hypothesis. At the same time Engel et al. were searching for a single primary magma [26] that had been produced throughout geologic time by mantle melting. In this context it is interesting to note that both Hess [27] and Engel et al. [28] were among the early visitors to see the Viljoens' exciting discovery of komatiites, and both thought that these new igneous rocks held promise for increasing our understanding of early Earth igneous processes.

The time interval of the discovery of the komatiites overlapped with the plate tectonic revo-

lution, the detailed exploration of the Earth's ocean floor and the return of the first lunar samples. Thoughts on the significance of komatiite magmas rapidly evolved in response to the context provided by these new discoveries. The original interpretation of the Viljoens [8] was that komatiites represented the first crust formed on Earth as a result of a catastrophic melting event triggered by convective overturn during core formation. A meteorite impact origin for komatiites [29] was also proposed. Fyfe [30] suggested that komatiites formed in an Archean plume-dominated environment. This mode of origin has become the most widely accepted. However, discussion of the processes and/or tectonic setting of komatiites did not end with the proposal put forth by Fyfe. Using chemical information and/or field setting, komatiites were proposed to form in mid-ocean ridge environments [31,32]. Others pointed out the uniqueness of komatiites and suggested that they could not be specifically associated with a tectonic environment [33]. Green [18] suggested that melting occurred as a result of the ascent of hot mantle diapirs from depths as great as 150 km. His later re-evaluation of this melting model led to the suggestion that melting began at this depth, but extended to very shallow depths [34,35]. The origin of komatiite in a wet melting environment was proposed by Allègre [36]. The similarity between modern mafic arc lavas and komatiitic lavas was noted by Brooks and Hart [33] and Cameron et al. [37] and implied komatiite generation in a subduction zone. The possibility of a planet-wide melting event was revitalized by Nisbet and Walker [38]. Others [39] have suggested that plate tectonics did not operate in the Archean, and that vertical tectonics drove magma generation processes. Of these many hypotheses, the plume model is currently the most popular, and proponents of it have recently reasserted their arguments for producing komatiites by this process [40].

### 3. Present status of the field: a re-evaluation of komatiite melting conditions

Several recent discoveries have led to a recon-

sideration of the significance of komatiite magmatism. New petrologic evidence from the komatiites in the Barberton Mountainland resulted in: (1) a revision of the MgO contents of the igneous protolith downward, lowering the anhydrous liquidus temperature to 1430°C, and (2) new estimates of magmatic water contents, indicating at least 3 wt% dissolved H<sub>2</sub>O in the komatiite magmas [41]. Petrologic evidence preserved in igneous minerals and melt inclusions that have escaped metamorphic alteration also shows dissolved H<sub>2</sub>O abundance levels from 0.3 to >2% in komatiite magmas from Munro Township, Canada, Belingwe, Zimbabwe and Kola Peninsula, Russia [42–45]. New occurrences of komatiites have been discovered where the komatiites are interlayered with Archean lavas that resemble modern ultramafic arc lavas (boninites). These include komatiites in the late Archean Tisdale volcanic belt [46,47], 3.0 Ga komatiites from the Uchi subprovince in the Superior Craton of Canada [48] and komatiite–boninite associations in the Nondweni, South Africa [49]. Finally, high-MgO, high-SiO<sub>2</sub> lavas, the 3.3 Ga Commondale ultramafic suite, have been discovered in the southern Kaapvaal Craton, South Africa [15,16] and represent a new variety of orthopyroxene-bearing komatiites. Wilson et al. [16] propose a hydrous melting origin in a subduction environment to explain this distinctive type of komatiite.

An increasing appreciation of the complex chemical diversity of komatiites is a major driving force for the re-evaluation of the existing melting models. In Fig. 1 we show the chemical compositional variations in MgO, SiO<sub>2</sub> and TiO<sub>2</sub> for komatiites from a variety of localities as well as modern plume and arc magmas. SiO<sub>2</sub> contents vary from 45 to 53 wt%, MgO contents from 18 (by definition) to ~30 wt% and TiO<sub>2</sub> varies by a factor of 5. Producing such chemical diversity with a single melting process is a challenge for all models of komatiite generation. Plume advocates tend to focus on the low-SiO<sub>2</sub> komatiites such as those from Munro [11,46] and Gorgona [12,50] and point to their compositional similarity to modern ocean island basalts. Subduction advocates point to the similarity of high-SiO<sub>2</sub> komatiites such as those in Barberton [51] and Common-

dale [15,16] with the most MgO-rich modern arc magmas (boninites), as well as the compositional overlap of boninites with basaltic komatiites interlayered with the komatiites (Fig. 1). The plume advocates dismiss the high-SiO<sub>2</sub> compositions as formed by either fractionation or crustal contamination of komatiite magmas, while subduction advocates question whether Gorgona magmas should be considered analogs of Archean komatiites. Neither model has successfully explained the complete spectrum of komatiite compositions.

### 3.1. Evidence from experimental petrology on the depth and temperature of komatiite melting

The first experimental study on komatiites was carried out by Green et al. [17] who concluded that komatiites were produced at high temperatures (~1650°C) and estimated a depth of 150 km or greater for melt segregation from the source. This initial conclusion of a deep melting origin was revisited in light of new evidence from experimental studies of the best available estimate of the primary komatiite magmas from Munro Township and Western Australia. Green reasoned that any process should be consistent with the existence of a thick, cold lithosphere of >150 km thick while other parts of the Earth yielded hot komatiite. He proposed that komatiite melting began at depths of >150 km, and a high-temperature mantle melting column extended to shallow depths and left a mantle residue that had olivine as its only residual phase [34,35]. Takahashi and Scarfe [52] carried out experiments at higher pressures and showed that a depth of 150 km and a temperature >1700°C were required to produce the most Mg-rich komatiite magmas. In the Takahashi model the depth of segregation was initially tied to the inferred liquidus temperature and melting was assumed to stop deep in the Earth's mantle, where the komatiite magma separated from its source, and the melt was delivered to the surface (batch melting). In more recent manifestations of the plume hypothesis, adiabatic decompression melting occurs and the initial depth of melting is controlled by the intersection of the adiabat with the peridotite solidus (Fig. 2). Compositional evidence (CaO/Al<sub>2</sub>O<sub>3</sub> and Gd/Yb

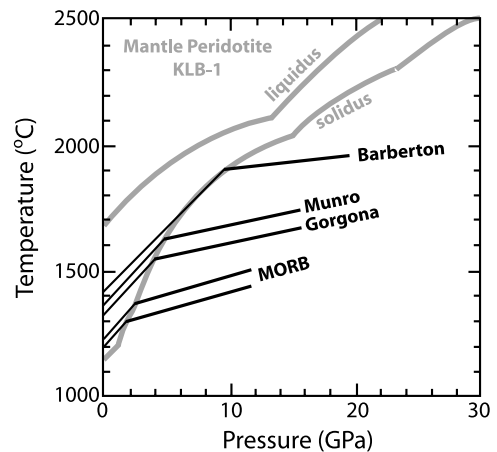


Fig. 2. Depths and temperatures of melting of komatiites in a plume setting inferred by Herzberg [86]. Black lines show the pressure–temperature path experienced by a body of mantle as it ascends adiabatically towards the surface. The gray lines are the solidus and liquidus of KLB-1, a fertile mantle composition. The solidus is the first point at which the mantle will begin melting. The liquidus is the point at which the mantle would be completely molten. Below the solidus, the slope of the lines reflects slight cooling due to decompression. The potential temperature is the temperature at which this path intersects the surface. The greater slope above the solidus reflects both the heat loss required to produce melting and the greater compressibility of melts relative to solid. In the plume model, the oldest komatiites (Barberton at 3.5 Ga) record the highest mantle potential temperatures, while late Archean (2.7 Ga) Munro komatiites and Cretaceous (88 Ma) Gorgona komatiites are formed in progressively cooler mantle plumes. Note that if melting occurs by adiabatic decompression, then higher melting temperatures require that melting begins at greater depths. The range of melting temperatures for present-day mid-ocean ridge basalts (MORB) is also shown.

ratios in the komatiite) is interpreted to indicate garnet was present along with olivine and orthopyroxene in the source region of komatiites. The latest experimental investigation of this melting process has been that of Walter [53] who melted peridotite and tried to produce a melt composition that was identical to komatiite. Walter matched some of the compositional characteristics at pressures of 6 GPa, but not all (e.g. the CaO/Al<sub>2</sub>O<sub>3</sub> of low-Al komatiites). Some recent estimates of komatiite melting conditions suggest even higher pressures (>10 GPa) and temperatures >2000°C [54,55]. However, these investiga-



tors use indirect evidence to arrive at these estimates.

In the plume hypothesis the depth and temperature of komatiite generation decrease with time. Archean komatiites (like Barberton at 3.5 Ga) are the hottest, and come from the greatest depth, while late Archean komatiites (like Munro at 2.7 Ga) come from shallower depths and the youngest komatiites from Gorgona (at 0.086 Ga) come from the shallowest depths (Fig. 2). However, this model has been called into question by the recent discovery of high-SiO<sub>2</sub> komatiites from Commondale. One indication of depth of melting is the SiO<sub>2</sub> content of the magma. As depth of melting increases, the effect of increasing pressure is to move the phase boundaries for melting to lower SiO<sub>2</sub> content and higher MgO and FeO contents. As Fig. 1 shows, the oldest komatiites (e.g. Barberton and Commondale) have higher SiO<sub>2</sub> than the younger ones (Gorgona and Munro). Thus, the age of komatiites and their depth of melting do not correlate.

If komatiites were produced in a mid-ocean ridge setting, the melt generation process would be adiabatic decompression fractional melting. The distinctive signature of this style of melting is that it begins when mantle ascending along an adiabat crosses its solidus and continues to shallow depths until it encounters lithospheric mantle (Fig. 3). This melting style characterizes the major mode of melt production in the Earth's present-day mid-ocean ridge system. The compositional systematics of modern mid-ocean ridge basalts [56–58] are interpreted to indicate variations in the temperature of 150–200°C for mantle upwelling beneath mid-ocean ridges [56]. Hotter mantle starts melting deeper, continues melting until shallow depths and records the maximum amount of melting in the ridge system through formation of the thickest crustal basaltic section. The cooler upwelling mantle does not reach its solidus temperature until a shallow depth, melting takes place over a smaller temperature–depth interval and less basaltic crust is formed. Presumably, the extrapolation of this melting process back into Archean mid-ocean ridges would result in a melting process that began at much greater depths, extended over a larger pressure–depth range to shallow

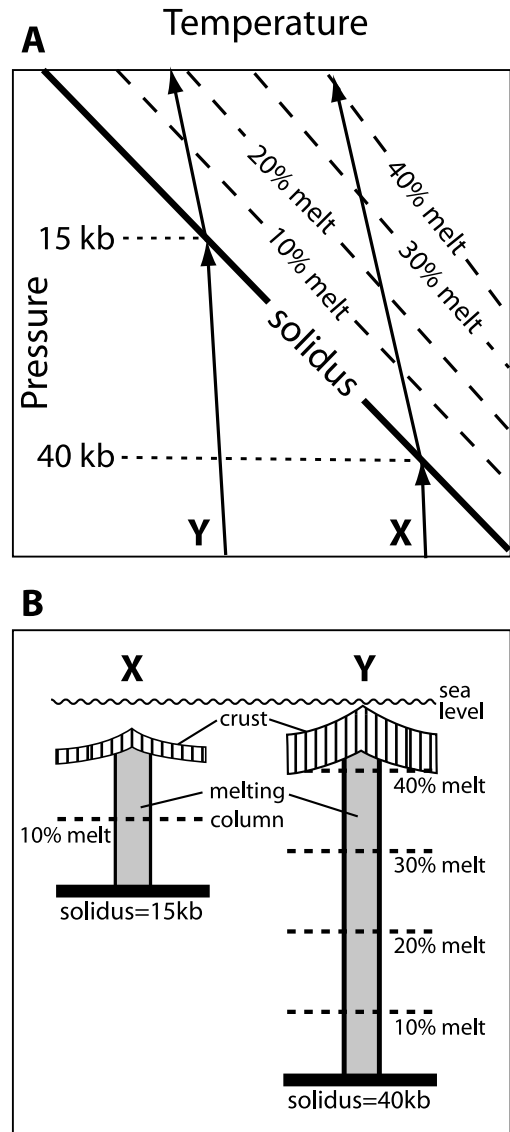


Fig. 3. (A) A schematic pressure–temperature diagram for melting of mantle peridotite by adiabatic decompression. Path X represents hotter mantle potential temperature that crosses the solidus at greater depth and higher temperature and undergoes a higher extent of melting. Path Y crosses the solidus at lower temperature and undergoes a lesser extent of melting. See caption of Fig. 2 for further explanation. (B) Cross-section of the oceanic crust and mantle corresponding to the melting histories shown by paths X and Y. Hotter mantle begins melting at greater depths and melts to a greater extent than cooler mantle [56]. This model was developed for mid-ocean ridge magmas, but is applicable to any decompression melting regime, such as mantle plumes.

mantle depths and resulted in larger degrees of melting and mantle depletion. Komatiites require at least 30–40% melting of the mantle. Models for this melting process predict melting rates of 0.15–0.3% per km of upwelling. Thus, to produce komatiites melting would have to begin at  $\sim 200$  km depth and extend to beneath the ridge.

The experiments discussed above were all done under anhydrous conditions, in the absence of  $H_2O$ . Green et al. [17] also performed hydrous experiments, but ruled out high magmatic  $H_2O$  contents for komatiites on the grounds that such magmas would devolatilize and vesiculate as they reached the Earth's surface. Other proponents of dry komatiites have put forth similar arguments [59]. Nevertheless, Green's experiments suggest that Barberton komatiite with 30 wt% MgO could be generated by hydrous melting at  $1500^\circ\text{C}$ . Recent experiments on a less altered, lower-MgO (25 wt%) composition indicates melting temperatures of  $1400$ – $1450^\circ\text{C}$  and depths of  $\sim 70$  km [60] (Fig. 4).

The pre-eruptive  $H_2O$  contents of Barberton komatiites were estimated using petrologic evidence by Parman et al. [41], who found that at least 3 wt% dissolved  $H_2O$  in the komatiite magma was required to reproduce the compositions of the igneous minerals preserved in the rock samples. They reasoned that such high  $H_2O$  contents might be preserved if the komatiites were shallow intrusives, as suggested by de Wit et al. [32]. Field observations have led Dann [61] to the interpretation that the Barberton komatiites are lava flows, and this evidence has been used to dismiss the petrologic estimates of 3–6 wt%  $H_2O$  in the Barberton komatiites [40,59]. However, there are abundant examples of modern high-MgO submarine lavas that have erupted and failed to vesiculate and degas. High-MgO (22 wt%) boninites have glassy chill margins that contain 2 wt%  $H_2O$  that is primary in origin [62] and the interiors of some of these pillow lavas contain up to 7 wt%  $H_2O$  in the interstitial glass. Thus, the petrologic evidence of hydrous komatiite magmas does not rely on whether they are extrusive or intrusive.

If some komatiites do contain high  $H_2O$ , then the next issue is: where did the  $H_2O$  come from?

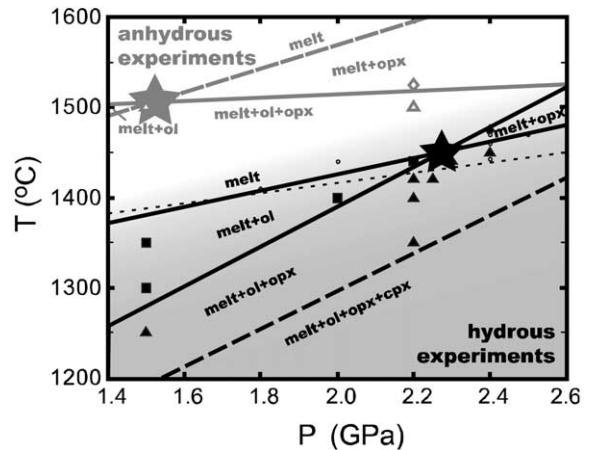


Fig. 4. Pressure–temperature phase diagram for a Barberton komatiite composition under hydrous (black lines) and anhydrous (gray lines) conditions [60]. Mafic melts are in equilibrium with various solid phases depending upon the pressure, temperature and  $H_2O$  content of the system. The melt is inferred to have been produced at the conditions where it is saturated with the minerals that it left as a residue in the mantle, in this case olivine and orthopyroxene. Under anhydrous conditions, the Barberton komatiite is multiply saturated at  $\sim 1.5$  GPa and  $\sim 1510^\circ\text{C}$  (gray star). With 6 wt%  $H_2O$  added, the melt saturates at a lower temperature ( $\sim 1450^\circ\text{C}$ ) but a higher pressure ( $\sim 2.3$  GPa, black star).

Modern plume magmas contain  $H_2O$  but in much lower amounts ( $< 0.5$  wt%) [63,64] than the amount estimated for the Barberton komatiites. Kawamoto et al. [65] have suggested that komatiites were produced by hydrous Archean plumes, thus reconciling the evidence for high  $H_2O$  contents in some komatiite magmas with the plume model. They suggest that the Archean mantle contained higher volatile contents, left over from the accretion of the Earth. In this model the initial few percent of melting in a plume would carry away all of the  $H_2O$  in the mantle. Subsequent high-degree melting would be anhydrous. Alternatively, proponents of the plume hypothesis have suggested that the  $H_2O$  was introduced by crustal contamination [59].

Modern hydrous melts are produced primarily by volatile fluxing in subduction zones [60,66]. This process leads to the generation of  $H_2O$  contents as high as 10 wt% in some mafic arc magmas [67]. Hydrous melting in subduction zones only reaches high extents because the mantle is contin-

uously fluxed by volatiles released from the subducting slab (i.e. the water–rock ratio is high) and because the inverted thermal gradient in the mantle wedge can drive the melting process. Melts ascend from cooler to hotter mantle, and continuously re-equilibrate with their enclosing mantle by increasing their melt fraction.

In many occurrences of komatiites, it has been recognized that they have compositional similarities to or are interlayered with lavas similar to boninites [16,47,49,68–71]. Boninites are generated by high extents of hydrous melting in subduction zones, and are characterized by high  $\text{SiO}_2$  and high MgO (Fig. 1). Boninites are produced by melting conditions associated with the inception of subduction [72]. In the early stages of subduction zone development, subduction is initiated along an active fault in the oceanic crust (Fig. 5) and the subducted plate rapidly sinks into the mantle, drawing hot, buoyant mantle asthenosphere into the forearc [73]. This early magmatism involves melting of hydrated, depleted mantle. Eventually as the subduction zone matures, this extreme form of melting ends and more normal island arc magmas predominate (Fig. 5).

The close spatial and temporal association of Archean komatiites with boninite-like magmas has led to the suggestion that the two magma types were produced by similar melting processes (i.e. hydrous melting in subduction zones) [51,68]. In modern settings this melting process occurs over a very broad zone in the forearc, is characterized by high magma production and eruption rates, an extensional environment and progressive migration of volcanism away from the trench [72]. In the Archean a similar scenario is envisioned where early boninite–komatiite activity is succeeded by island arc tholeiitic magmatism (Fig. 5). The absence of komatiites from modern boninite settings presumably reflects the thermal evolution of the Earth's mantle [68]. When komatiites were first recognized boninites were also in the process of being discovered [74–76], and their distinctive compositional characteristics and tectonic setting had not yet been recognized. This is perhaps responsible for the delayed apprecia-

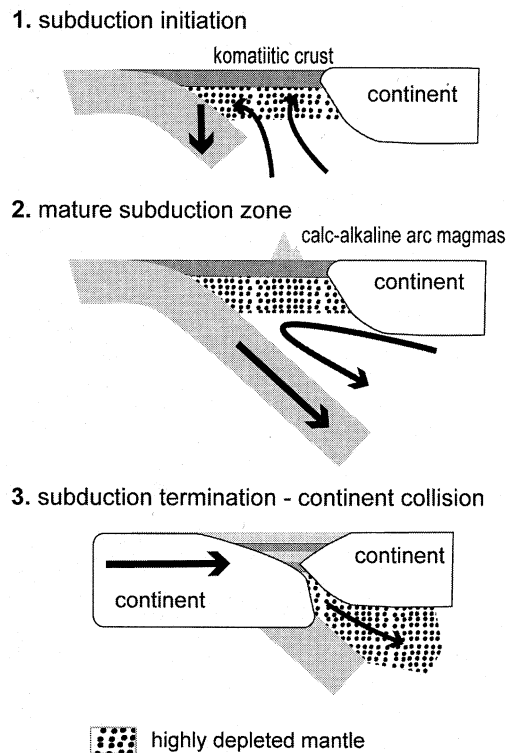


Fig. 5. Subduction model for the origin of komatiites in subduction zones [51], modeled after melting process inferred for boninites [72]. (1) Boninite-like melting event produces a range of high-MgO melts: komatiite, komatiitic basaltic magmas and low-Ti tholeiites (dark shading) and a corresponding heavily depleted mantle residue (stippled region). (2) The continued subduction of the lithosphere cools the mantle and establishes a mature subduction zone. Subsequent lower-temperature hydrous magmas (calc-alkaline andesites) are emplaced on top of early, ultramafic crust. The cold, buoyant residual mantle remains beneath the forearc. (3) The komatiitic crust is obducted onto continents during continent collision at the end of subduction. The depleted mantle is thickened and incorporated into the continental lithospheric mantle.

tion of the compositional similarities between boninites and Archean komatiites.

#### 4. Constraints on early Earth thermal history

In the modern Earth a range of mantle temperatures is recorded in plume, mid-ocean ridge and subduction zone environments (Fig. 6). The best-characterized melt generation process in a plume



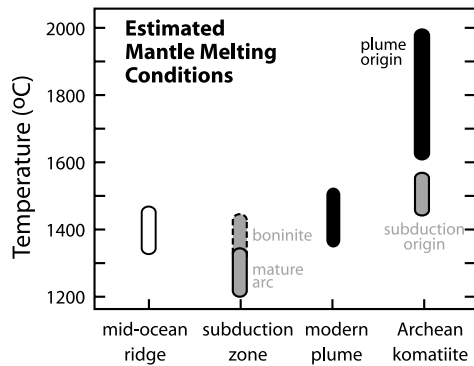


Fig. 6. The range of mantle melt generation temperatures estimated for various modern tectonic settings compared to temperatures inferred for komatiite melt generation by plume model (black filled field) and subduction model (gray filled field). MORB estimates are from Kinzler and Grove [58]. The Hawaiian plume temperature is based on experimental work of Egginis [77] and Wagner et al. [78]. Subduction zone estimates are separated in boninite melting (dashed boundary [83]) and melting in steady-state subduction environments (solid boundary [79–82]). Considering the maximum estimated temperatures for each category, the plume model requires  $\sim 500^\circ\text{C}$  cooling between 3.5 Ga and now, while the subduction model requires  $\sim 100^\circ\text{C}$  cooling.

environment is Hawaii. Primitive Hawaiian picrites provide evidence for melt segregation temperature and depth at the top of the Hawaiian plume of  $1420^\circ\text{C}$  at 66 km [77,78]. The Hawaiian plume erodes thick lithosphere beneath Hawaii, altering the major and trace element compositions of melts; depending on the model parameters, the mean mantle potential temperature is  $1530^\circ\text{C}$ . For mid-ocean ridges, estimates of mantle potential temperatures range from  $1320$  to  $1475^\circ\text{C}$  [58]. In subduction zones, primitive magmas from mature arcs provide evidence of mantle wedge melting temperatures that range from  $1200$ – $1250^\circ\text{C}$  [79,80] to  $1300$ – $1350^\circ\text{C}$  [81,82]. At the initiation of subduction, boninite magmas record melting conditions of  $1400$ – $1450^\circ\text{C}$  at shallow depths (15–45 km) [83].

Geodynamic models of mantle convection have used the estimates of modern mantle temperatures as boundary conditions to solve for the thermal evolution of the mantle [2,84]. The models have considered the effects of variable rheology, variable contributions of plumes to cooling and the effects of phase transitions in the mantle, among

other parameters. The temperature evolution curves produced have been diverse, from near-linear cooling, to rapid early cooling, to complex, episodic cooling. The plume model is most consistent with models that argue for slow cooling of the Earth, so as to retain high temperatures in the mantle 1–2 billion years after the formation of the Earth (Fig. 7). The subduction model argues for only moderately higher mantle temperatures in the Archean, and therefore for convection models in which the mantle cools rapidly in the first 500 million years.

In either case, linking komatiite melting temperatures to the temperature structure of the Archean mantle is not straightforward. If komatiites are the product of plumes, the geodynamic models indicate they likely originated at the core–mantle boundary, and reflect unusually hot lower mantle temperatures (or they would not form thermal plumes). If komatiites are subduction-related, then they record the temperature of shallow upper mantle that was drawn towards the surface and hydrated by the movements of lithospheric plates. Modern boninites are only produced in a minority of subduction zones, presumably where subduction has occurred over relatively hot mantle. If the boninite analogy holds for komatiites, then they record only the high end of the spectrum of Archean upper mantle temperatures. In

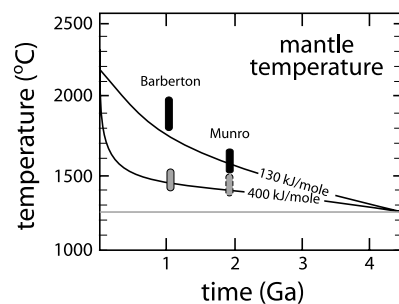


Fig. 7. Evolution of mantle potential temperatures with time in an Earth that is cooled by both plumes and plates (from Davies [84]). Curves show thermal evolution for a highly temperature-dependent mantle viscosity (activation energy =  $400$  kJ/mol) and for a weakly temperature-dependent viscosity ( $130$  kJ/mol). Melting temperature estimates for hydrous (gray fields) and dry (black fields) komatiite melting of Barberton komatiites at 3.5 and 2.7 Ga (Barberton [40,54,55,60]).

both cases, the inferred mantle temperatures are likely to be upper bounds and not representative of the entire temperature range present in the convecting mantle.

## 5. Future challenges and directions

### 5.1. Constraining temperatures of melt production

The extremely high temperature estimates for komatiite generation are based upon the assumption that komatiite samples with the highest MgO contents are representative of a preserved igneous rock composition. These high-MgO compositions lead to liquidus temperature estimates that range from 1800°C to 1675°C [53,85,86]. In contrast, Parman et al. [41] conclude that these samples have been altered during greenschist metamorphism to enrich the MgO content over that of the original igneous rock. When the least altered samples are considered, the liquidus temperatures are significantly lower (Figs. 6 and 7), from 1450 to 1550°C. Estimating the melting conditions of these complex metamorphosed igneous rocks is problematic. It should only be attempted when evidence can be found in the rock itself that it is representative of an igneous magma composition. The composition of preserved magmatic olivine provides the best mineralogical evidence to determine that a rock represents a liquid composition, but such olivines are rarely preserved. Even when olivine is preserved, its composition can be modified by metamorphic processes. In the case of the more fluid-mobile major and trace elements (e.g. Na and Sr), there is little hope that these will be directly preserved in the metamorphosed igneous rock, but preserved igneous minerals (e.g. pyroxene, [87]) can provide an estimate. Temperature constraints obtained from natural komatiite bulk rock compositions in the absence of evidence that they represent liquid compositions should be considered questionable. All komatiites are altered metamorphic rocks and the use of all samples for temperature estimation purposes is not justified. A few well-constrained temperature estimates are probably better than many unconstrained estimates.

Experimental studies of the well-constrained komatiite bulk compositions can provide further evidence of melt segregation conditions. There are only a few recent experimental studies of the liquidus phase relations of natural komatiites [34,41,60]. The first studies on komatiites [88,89] were done in the early days of experimental melting and some suffered from shortcomings that have been eliminated by advances and improvements in technique. Direct determinations of komatiite liquidus phase relations provide complementary information to the magmatic compositions obtained from peridotite melting experiments. In the latter, a peridotite starting composition is partly melted over a range of pressures and temperatures to define a set of conditions that produce a komatiite liquid. Melting experiments have successfully produced some of the major element characteristics of komatiites, but have not matched other key major element characteristics, notably the high Ca/Al, that characterize some Archean komatiites [53]. The major element, trace element and isotopic compositions of komatiites require that the source was strongly depleted, while the experimental studies of mantle melting [53,90,91] have almost exclusively used mantle compositions that have never been melted (i.e. primitive or fertile). There are many potential depleted mantle compositions whose melting behavior should be experimentally investigated. Furthermore, at the high temperatures required by these melting studies it is often difficult to preserve and analyze the liquid composition [54]. Comparing experiments on natural komatiite compositions and peridotites should yield better constraints on pressure and temperature of melting, possibly eliminating some of the variability of liquidus temperature estimates that currently exist.

### 5.2. Field evidence for the tectonic setting of komatiites

Field evidence can provide valuable constraints on tectonic processes related to komatiite production. A weakness of many komatiite studies, particularly experimental ones, is that they focus just on the komatiites and ignore the majority of the magmatic sequence in which the komatiites are

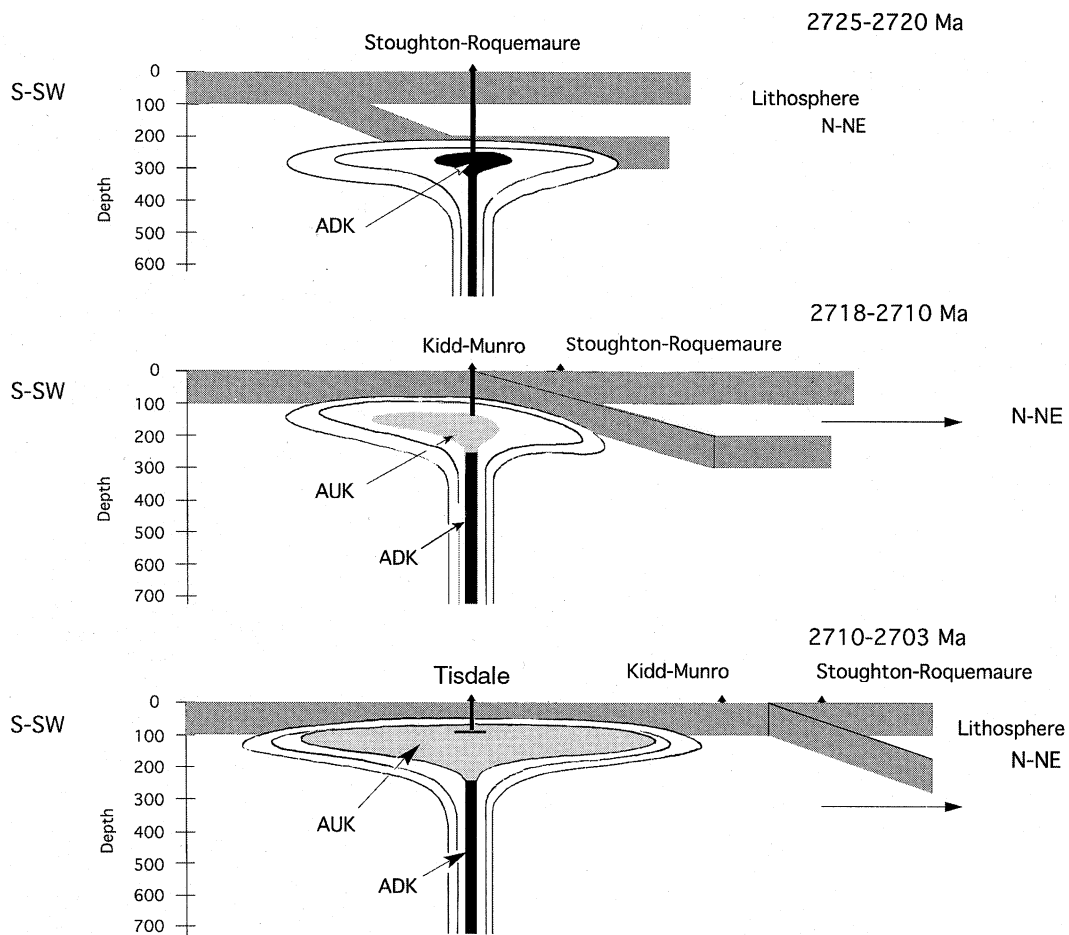


Fig. 8. Model that explains the interlayering of komatiites with subduction-related magmas by the interaction of a plume and a subduction zone. Alumina-undepleted komatiites (AUK) and alumina-depleted komatiites (ADK) are considered to come from different parts of the ascending plume [94].

found, particularly the basaltic komatiites. Currently there is no consensus on whether these magmas are just fractionated and/or crustally contaminated komatiites or are truly primitive magmas that record mantle melting conditions distinct from the komatiites. If they are primary and their arc-like geochemical signatures were not produced by crustal contamination, they pose a significant challenge to the plume hypothesis, requiring unappealing models of plumes repeatedly impinging upon arcs (Fig. 8).

Likewise, the interpretation of the trace element geochemistry of the komatiites themselves is

clouded. Like the basaltic komatiites, many komatiites have chemical features that are typical of modern subduction-related magmas (e.g. [48]). These characteristics include variable enrichments in large ion lithophile and light rare earth elements along with depletions in high field strength elements. Both models agree that these indicate input of trace element-enriched material into the komatiites. The difference is whether it was added as a hydrous fluid into the komatiite source in a subduction zone (subduction model), or was introduced by the addition of granitic material as the komatiite traversed the crust (plume model).

## 6. Conclusions

The recent discovery of an entirely new class of komatiites in Comondale demonstrates that there is still much to learn from fundamental field observations. Experimental studies should be undertaken to constrain the range of possible melting conditions implied by both models, though the data are particularly scarce for hydrous mantle melting. The challenge for trace element geochemistry is to distinguish the chemical signatures of crustal contamination from the addition of a subduction-derived hydrous fluid component. This can be a difficult task in unaltered modern magmas, let alone in altered and metamorphosed samples. Perhaps advances in micro-sampling techniques such as laser-ablation inductively coupled mass spectrometry and ion microprobe will allow the preserved igneous minerals (olivine, pyroxene and spinel) to be used more effectively.

In sum, the origin and implications of komatiites is an open and active debate that has far-reaching implications for the thermal and chemical evolution of the Earth. The number of competing hypotheses seems to have multiplied in the recent literature with plumes, hydrous plumes, plumes interacting with subduction zones and boninite-like melting all being advocated. It is possible that komatiites were generated by more than one process in the Archean, in the same way that basalts are produced in a range of tectonic settings today. This may explain why advocates of the plume and subduction models tend to focus on different komatiite localities and would challenge us to discover reliable means to distinguish between them. Kuhn [92] argues that paradigm shifts are preceded by times of confusion, heated debate and a multiplicity of hypotheses that explain differing subsets of the existing data. This description seems to provide an accurate account of the current state of komatiite research and promises an exciting future.

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