Komatiites, kimberlites, and boninites

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[1] When the mantle melts, it produces ultramafic magma if the site of melting is unusually deep, the degree of melting is unusually high, or the source is refractory. For such melting to happen, the source must be unusually hot or very rich in volatiles. Differing conditions produce a spectrum of ultramafic magma types. Komatiites form by high degrees of melting, at great depths, of an essentially anhydrous source. Barberton-type komatiites are moderately high degree melts from a particularly hot and deep source; Munro-type komatiites are very high degree melts of a slightly cooler source. Kimberlites result from low-degree melting, also at great depth, of sources rich in incompatible elements and CO_2 + H_2O. They become further enriched through interaction with overlying asthenospheric or lithospheric mantle. Boninites form by hydrous melting of metasomatized mantle above a subduction zone. Just like basalts, the different types of ultramafic magma, and the conditions in which they form, are readily identified using major and trace element criteria. *INDEX TERMS:* 1065 Geochemistry: Trace elements (3670); 3640 Mineralogy, Petrology, and Mineral Physics: Igneous petrology; 3670 Mineralogy, Petrology, and Mineral Physics: Minor and trace element composition; 8439 Volcanology: Physics and chemistry of magma bodies; *KEYWORDS:* komatiite, kimberlite, boninite, petrology, geochemistry, mantle

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1. Introduction

[2] Three broad types of basalt form through partial melting in the mantle. As explained in any standard petrology textbook, mid-ocean ridge basalts and the tholeiites of oceanic islands are the products of relatively high degrees of melting of a near-anhydrous peridotitic source. Alkali basalts and other members of the alkaline magma series are produced by lower degrees of melting, commonly of a source that is geochemically enriched or contains a relatively high proportion of basaltic or eclogitic material. Calc-alkaline basalt forms through partial melting of the metasomatised mantle wedge overlying a subduction zone. Each type of basalt has a distinctive major and trace element pattern, and these patterns can be used to infer the tectonic setting and the conditions of melting. The enriched source of alkali magmas may contain high levels of CO_2 that play an important role in the generation of silica-undersaturated members of the magma series. The Si-rich character of calc-alkaline basalts is attributed to the presence of water, which is added to the source during dehydration and/or partial melting of the subducting slab.

[3] In this paper, I make the case that a parallel spectrum of magma types exists for more magnesian, highly mafic to ultramafic magmas. Komatiites form through large degrees of partial melting of an essentially anhydrous sources; kimberlites and meimechites result from lower degrees of melting of a source rich in volatiles; and boninites form through melting of a water-rich source in a subduction environment.

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2. Komatiites

[4] According to the simple definition, a komatiite is an ultramafic volcanic rock (a lava or volcanoclastic rock containing more than 18% MgO) [*Arndt and Nisbet*, 1982]. This simple definition includes some of the other ultramafic rocks will be discussed in this paper, so, to distinguish these rock types from komatiites, it is essential to include additional textural and geochemical criteria. The presence of spinifex textures is one important element of a more complete definition [*Kerr and Arndt*, 2001] and the diagnostic geochemical criteria are developed below.

[5] Grove and coworkers [*Grove et al.*, 1997, 1999; *Parman et al.*, 1997] recently suggested that komatiites from the type section in the Barberton Greenstone Belt in South Africa [*Viljoen and Viljoen*, 1969] were emplaced not as lava flows but as a series of high-level intrusions. The situation has since become clearer, however, with the publication by *Dann* [2000, 2001] of detailed maps that show conclusively that these units are extrusive. Their morphological features and textures are very like those of lava flows in other regions and there is no reason to believe that they formed in a different manner. This is an important conclusion, because it provides strong evidence that komatiite erupted and crystallized at the surface as essentially anhydrous lava [*Arndt et al.*, 1998a].

[6] The two main geochemical types of komatiite are distinguished by their major and trace element contents [*Nesbitt and Sun*, 1976; *Sun*, 1984]. Barberton-type, or Al-

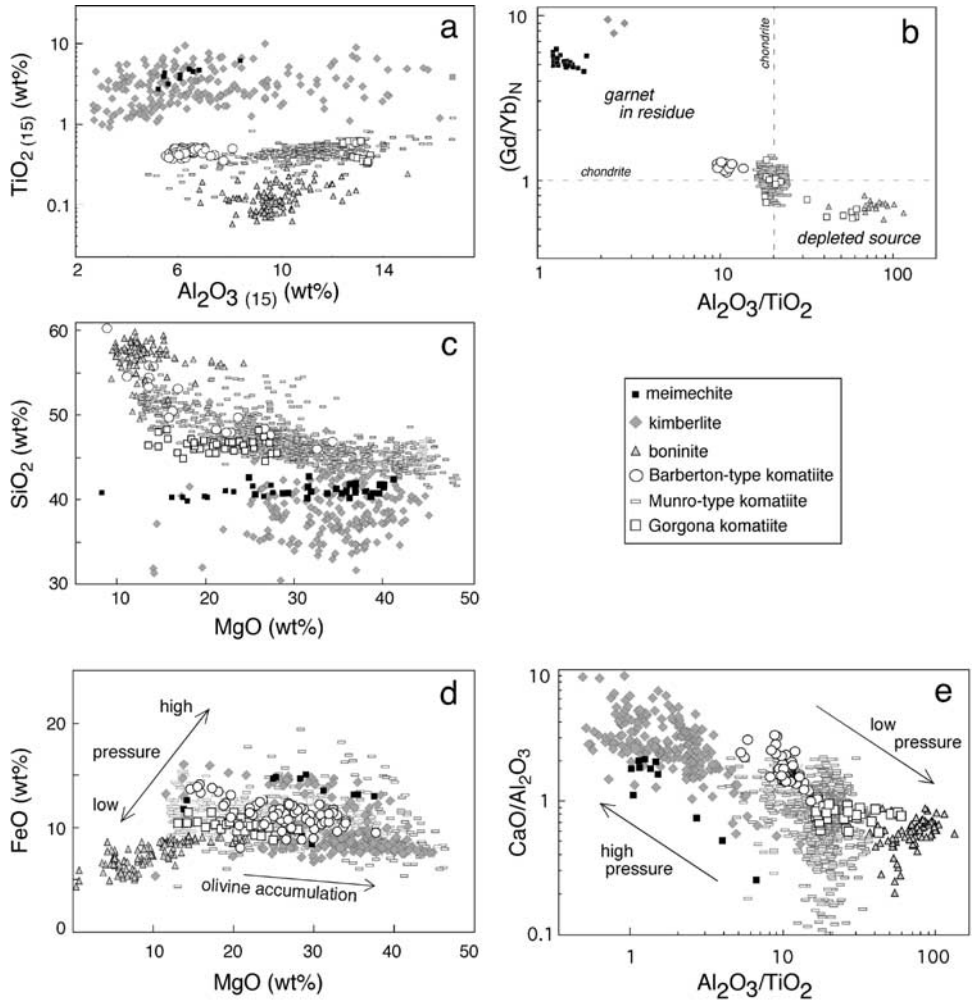

Figure 1. Comparison of key major elements in rocks that crystallized from ultramafic or highly mafic magmas. Figure 1c, MgO versus SiO_2, shows the wide range of SiO_2 in these rocks, from high values in boninites and some komatiites to low values in kimberlites, and Figure 1d shows the range in FeO contents (FeO = total Fe). In Figure 1a, the plotted data are normalized to 15% MgO to eliminate the effects of the fractionation or accumulation of olivine (± orthopyroxene). For the komatiites, meimechites, and kimberlites, olivine of appropriate composition was added or subtracted; for the boninites, a mixture of olivine and orthopyroxene was used. Figures 1a, 1b, and 1e show the large differences in TiO_2 of the different series and the large variations in Al_2O_3 contents of the three types of komatiite. Data are from numerous sources including GEOROC (available at http://georoc.mpch-mainz.gwdg.de/) (boninites); *Mitchell* [1995] and a compilation of C. B. Smith (kimberlites); *Arndt et al.* [1998b, 1995] (meimechites); *Aitken and Echeverria* [1984], *Arndt et al.* [1997], *Gruau et al.* [1990], *Kerr et al.* [1995], *Lahaye et al.* [1995], *Sun* [1984], *Xie et al.* [1993], and unpublished data of C.M. Lesher and R. Sproule (komatiites).

depleted komatiites, have relatively low Al contents (low Al_2O_3/TiO_2 ratios) and moderately high levels of incompatible trace elements [*Sun and Nesbitt*, 1978; *Viljoen and Viljoen*, 1969] (Figure 1). Their rare earth element (REE) patterns are flat to slightly fractionated, with distinct depletion of the heavy REE (high Gd/Yb; Figures 1–3). This type of komatiite is most common in the oldest, 3.5 Ga, Archean greenstone belts.

[7] Munro-type, or Al-undepleted, komatiites have higher, near chondritic Al_2O_3/TiO_2 and lower levels of incompatible trace elements [*Arndt*, 1984; *Arndt and Nesbitt*, 1982]. Their REE patterns show depletion of the lighter elements and near-chondritic ratios of the middle to heavy elements. This type of komatiite is characteristic of late Archean (2.7 Ga) greenstone belts, and is also found in several Proterozoic and younger regions, such as in the well-known Gorgona Island locality [*Echeverria*, 1980; *Kerr et al.*, 1995].

[8] Because all komatiites are metamorphosed, the measured concentrations of mobile elements such as Rb, Ba and Sr do not represent those of the original magmas. Reliable information about these elements, which are useful for identifying the tectonic setting in which the magma erupted, can be obtained by analyzing melt inclusions in olivines. The data reported in Figures 2 and 3 show that komatiites have near-chondritic values for key ratios such as Rb/La or Sr/Sm.

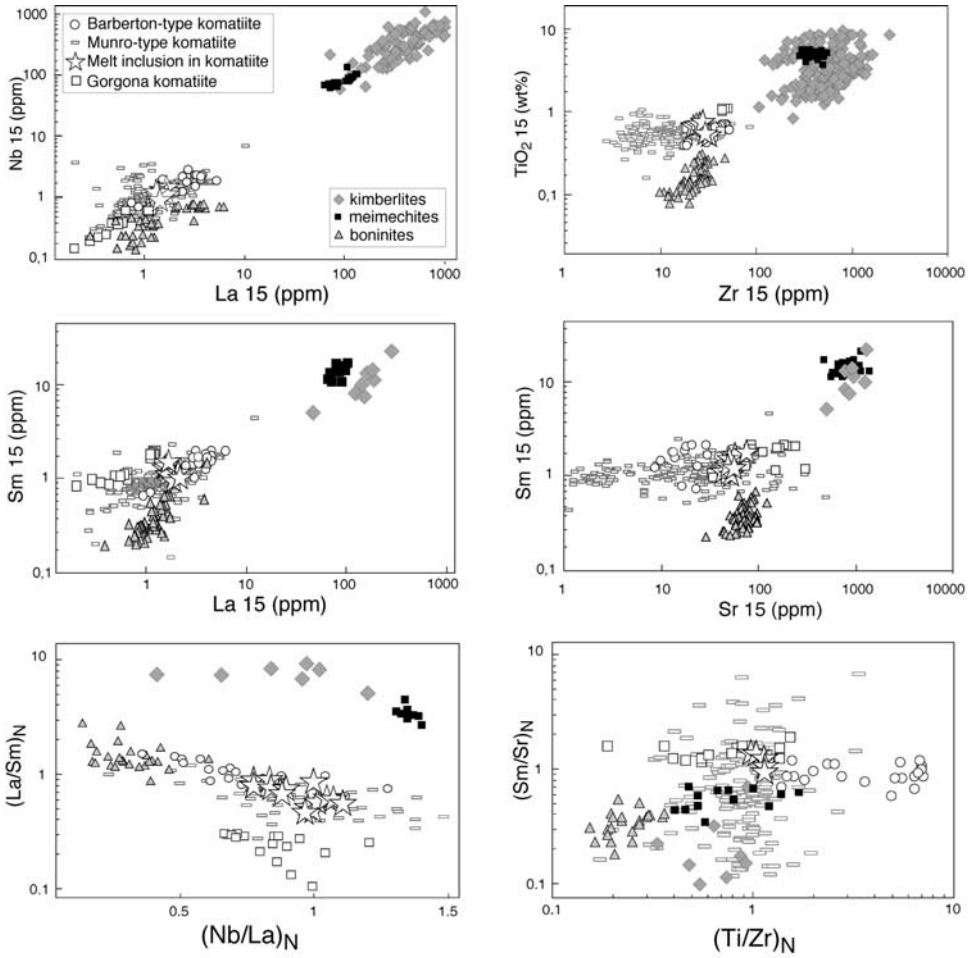

Figure 2. Comparison of trace element contents of ultramafic rocks, normalized to 15% MgO. The melt inclusions in olivines from 2.7 Ga Zimbabwe komatiites (M. Gee and L. Danushevsky, unpublished data, 2002) were homogenized before being analyzed to compositions containing ~15% MgO, and these data are not normalized. These analyses are included because they provide a reliable indication of the Sr and Ba contents of komatiites, data that are not available in all whole rock compositions because of the mobility of these elements during metamorphism. Note the large differences in absolute concentrations and trace element ratios of the various types of ultramafic rocks. Boninites are distinguished by low TiO_2 and low Nb/La, La/Sm, and Sr/Sm. Other data sources are as for Figure 1.

[9] Some komatiites have assimilated continental crust. The product is magnesian basalt characterized by enrichment of incompatible trace elements, negative Nb-Ta anomalies, high $^{87}Sr/^{86}Sr$ and low $^{143}Nd/^{144}Nd$ [*Arndt and Jenner*, 1986; *Barley*, 1986; *Sun et al.*, 1989]. Caution is needed to distinguish these rocks from magmas formed in subduction settings.

[10] The two main types of komatiite crystallized from highly magnesian parental magmas. Using the compositions of fine-grained samples and the forsterite contents of olivine grains, the MgO contents of these liquids are estimated to range from about 20 to 30% [*Arndt*, 1994; *Nisbet et al.*, 1993]. Their 1-atm anhydrous liquidus temperatures are 1400 to 1600°C [*Nisbet*, 1982; *Nisbet et al.*, 1993].

3. Kimberlites, Meimechites, and Other Alkaline Ultramafic Rocks

[11] This group includes a rather large range of rock types (just as mafic alkaline rocks vary widely in their mineralogy, geochemical compositions and occurrence). Because they contain diamonds and have transported mantle xenoliths to the surface, kimberlites are the best known. These rocks occur as volcanic diatremes and as dykes and sills, and have complex petrography because of the presence of abundant xenocrysts, megacrysts and xenoliths [*Mitchell*, 1986, 1995]. Hydrous minerals and carbonates are common. Their chemical compositions are characterized by high MgO contents and low SiO_2 and Al_2O_3 contents, by enormous concentrations of incompatible trace elements (Figures 1–3), and by high H_2O and CO_2 contents.

[12] Kimberlites have been subdivided into Group 1 (basaltic) and Group II (micaceous). Their mineralogy provides one means of distinguishing between the two types: the former is relatively rich in ilmenite and contains a characteristic suite of low-Cr megacrysts and high-T sheared xenoliths; the latter is distinguished by abundant mica. More important, however, are their trace element and isotopic compositions [*Smith et al.*, 1984, 1985]. Group II

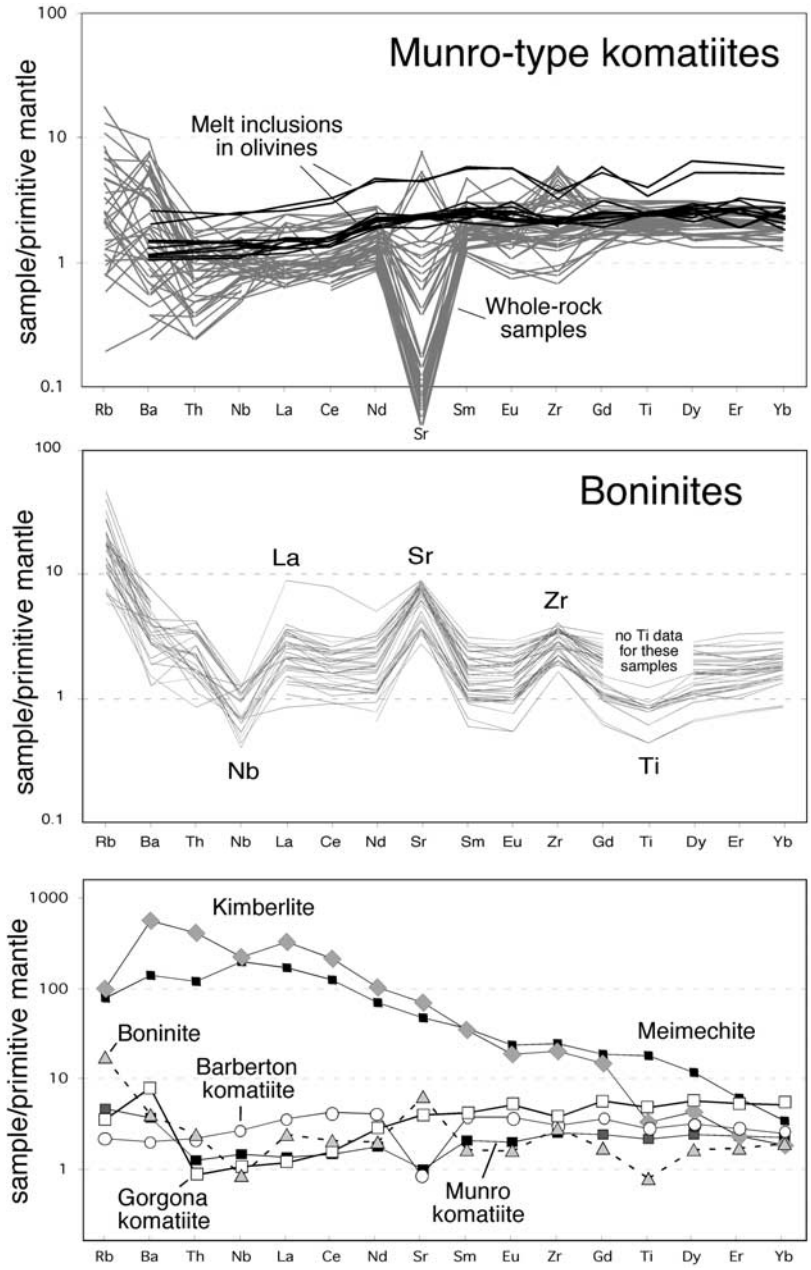

Figure 3. Trace element concentrations, normalized to the primitive mantle of *Hofmann* [1988]. The two upper profiles of melt inclusions are from *McDonough and Ireland* [1993]; these inclusions were not homogenized, and their high trace element contents result from crystallization after entrapment. The lower profiles represent the homogenized inclusions of M. Gee and L. Danushevsky (unpublished data, 2002). Comparison of the whole rock and melt inclusion data shows that the widely variable Sr contents in the komatiite whole rocks result from mobility of this element during alteration. The reason for the variable Zr contents of some komatiite samples is not known. Note the distinctive Nb, Sr, and Ti anomalies in the boninites and the absence of these anomalies in the komatiites. Data sources are as for Figure 1.

kimberlites have higher concentrations of incompatible elements than Group I kimberlites, and their isotopic compositions are those of an old, geochemically enriched source (high $^{87}Sr/^{86}Sr$, low $^{143}Nd/^{144}Nd$). Group I kimberlites have the isotopic features of a more depleted source, like a mantle plume or convecting upper mantle [*Mitchell*, 1986].

[13] In a MgO versus FeO diagram (Figure 4a), the compositions of kimberlites define a series of trends that appear to be derived, at least in part, from the fractionation or accumulation of olivine. The composition of the olivine that controls each trend corresponds to that of olivine of the lithospheric mantle through which the kimberlite passed on their way to the surface. For example, the compositions of

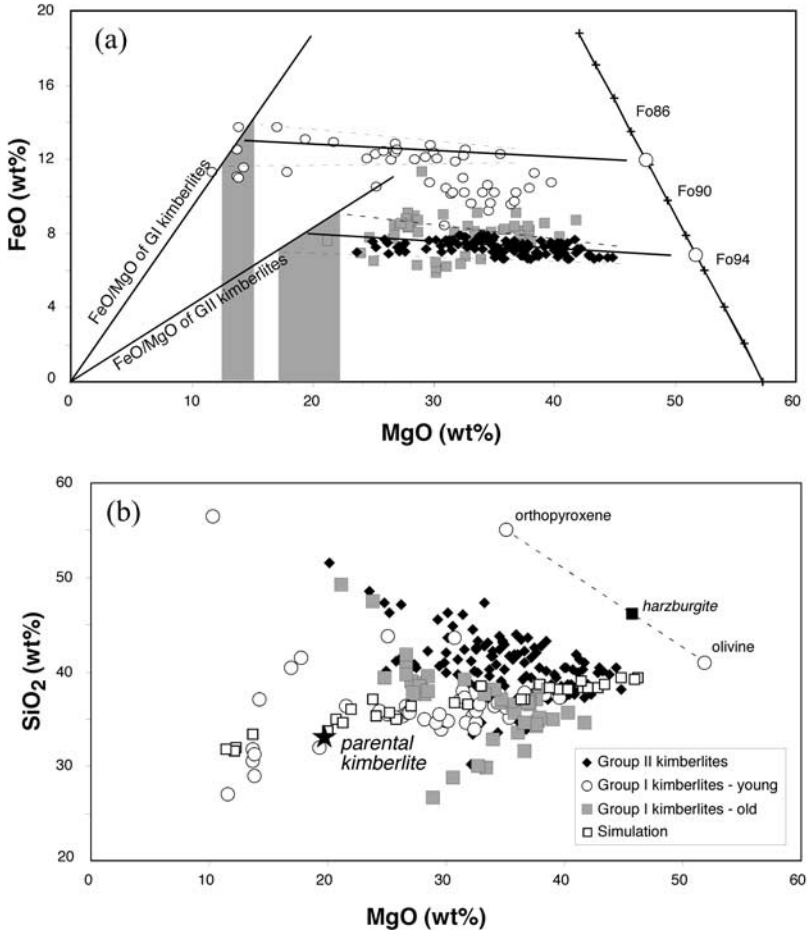

Figure 4. (a) MgO versus FeO in kimberlites and in olivine. For the whole rock compositions 0.85*FeO(tot) is plotted on the assumption that 15% of the iron is Fe^{3+}. Kimberlites from the Kaapvaal craton plot on an olivine control line that projects to Fo_{93}, a composition like that recorded in peridotite xenoliths from the Kaapvaal lithospheric mantle; kimberlites from younger cratons project to less magnesian olivine compositions. The sloping lines represent the FeO/MgO ratios of liquid in equilibrium with Fo_{93} for the Kaapvaal kimberlites and with $Fo_{86.5}$ for the younger kimberlites. The intersections of these lines with the kimberlite data give the MgO contents of the parental kimberlitic liquids, as shown with the grey fields. Data are from the compilation of published and unpublished sources of C. B. Smith. (b) MgO versus SiO_2. The data project to the compositions of olivine and not to a mixture of olivine and orthopyroxene, as exists in lithospheric mantle. The trend labeled ''Simulation'' was calculated in the following way. First, a mixture of 2/3 olivine and 1/3 orthopyroxene was added to a hypothetical parental kimberlite liquid containing 33% SiO_2 and 20% MgO to simulate the assimilation of lithospheric harzburgite. Both olivine and orthopyroxene had Mg/(Mg + Fe) = 0.93; the amount added varied randomly between 5 and 35%. Then 5 to 85% of olivine with the composition Fo_{93} was added or subtracted to simulate the accumulation or fractionation of olivine into or from the hybrid liquid. The simulated trend corresponds to that of the Kaapvaal (Group II) kimberlites.

kimberlites that erupted on the Kaapvaal craton in South Africa are controlled by highly forsterite-rich olivine (Fo_{93}), like the distinctive olivine in mantle xenoliths from that region [*Boyd and Mertzman*, 1987; *Pearson et al.*, 2003]. The compositions of kimberlites from post-Archean settings are controlled by less magnesian olivine, like that in xenoliths from younger cratons [*Menzies*, 1990]. This relationship strongly suggests that some or most of the olivine grains in kimberlites are xenocrysts. On the other hand, lithospheric mantle, particularly that beneath the Kaapvaal craton, is unusually rich in orthopyroxene [*Boyd*, 1989; *Griffin et al.*, 1999], yet this mineral appears absent from the macrocryst assemblages in kimberlites [*Mitchell*, 1995]. What appears to have happened is that the orthopyroxene has been resorbed into the kimberlite liquid, producing a hybrid magma in which olivine xenocrysts accumulated and from which olivine crystallized.

[14] I simulated this process using the procedure described in the figure caption to produce the trend shown in Figure 4b, a trend that matches the dominant trend for kimberlites from the Kaapvaal Craton. The same can be done with less magnesian olivines from other cratons. On the basis of these results, kimberlites can be supposed to be magmas from a deep, probably sublithosphere source that

assimilated considerable material from the mantle through which they passed. Along with the refractory orthopyroxene, the kimberlite would have assimilated a large amount of more fusible material. The measured major element concentrations, particularly SiO_2 and the trace element and isotopic compositions of kimberlites, must have been strongly influenced, if not controlled, by this material.

[15] We can use the compositions of olivine phenocrysts in the matrix of kimberlites to estimate the composition of the kimberlite liquid. In Group I kimberlites, the majority of these grains contain between 88 and 91% forsterite, with an additional peak at Fo_{93}; in Group II kimberlites, the range is from 91 to 93% forsterite [*Mitchell*, 1986]. Using a Mg-Fe distribution coefficient of 0.33, the liquid in equilibrium with Fo_{93} is calculated to have FeO/MgO (wt %) = 0.41. In Figure 4a, I show how this ratio can be related to the MgO content of the liquid; for the Fe-poor Group I kimberlites, the liquid contained between 18 and 22 wt % MgO; for the younger, more Fe rich kimberlites, the value is 13–16 wt %. Figure 4 also shows that the two types of kimberlites are mixtures between these relatively magnesian liquids and abundant olivine xenocrysts and phenocrysts.

[16] Meimechite is a rare type of ultramafic, potassium-rich volcanic rock found in northern Siberia, in close association with the flood basalts of this region [*Arndt et al.*, 1998b, 1995]. These rocks occur as massive flows of olivine-phyric lava. From the compositions of olivine phenocrysts and studies of melt inclusions [*Sobolev et al.*, 1991], the MgO content of the magma is estimated to be in the range 20–25%. These are true ultramafic liquids. Their chemical characteristics are qualitatively similar, though not so extreme, as those of kimberlites (high MgO is combined with low SiO_2 and Al_2O_3 and high concentrations of incompatible trace elements) and their isotope compositions are those of depleted upper mantle or plume source. These rocks may form the magnesian end-member of a suite of continental ultrapotassic rocks that also includes lamproites and some lamprophyres. The latter rocks have even higher contents of incompatible elements.

4. Boninites

[17] Boninites do not normally have ultramafic composition but are included here because they illustrate how highly magnesian magmas can form in a very different environment and by another type of partial melting. It is generally agreed that they form by low-pressure, fluid-fluxed melting of metasomatised refractory peridotite in the mantle wedge above a subduction zone [*Crawford et al.*, 1989; *Falloon and Danyushevsky*, 2000; *Tatsumi and Maruyama*, 1989; *Taylor et al.*, 1994]. Boninites are porphyritic rocks containing abundant phenocrysts of olivine, orthopyroxene and clinopyroxene, often in a hydrous glassy matrix [*Crawford et al.*, 1989]. They erupt as massive, or in some cases, pillowed lava flows, normally in forearc basins. Their chemical compositions are distinctive, being marked by high SiO_2 contents (>53%) and high Mg# ($Mg/(Mg + Fe^{2+})$) (Figure 1). Their REE patterns commonly have a characteristic U shape due to low concentrations of the middle REE compared to the LREE and HREE (Figures 2 and 3). In addition, in mantle-normalized diagrams, they normally have negative anomalies (unusually low concentrations) of Nb-Ta and Ti, and positive anomalies of Rb, Ba and Sr [*Crawford et al.*, 1989; *Hickey-Vargas*, 1989; *Taylor et al.*, 1994].

5. Origins of Ultramafic Magma

[18] When mantle peridotite partially melts under normal conditions, the liquid that forms has a basaltic composition. Reference to standard petrology texts shows that there are three principal ways to produce more magnesian, ultramafic magma:

[19] The first is high-degree melting. Basaltic magma is produced under normal conditions of low to intermediate degrees of partial melting (1–15%) because garnet and clinopyroxene, the mantle minerals rich in Na, Ca and Al, melt preferentially under these conditions. At higher degrees of partial melting these minerals are eliminated and the liquid becomes more magnesian because of the fusion of MgO-rich refractory minerals such as orthopyroxene and olivine.

[20] The second is melting at high pressures. Increasing pressure decreases the stability of olivine relative to other mantle minerals. High-pressure liquids contain a higher proportion of olivine and are more magnesian than liquids produced at low pressures.

[21] The third is melting of a depleted, refractory source. If the source is depleted in low-temperature minerals and enriched in olivine and orthopyroxene, at a given degree of melting it will produce liquids that are more magnesian than magma derived from a more ''fertile'' source. A fertile source is transformed to a depleted source by the extraction of magma. This may happen long before the melting event that produces the ultramafic magma, such as during the formation of depleted upper mantle. Or it may happen during fractional melting, when the initial low-degree melts escape the source to leave a refractory residue that undergoes further melting.

6. Causes of Melting

[22] Ultramafic magma forms from a source that was either unusually hot or unusually rich in volatiles. As shown in Figure 5a, a hot source intersects the peridotite solidus at greater depths than a cool source. The near-solidus melt that forms under these conditions has an ultramafic composition because of the pressure effect. If the hot source continues to ascend, the degree of melting increases, and the resultant high-degree melt will retain its ultramafic composition. The presence of volatiles (Figure 5b) lowers the solidus so that melting starts deeper, or so that, at a given depth and temperature and for a given source composition, the degree of partial melting is higher than for a volatile-free source. In section 7, I explore how these effects combine to produce the spectrum of ultramafic rock types described in the earlier section.

6.1. Komatiites

[23] The compositions of both types of komatiite are best explained by melting of an essentially anhydrous but unusually hot source [*Arndt et al.*, 1998a; *Herzberg*, 1992; *Walter*, 1998]. Even though the two main types have rather similar major element compositions, it is possible that they

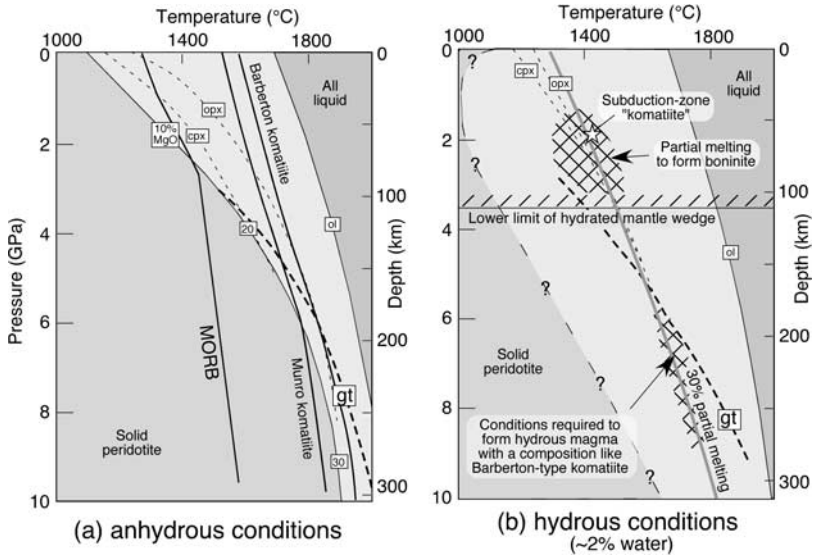

Figure 5. Phase diagrams of mantle peridotite showing the conditions under which ultramafic magmas are generated [from *Walter*, 1997; *Herzberg and O'Hara*, 2002]. (a) Komatiites form from an essentially anhydrous source. Barberton komatiite may have resulted from about 30% of batch melting in equilibrium with garnet under conditions where the liquid had neutral buoyancy. This requires that the melting took place at great depths, probably greater than 10 GPa. Munro-type komatiites form through fractional melting at slightly shallower depths. (b) Phase relations for hydrous peridotite drawn using the data of *Asahara et al.* [1998]. Boninites form by melting in the hydrated mantle wedge overlying subduction zone at depths less than about 100 km. To produce a Barberton-type komatiite with 25% MgO and the geochemical signature of residual garnet, the depth must be greater than about 250 km. This depth is far greater than that at the base of hydrated mantle wedge.

formed by quite different melting mechanisms. Barberton-type komatiite may a rare example of a mantle-derived magma that formed by batch melting. Under normal conditions, silicate melt has a lower density than the solid from which it forms. For normal mafic magma, the density difference is sufficient to cause the magma to escape from its source as soon as the degree of melting exceeds a low threshold, probably 1–3%. Fractional melting of the source then produces more magma. This magma may pond, or mix with the products of low-degree melting, or may, under exceptional circumstances, escape to the surface [*Kerr et al.*, 1995]. At high pressures the situation is different. Silicate liquids are more compressible than solid silicate minerals, which means that as pressure increases, the difference in density between magma and solid residue decreases [*Ohtani*, 1984; *Rigden et al.*, 1984; *Miller et al.*, 1991]. Recent experiments of *Ohtani et al.* [1998] have shown that at pressures of about 13–17 GPa, the density of an ultramafic liquid may be slightly greater than that of olivine.

[24] The peculiar Al depletion and the low levels of HREE of Barberton-type komatiites (Figures 1 and 2) are attributed to melting in the presence of garnet [*Green*, 1981; *Sun*, 1984]. At low pressure, garnet melts near the solidus and is eliminated from the residue before the melt acquires an ultramafic composition. For garnet to be retained in the residue of an ultramafic magma, the pressure must be high. Experimental studies [*Ohtani et al.*, 1989; *Walter*, 1997; *Herzberg*, 1999] have shown that the major element compositions of Barberton-type komatiites are best explained by partial melting at pressures greater than 8 GPa.

[25] The concentrations of incompatible trace elements give some indication of the percentage of partial melting. As shown the Figure 6, Barberton- and Munro-type komatiites result from about 30% and 50% melting, respectively.

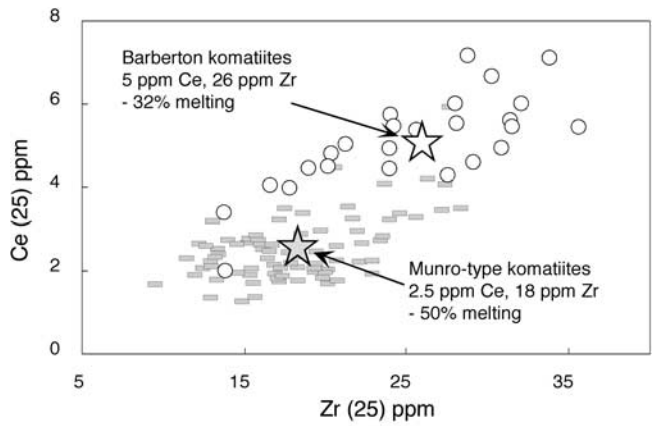

Figure 6. Estimated degree of partial melting of the two types of komatiite. The primary liquid is assumed to have had 28% MgO, and at this value, Barberton-type komatiite has about 25 ppm Zr, and Munro-type komatiite has about 15 ppm Zr. If it is assumed that the source contained 50% olivine, 25% opx, 15% cpx, and 10% garnet and adopting literature values for partition coefficients [e.g., *Green*, 1994], the degree of melting is about 30%. For Munro-type komatiites, garnet is absent from the source, and the degree of melting is calculated to be about 50%.

[26] Both types of komatiite form in mantle plumes that rise because they are hotter, and therefore less dense, than the surrounding mantle. If the plume source crosses the liquidus at extreme depths, it produces a liquid with near-neutral density that has little tendency to escape from the plume. However, even though the density of the melt may be slightly greater than that of the hot residual solid in the plume, its remains less than that of the cooler surrounding mantle. The plume as a whole maintains its positive buoyancy and it continues to rise, taking the partial melt with it. As pressure decreases, the density difference between liquid and solid gradually increases until, when a threshold controlled by the density contrast and the permeability of the source is reached, the liquid starts to leave the plume. This magma, which has a composition like that of Barberton komatiite, may escape as a single batch of high-degree melt. The residue left in the plume is refractory mixture of olivine, orthopyroxene and garnet containing low concentrations of incompatible elements. This residue will undergo further melting that will lead, with decreasing pressure, to the elimination of garnet. The relatively rare Al-undepleted komatiites of the Barberton sequence [*Smith and Erlank*, 1982] may form this way. Once these magmas have left the plume, the residue will consist entirely of refractory olivine and will undergo little further melting.

[27] Munro-type komatiites do not show a garnet depletion chemical signature and they probably form in another way. Their plume source apparently was slightly cooler than that of Barberton-type komatiites and it would have intersected the solidus at a shallower level; a level at which near-solidus ultramafic melt is less dense than the solid matrix. The initial melts escapes, and because this melt contains a high proportion of high-density components such as garnet and Fe, it leaves a residue that is less dense than before. This residue continues to rise, and as it rises it continues to melt. The low contents of trace elements and the strong depletion of the more incompatible elements, in both Munro-type Archean komatiites and the Cretaceous komatiites from Gorgona Island, are consistent with about 30–50% fractional melting [*Arndt*, 1994; *Arndt et al.*, 1997].

6.2. Kimberlites and Meimechites

[28] In kimberlites the concentrations of highly incompatible trace elements such as Nb and Th are enormous, up to 800 times the concentration in primitive mantle. If partial melting of a primitive peridotitic source produced these magmas, the degree of melting must have been miniscule, less than 0.1%. In meimechites, concentrations range up to 300 times primitive mantle values. For these magmas, the required degree of melting is greater, around 0.2%, but still remarkably small. It is difficult to imagine that such small fractions of liquid could be extracted from normal mantle peridotite, and for this reason, it is commonly proposed that kimberlites and meimechites come from an enriched source [*Foley*, 1992; *Mitchell*, 1995]. In most papers the enrichment is attributed to the influx of fluids, either volatile-rich or low-degree silicate melts; commonly this enrichment is said to take place in the lithospheric mantle.

[29] The chemical features of kimberlites and meimechites (their high MgO contents and their strongly fractionated REE) are difficult to explain if the magma source was in the subcontinental lithosphere. There are two main arguments, the first based on the overall compositions of kimberlites, the second on the contrasting isotope compositions of Group I and II kimberlites. The high concentration of incompatible elements and the strong fractionation of incompatible from compatible elements eliminate the possibility that the high concentration of MgO resulted from a large degree of melting. To produce magma with 18–22% MgO (the calculated MgO of Group I kimberlite liquid) by near-solidus melting of normal mantle peridotite requires depths greater than 100 km [*Herzberg and Zhang*, 1996], which places the site of melting near or below the base of the lithosphere. To produce 25% MgO meimechites requires 6–7 GPa pressure or 200 km depth. The modal effects of metasomatism, which replace high-Mg minerals like olivine by low-Mg minerals like clinopyroxene, amphibole and phlogopite, produce a low-MgO source that is less able to form high MgO magma. In view of these factors, it seems more probable that the ultramafic magmas parental to kimberlites formed well below the base of the lithosphere.

[30] The isotopic compositions provide additional constraints. Group II kimberlites have Sr and Nd isotope ratios like those of old enriched mantle material, such as forms in the lower metasomatised part of the lithosphere [*Smith*, 1983; *Nowell et al.*, 1999]: this similarity raises the possibility that magma from a deep source acquired unusual isotopic, and trace element characteristics through interaction with the lithosphere. Group I kimberlites and meimechites, on the other hand, have isotopic compositions like convecting mantle (asthenosphere or plume) and they do not seem to have interacted with the lithosphere. Their high trace element contents, which approach those of Group I kimberlites, must have an asthenospheric origin.

[31] We have very few constraints on the nature of primary kimberlite magma. It certainly formed by deep melting and it probably had an ultramafic composition. Because of the high contents of H_2O and CO_2 in kimberlites, the source must have been rich in volatiles. This source may have been richer in incompatible elements than normal mantle and it could have consisted largely of recycled basalt like the source of certain mantle plumes [*le Roex*, 1986; *Nowell et al.*, 1999]. A source with high concentrations of heat-producing elements will heat up to temperatures higher than those of normal mantle. How much hotter depends on the age and the geometry (size and form) of the source. We therefore develop a picture of a source of kimberlites and meimechites that consists of blobs, streaks or layers that are slightly hotter than the surrounding mantle. The blobs or streaks melt at lower temperature than the matrix because of their high content of volatiles and incompatible components. If this material formed part of a plume, or a rising limb of a convection cell, it would melt at great depths, well before the onset of generalized melting, to produce small packets of volatile-charged, incompatible-element-rich magma. These would escape from the source and rise toward the surface.

[32] Group II kimberlites interacted with lithospheric peridotite. The exact mechanism is unclear, but probably involved percolation of magma through lithospheric perid-

otite. During the interaction, the wall rocks disaggregated, releasing olivine grains that were incorporated into the magma as xenocrysts, and polluting the magma with orthopyroxene and more fusible components. This process increased SiO_2 contents from initially very low concentrations, and adjusted the Mg/Fe ratio of the magma so that it crystallized olivine with composition like that in the assimilated material. It also increased the concentrations of incompatible trace elements and changed isotope ratios from asthenospheric to lithospheric values.

[33] Group I kimberlites and meimechites lack the isotope signature of the lithosphere but their concentrations of incompatible elements are similar to those of the Group II kimberlites. They appear to have interacted with mantle of normal isotopic composition, but not with old lithospheric mantle. Mantle xenoliths are common in Group I kimberlites but relatively rare in Group II kimberlites. Group I kimberlites apparently passed rapidly through the lithosphere, plucking fragments from the conduit margins but resorbing little of this material. How do we explain the differences in behavior between the two types? One possibility is that the levels of volatiles in the primary magmas, particularly CO_2, were different. The level of CO_2 in Group I kimberlite could have been higher and this phase may have started to exsolve at depths near the base of the lithosphere, forming a gas-charged magma that was propelled rapidly to the surface without interacting with the wall rocks. Group II kimberlites, because of lower levels of CO_2, exsolved the volatile phase only at shallower depths. Before this happened, the magma had percolated slowly through the lithosphere and had interacted strongly with it.

6.3. Boninites

[34] Boninites form in a very different environment. Their peculiar REE pattern (U-shaped, with lower concentrations of intermediate elements than LREE and HREE), their low overall concentrations of these elements, and their positive and negative Nb-Ta, Sr and Ti anomalies, all point to a source with a complex history. Boninites are found in forearc basins and are thought to form through fluid-fluxed partial melting in the mantle wedge above the subduction zone [*Crawford et al.*, 1989; *Hickey-Vargas*, 1989; *Tatsumi and Maruyama*, 1989]. Low concentrations and the positively sloping HREE provide evidence that their source originally was strongly depleted in incompatible elements. The relative enrichment of LREE as well as Rb, Sr and Cs (not shown), and relatively high Sr isotopic compositions, are all explained by the addition to this source of a ''subduction component'' - aqueous fluid and/or silicate melt from the subducting slab [*Taylor et al.*, 1994; *Falloon and Danyushevsky*, 2000]. Peculiarities of the major element compositions, such as the high SiO_2 contents and the low levels of FeO and TiO_2 (Figure 1), are attributed to hydrous melting of a depleted source. The highly mafic compositions of boninites are a consequence of high degrees of partial melting of the refractory, depleted source, melting that was possible only in the presence of large amounts of aqueous subduction fluid.

[35] As shown in Figure 1, several features of the major element contents of boninites are diagnostic of melting at low pressure, such as exist in the mantle wedge above a subduction zone. Particularly telling are the high Al_2O_3 contents, as expressed by high Al_2O_3/TiO_2 and low CaO/Al_2O_3 and the low FeO contents (Figures 1–3).

7. Boninites and Komatiites

[36] *Parman et al.* [1997], *Grove et al.* [1999] and *Parman et al.* [2001] have suggested that komatiite or komatiitic basalt is the Archean equivalent of boninite. According to these authors, fluid-fluxed melting of the unusually hot mantle wedge above an Archean subduction zone produces magma that is more magnesian than modern boninite. The data presented above shows, however, that Barberton-type komatiites cannot form in such a setting. For garnet to be stable in ultramafic liquid, and to realize a high degree of melting, extremely high pressures are required. Figure 5 shows that the formation of Barberton-type komatiites is restricted to pressures greater than 10 GPa, or depths greater than 300 km. In the modern mantle, aqueous fluid is released from dehydrating subducting crust at depths far shallower than these, generally at less than 100 km. The hydrated mantle-wedge peridotite might be dragged to somewhat greater depths by subduction-linked circulation, but melting in the wedge is most unlikely to take place at depths below about 120 km. The major element composition of boninites reflects melting at these low pressures. In the hotter Archean environment, where oceanic crust is thicker and hotter than at present, fluid would probably be released at shallower levels and the wedge itself would melt at still shallower depths.

[37] The effect of adding water to peridotite is to destabilize garnet. *Asahara et al.* [1998] have shown that in mantle peridotite with 2% water, pressures greater than 7.7 GPa, or depths of 230 km are needed to produce ultramafic magma in equilibrium with garnet, compared with about 6 GPa under dry conditions. The presence of water increases the margin between the conditions required to form komatiite and conditions in the mantle wedge above a subduction zone. It can be concluded that melting above subduction zones, particularly hot Archean subduction zones, cannot produce Barberton-type komatiites.

[38] If Munro-type komatiites formed through fractional melting, as suggested above, they too must have formed at depths greater than those of an active subduction zone. As shown in Figure 5, to realize the 50% melting needed to form these magmas, it is necessary that the source started to melt at great depths. The moderate to extreme depletion of incompatible trace elements and the absence of the ''subduction'' signature (low Nb/La and Ti/Zr, Sm/Sr; Figures 1–3) in komatiites from 2.7 Ga greenstone belts, and in their melt inclusions, provide further convincing evidence that these magmas did not form in a subduction zone. Although komatiites and boninites are superficially similar in that both have high MgO contents, moderately high SiO_2 and low contents of incompatible elements, in terms of their overall major and trace element compositions and in their manner of formation, they are radically different.

8. Summary

[39] Just as with basaltic magmas, there is a spectrum of ultramafic magma types. Their ultramafic character has contrasting origins. In kimberlites and meimechites, it

results from low-degree melting at great depth; in komatiites from moderate- to high-degree melting, also at great depth; and in boninites from melting of a refractory source at shallow depths. Alkaline ultramafic magmas (kimberlites and meimechites) are comparable in some ways to alkaline basalts. They owe their special character to low-degree melting at large depths, of a source relatively enriched in incompatible elements. They undergo further enrichment through interaction with overlying asthenosphere or lithosphere. Boninites are rather like calc-alkaline basalts, the products of fluid-fluxed partial melting, at shallow depths, in the mantle above a subduction zone. Komatiites stand apart. They are fundamentally different from mid-ocean ridge basalts for which relatively high degrees of melting are realized only because the source rises almost to the surface. The closest basaltic analogue of komatiite probably is tholeiite from oceanic islands, a type of magma that results from moderately high degrees of melting in a hot mantle plume. Komatiite represents an extreme example of this type—the consequence of high-degree melting in an extremely hot plume.

[40] The contrasting origins of these magmas are reflected in their chemical compositions. Just as in basalts, each process imparts a distinctive chemical signature that can be used distinguish one rock type from another. The diagrams presented in Figures 1–3 show the types of criteria that are useful in this respect. The presence of the ''subduction signature'' of high SiO_2, high Rb and Sr, and low contents of high-field-strength elements like Nb and Ti, identifies boninite, the magma produced by hydrous melting in a subduction environment. High Al and low Fe contents provide evidence of melting at relatively low pressures. Extreme enrichment of incompatible elements and very low Al_2O_3 contents characterizes kimberlite and meimechite, magmas that are derived by low-degree melting at high pressures of enriched sources. And finally high MgO contents, low concentrations of incompatible elements, intermediate to low Al_2O_3 contents, and the absence of the subduction signature identifies komatiite, the product of high-degree anhydrous melting at extreme mantle depths.

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References

Aitken, B. G., and L. M. Echeverria, Petrology and geochemistry of komatiites and tholeiites from Gorgona Island, Colombia, *Contrib. Mineral. Petrol.*, *86*, 94–105, 1984.

Arndt, N. T., Magma mixing in komatiitic lavas from Munro Township, Ontario, in *Archaean Geochemistry*, edited by A. Kröner, G. N. Hanson, and A. M. Goodwin, pp. 99–115, Springer-Verlag, New York, 1984.

Arndt, N. T., Archean komatiites, in *Archean Crustal Evolution*, edited by K. C. Condie, pp. 11–44, Elsevier Sci., New York, 1994.

Arndt, N. T., and G. A. Jenner, Crustally contaminated komatiites and basalts from Kambalda, Western Australia, *Chem. Geol.*, *56*, 229–255, 1986.

Arndt, N. T., and R. W. Nesbitt, Geochemistry of Munro Township basalts, in *Komatiites*, edited by N. T. Arndt and E. G. Nisbet, pp. 309–330, Allen and Unwin, Concord, Mass., 1982.

Arndt, N. T., and E. G. Nisbet, What is a komatiite?, in *Komatiites*, edited by N. T. Arndt and E. G. Nisbet, pp. 19–28, Allen and Unwin, Concord, Mass., 1982.

Arndt, N. T., K. Lehnert, and Y. Vasil'ev, Meimechites: Highly magnesian alkaline magmas from the subcontinental lithosphere?, *Lithos*, *34*, 41–59, 1995.

Arndt, N. T., A. C. Kerr, and J. Tarney, Dynamic melting in plume heads: The formation of Gorgona komatiites and basalts, *Earth Planet. Sci. Lett.*, *146*, 289–301, 1997.

Arndt, N. T., F. Albarède, M. M. Cheadle, C. Ginibre, C. Herzberg, G. Jenner, C. Chauvel, and Y. Lahaye, Were komatiites wet?, *Geology*, *26*, 739–742, 1998a.

Arndt, N. T., C. Chauvel, V. Fedorenko, and G. Czamanske, Two mantle sources, two plumbing systems: Tholeiitic and alkaline magmatism of the Maymecha River basin, Siberian flood volcanic province, *Contrib. Mineral. Petrol.*, *133*, 297–313, 1998b.

Asahara, Y., E. Ohtani, and A. Suzuki, Melting relations of hydrous and dry mantle compositions and the genesis of komatiites, *Geophys. Res. Lett.*, *25*, 2201–2204, 1998.

Barley, M. E., Incompatible element enrichment in Archaean basalts: A consequence of contamination by older sialic crust rather than mantle heterogeneity, *Geology*, *14*, 947–950, 1986.

Boyd, F. R., Compositional distinction between oceanic and cratonic lithosphere, *Earth Planet. Sci. Lett.*, *96*, 15–26, 1989.

Boyd, F. R., and S. A. Mertzman, Composition and structure of the Kaapvaal lithosphere, southern Africa, in *Magmatic Processes: Physicochemical Principles*, edited by B. O. Mysen, *Spec. Publ. Geochem. Soc.*, *1*, 13–24, 1987.

Crawford, A. J., T. J. Falloon, and D. H. Green, Classification, petrogenesis and tectonic setting of boninites, in *Boninites*, edited by A. J. Crawford, pp. 1–49, Chapman and Hall, New York, 1989.

Dann, J. C., The Komati Formation, Barberton Greenstone Belt, South Africa, part I: New map and magmatic architecture, *S. Afr. J. Earth Sci.*, *6*, 681–730, 2000.

Dann, J. C., Vesicular komatiites, 3.5-Ga Komati Formation, Barberton Greenstone Belt, South Africa: Inflation of submarine lavas and origin of spinifex zones, *Bull. Volcanol.*, *63*, 462–481, 2001.

Echeverria, L. M., Tertiary or Mesozoic komatiites from Gorgona Island, Colombia: Field relations and geochemistry, *Contrib. Mineral. Petrol.*, *73*, 253–266, 1980.

Falloon, T. J., and L. V. Danyushevsky, Melting of refractory mantle at 1. 5, 2 and 2.5 GPa under anhydrous and H_2O-undersaturated conditions: Implications for the petrogenesis of high-Ca boninites and the influence of subduction components on mantle melting, *J. Petrol.*, *41*, 257–356, 2000.

Foley, S. F., Petrological characterization of the source components of potassic magmas: Geochemical and experimental constraints, *Lithos*, *28*, 435–453, 1992.

Green, D. H., Petrogenesis of Archean ultramafic magmas and implications for Archaean tectonics, in *Precambrian Plate Tectonics*, edited by A. Kröner, pp. 469–490, Elsevier Sci., New York, 1981.

Green, T. H., Experimental studies of trace-element partitioning applicable to igneous petrogenesis-Sedona 16 years later, *Chem. Geol.*, *117*, 1–36, 1994.

Griffin, W. L., S. Y. O'Reilly, and C. G. Ryan, The composition and origin of sub-continental lithospheric mantle, in *Mantle Petrology: Field Observations and High-Pressure Experimentation*, edited by Y. Fei, C. M. Bertka, and B. O. Mysen, *Spec. Publ. Geochem. Soc.*, *6*, 13–46, 1999.

Grove, T. L., M. J. deWit, and J. Dann, Komatiites from the Komati type section, Barberton, South Africa, in *Greenstone Belts*, edited by M. J. de Wit and L. D. Ashwal, pp. 422–437, Oxford Sci., Oxford, U.K., 1997.

Grove, T. L., S. W. Parman, and J. C. Dann, Conditions of magma generation for Archean komatiites from the Barberton Mountainland, South Africa, in *Mantle Petrology: Field Observations and High-Pressure Experimentation*, edited by Y. Fei, C. M. Bertka, and B. O. Mysen, *Spec. Publ. Geochem. Soc.*, *6*, 155–167, 1999.

Gruau, G., C. Chauvel, N. T. Arndt, and J. Cornichet, Al-depletion in komatiites and garnet fractionation in the early Archean mantle: Hf isotopic constraints, *Geochim. Cosmochim. Acta*, *54*, 3095–3101, 1990.

Herzberg, C., Depth and degree of melting of komatiite, *J. Geophys. Res.*, *97*, 4521–4540, 1992.

Herzberg, C., Phase equilibrium constraints on the formation of cratonic mantle, in *Mantle Petrology: Field Observations and High-Pressure Experimentation*, edited by Y. Fei, C. M. Bertka, and B. O. Mysen, *Spec. Publ. Geochem. Soc.*, *6*, 241–257, 1999.

Herzberg, C., and M. J. O'Hara, Plume-associated ultramafic magmas of Phanerozoic aAge, *J. Petrol.*, *43*, 1857–1883, 2002.

Herzberg, C., and J. Zhang, Melting experiments on anhydrous peridotite KLB-1: Compositions of magmas in the upper mantle and transition zone, *J. Geophys. Res.*, *101*, 8271–8295, 1996.

Hickey-Vargas, R., Boninites and tholeiites from DSDP Site 458, Mariana forearc, in *Boninites*, edited by A. J. Crawford, pp. 257–356, Chapman and Hall, New York, 1989.

Hofmann, A. W., Chemical differentiation of the Earth: The relationship between mantle, continental crust, and oceanic crust, *Earth Planet. Sci. Lett.*, *90*, 297–314, 1988.

Kerr, A. C., and N. T. Arndt, A note on the IUGS reclassification of the high-Mg and picritic volcanic rocks, *J. Petrol.*, *42*(11), 2169–2171, 2001.

Kerr, A., G. Marriner, N. T. Arndt, J. Tarney, A. Nivia, A. Saunders, M. J. Storey, and R. A. Duncan, The petrogenesis of Gorgona komatiites, picrites and basalts: New field, petrographic and geochemical constraints, *Lithos*, *37*, 245–260, 1995.

Lahaye, Y., N. T. Arndt, G. Byerly, G. Gruau, S. Fourcade, and C. Chauvel, The influence of alteration on the trace–element and Nd isotope compositions of komatiites, *Chem. Geol.*, *126*, 43–64, 1995.

le Roex, A. P., Geochemical correlation between Southern African kimberlites and South Atlantic hot spots, *Nature*, *324*, 243–245, 1986.

McDonough, W. F., and T. R. Ireland, Intraplate origin of komatiites inferred from trace elements in glass inclusions, *Nature*, *365*, 432–434, 1993.

Menzies, M. A., Archaean, Proterozoic and Phanerozoic lithospheres, in *Continental Mantle*, edited by M. A. Menzies, pp. 67–86, Clarendon, Oxford, U.K., 1990.

Miller, G. H., E. M. Stolper, and T. J. Ahrens, The equation of state of molten komatiite: 2. Application to komatiite petrogenesis and the Hadean mantle, *J. Geophys. Res.*, *96*, 11,849–11,864, 1991.

Mitchell, R. H., *Kimberlites: Mineralogy, Geochemistry, and Petrology*, 442 pp., Plenum, New York, 1986.

Mitchell, R. H., *Kimberlites, Orangites, and Related Rocks*, 410 pp., Plenum, New York, 1995.

Nesbitt, R. W., and S.-S. Sun, Geochemistry of Archaean spinifex-textured peridotites and magnesian and low-magnesian tholeiites, *Earth Planet. Sci. Lett.*, *31*, 433–453, 1976.

Nisbet, E. G., The tectonic setting and petrogenesis of komatiites, in *Komatiites*, edited by N. T. Arndt and E. G. Nisbet, pp. 501–520, Allen and Unwin, Concord, Mass., 1982.

Nisbet, E. G., M. J. Cheadle, N. T. Arndt, and M. J. Bickle, Constraining the potential temperature of the Archaean mantle: A review of the evidence from komatiites., *Lithos*, *30*, 291–307, 1993.

Nowell, G. M., D. G. Pearson, P. D. Kempton, S. R. Noble, and C. B. Smith, Origins of kimberlites, in *Proceeding of the 7th International Kimberlite Conference, Cape Town*, edited by J. J. Gurney et al., pp. 616–624, Natl. Book, Cape Town, 1999.

Ohtani, E., Generation of komatiite magma and gravitational differentiation in the deep upper mantle, *Earth Planet. Sci. Lett.*, *67*, 261–272, 1984.

Ohtani, E., I. Kawabe, J. Moriyama, and Y. Nagata, Partitioning of elements between majorite garnet and melt and implications for petrogenesis of komatiite, *Contrib. Mineral. Petrol.*, *103*, 263–269, 1989.

Ohtani, E., A. Suzuki, and T. Kato, Flotation of olivine and diamond in mantle melt at high pressure: Implications for fractionation in the deep mantle and ultradeep origin of diamond, in *Properties of Earth and Planetary Materials*, *Geophys. Monogr. Ser.*, vol. 101, edited by M. H. Manghnani and T. Yagi, pp. 227–239, AGU, Washington, D.C., 1998.

Parman, S., J. Dann, T. L. Grove, and M. J. de Wit, Emplacement conditions of komatiite magmas from the 3. 49 Ga Komati Formation, Barberton Greenstone Belt, South Africa, *Earth Planet. Sci. Lett.*, *150*, 303–323, 1997.

Parman, S., T. L. Grove, and J. Dann, The production of Barberton komatiites in an Archean subduction zone, *Geophys. Res. Lett.*, *28*, 2513–2516, 2001.

Pearson, D. G., G. J. Irvine, R. W. Carlson, M. G. Kopylova, and D. A. Ionov, The development of lithospheric keels beneath the earliest continents: Time constraints using PGE and Re-Os isotope systematics, in *The Early Earth: Physical, Chemical and Biological Development*, edited by C. M. R. Fowler, *Geol. Soc. Spec. Publ.*, *199*, 65–88, 2003.

Rigden, S. B., T. J. Ahrens, and E. M. Stolper, Densities of liquid silicates at high pressures, *Science*, *226*, 1071–1074, 1984.

Smith, C. B., Pb, Sr, and Nd isotopic evidence for sources of African Cretaceous kimberlites, *Nature*, *304*, 51–54, 1983.

Smith, C. B., J. J. Gurney, E. M. W. Skinner, C. R. Clement, and N. Ebrahim, Geochemical character of southern African kimberlites: A new approach based on isotopic constraints, *Trans. Geol. Soc. S. Afr.*, *88*, 267–280, 1985.

Smith, H. S., and A. J. Erlank, Geochemistry and petrogenesis of komatiites from the Barberton greenstone belt, South Africa, in *Komatiites*, edited by N. T. Arndt and E. G. Nisbet, pp. 347–398, Allen and Unwin, Concord, Mass., 1982.

Smith, H. S., J. R. O'Neil, and A. J. Erlank, Oxygen isotope compositions of minerals and rocks and chemical alteration patterns in pillow lavas from the Barberton greenstone belt, South Africa, in *Archaean Geochemistry*, edited by A. Kröner, G. N. Hanson, and A. M. Goodwin, pp. 115–138, Springer-Verlag, New York, 1984.

Sobolev, A. V., V. S. Kamenetskiy, and N. N. Kononkova, New data on Siberian meymechite petrology, *Geokhimiya*, *8*, 1084–1095, 1991.

Sun, S.-S., Geochemical characteristics of Archean ultramafic and mafic volcanic rocks: Implications for mantle composition and evolution, in *Archaean Geochemistry*, edited by A. Kröner, G. N. Hanson, and A. M. Goodwin, pp. 25–47, Springer-Verlag, New York, 1984.

Sun, S. S., and R. W. Nesbitt, Petrogenesis of Archean ultrabasic and basic volcanics: Evidence from rare earth elements, *Contrib. Mineral. Petrol.*, *65*, 301–325, 1978.

Sun, S.-S., R. W. Nesbitt, and M. T. McCulloch, Geochemistry and petrogenesis of Archaean and early Proterozoic siliceous high magnesian basalts, in *Boninites and Related Rocks*, edited by A. J. Crawford, pp. 148–173, Allen and Unwin, Concord, Mass., 1989.

Tatsumi, Y., and S. Maruyama, Boninites and high-Mg andesites: Tectonics and petrogenesis, in *Boninites*, edited by A. J. Crawford, pp. 50–71, Chapman and Hall, New York, 1989.

Taylor, R. N., R. W. Nesbitt, P. Vidal, R. S. Harmon, B. Auvray, and I. W. Croudace, Mineralogy, chemistry and genesis of the boninite series volcanics, Chichijima, Bonin Islands, Japan, *J. Petrol.*, *35*, 577–617, 1994.

Viljoen, M. J., and R. P. Viljoen, The geology and geochemistry of the lower ultramafic unit of the Onverwacht Group and a proposed new class of igneous rocks, *Spec. Publ. Geol. Soc. S. Afr.*, *2*, 55–85, 1969.

Walter, M. J., Melting of garnet peridotite and the origin of komatiite and depleted lithosphere, *J. Petrol.*, *39*, 29–60, 1997.

Walter, M. J., Melting of garnet peridotite and the origin of komatiites and depleted lithosphere, *J. Petrol.*, *39*, 29–60, 1998.

Xie, Q., R. Kerrich, and J. Fan, HFSE/REE fractionations recorded in three komatiite-basalt sequences, Archean Abitibi greenstone belt: Implications for multiple plume sources and depths, *Geochim. Cosmochim. Acta*, *57*, 4111–4118, 1993.

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