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Komatiite

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Introduction

It is easy to explain roughly what a komatiite is but difficult to give a rigorous definition. The simple definition is that *komatiite* is an ultramafic volcanic rock (Arndt and Nisbet 1982). A limit of 18% MgO separates komatiites from less magnesian volcanic rocks such as picrites, ankaramites or magnesian basalts. The term *komatiitic basalt* is applied to volcanic rocks containing less than 18% MgO that can be linked, using petrological, textural or geochemical arguments, to komatiites.

Implicit to the definition of komatiite is the notion — difficult to prove — that komatiites crystallize from liquids that contained more than about 18% MgO. Complications arise from the existence of other MgO-rich volcanic rocks that either formed through the accumulation of olivine from less magnesian liquids, or crystallized from magmas with geochemical characteristics quite unlike those of most komatiites. An example of the first type is a phenocryst-charged basaltic liquid (a picrite according to some definitions); an example of the second is meimechite (Arndt et al. 1995; Vasil'yev and Zolotukhin 1975), a rare alkaline ultramafic lava with unusual major and trace element composition.

To distinguish komatiite from other types of highly magnesian volcanic rock, it is useful to include spinifex texture in the definition (Fig. 1a, b). Spinifex, a texture characterized by the presence of large skeletal or dendritic crystals of olivine or pyroxene, is present in many, but not all komatiite flows (Nesbitt 1971). A workable definition of komatiite should include the phrase “komatiite is an ultramafic volcanic rock containing spinifex or related to lavas containing this texture”. With the last part of the definition we can make allowance for the manner in which texture varies within komatiitic units. For example, many komatiite flows have an upper spinifex-textured layer and a lower olivine-cumulate layer (Fig. 1c); and other flows grade along strike from layered spinifex-textured portions to massive olivine-phyric units. With the inclusion of the phrase about spinifex, the lower olivine-cumulate portions of layered flows or the olivine-phyric units can also be described as komatiite. On the other hand, meimechites, picrites and other rock types that contain no spinifex are excluded. For further discussion, see (Le Maitre et al. 1989) and (Kerr and Arndt 2001).

Because of the facility with which olivine fractionates or accumulates in low-viscosity ultrabasic liquids, the compositions of komatiite lavas vary considerably. MgO contents range from 18%, (the limit between komatiite and komatiitic basalt) to as high as 50% in the lower cumulate portions of layered flows (Fig. 2). Elements that are immobile during the metamorphism and hydrothermal alteration, which affects all komatiites to a greater or lesser

extent, plot on olivine-control lines in variation diagrams (Arndt 1994). The least magnesian compositions are found in the lower parts of spinifex zones, the most magnesian in the olivine cumulates. Chilled flow tops and porphyritic lavas have intermediate compositions.

The maximum MgO contents of komatiite liquids, estimated using the compositions of chilled flow margins and the forsterite contents of olivine, are between 28 and 30% (Nisbet 1993). The dry 1-atmosphere liquidus temperature of these liquids, calculated from experimental data, is between 1560 and about 1600°C (Bickle et al. 1977; Green 1974; Nisbet 1982).

Several different geochemical types can be distinguished using $\text{Al}_2\text{O}_3/\text{TiO}_2$ and rare earth elements (REE) (Jahn et al. 1982; Nesbitt et al. 1982; Sun and Nesbitt 1978). The komatiites first discovered by Viljoen and Viljoen (1969) are of the “Al-depleted” or Barberton type. As shown in Fig. 3, these rocks have relatively low $\text{Al}_2\text{O}_3/\text{TiO}_2$ and Gd/Yb, the latter ratio being a measure of relative depletion of the heavy rare earth elements (HREE). The second group of komatiites, called “Al-undepleted” or Munro-type, has near chondritic ratios of $\text{Al}_2\text{O}_3/\text{TiO}_2$ and Gd/Yb. A third type, Al-enriched komatiite, is common in komatiites from Gorgona Island, Colombia (Echeverria 1980), and a fourth type, Ti-rich komatiite occurs in the Baltic shield (Barnes and Often, 1990; Puchtel et al. 1998) and in other parts of Ontario (Sproule et al. 2002).

The typical habitat of komatiite is an Archean greenstone belt. Ultramafic lavas comprise between 0 and about 20% of well-preserved volcanic successions and appear have similar abundances in both middle- and late-Archean belts. True komatiites are rare or absent in Proterozoic sequences — the spinifex-textured lavas of the Cape Smith belt (Arndt 1982; Baragar and Scoates 1981) have komatiitic basaltic compositions — but reappear in one notable example in the Cretaceous. The ~190 Ma ultramafic lavas of Gorgona Island (Echeverria 1980; Echeverría 1982) are true komatiites which crystallized as spinifex-textured flows from liquids containing at least 20% MgO (Révillon et al. 2000).

Formation of high-MgO liquids:

As shown in Fig. 4a, magmas with highly magnesian, ultrabasic compositions form either through melting at high pressures, or by high percentages of mantle melting. The effect of increasing the pressure or depth of melting is to increase the stability of orthopyroxene relative to olivine, and that of garnet relative to the more magnesian mantle minerals. The consequence is the formation of ever more magnesian magma as the pressure increases. Herzberg (Herzberg 1992; Herzberg and Ohtani 1988) has shown that at high pressures, above about 8 GPa, near-solidus melts (liquids produced by melting of mantle peridotite at temperatures only slightly above the solidus) contain more than 30% MgO and have ultrabasic compositions. Increasing the percentage of melting has a similar effect. At shallower levels in the upper mantle, at pressures of ~0.5 to 5 GPa, the minerals that melt at low temperatures (plagioclase, spinel, garnet and clinopyroxene) have relatively low MgO contents. As the degree of melting increases, the more magnesian minerals, olivine and orthopyroxene, progressively enter the liquid, increasing its MgO content. Figure 4a shows schematically how magmas with 30% MgO form either through deep melting near the solidus, or by higher degrees of melting at shallower levels. However, komatiites contain low concentrations of incompatible elements (e.g. Sun and Nesbitt, 1978), which indicates that they formed through relatively high degrees of partial melting. Near-solidus melting therefore

is an improbable explanation for most komatiites: from Fig. 5, we see that on the basis of Ce and Zr contents, they would have formed by 30 to 60% melting of mantle peridotite.

Eruption and Solidification

The viscosity of komatiite magma is very low, one to two orders of magnitude less than that of basalt. Renner et al. (Huppert and Sparks 1985; Renner et al. 1993) estimated a viscosity of 1-2 Pascal-seconds for dry komatiite containing 28% MgO, which compares with 500-1000 Pascal-seconds for typical basalts. The low viscosity influences the way komatiite segregates from its source, rises through the lithosphere, and erupts on the surface.

Komatiite is a fragile magma. It is far hotter than surrounding rocks, especially when it passes through the lithosphere, and it has a strong capacity to interact with them. When it flows rapidly past crustal rocks, it is capable of thermally eroding and assimilating them; if it ponds in a crustal magma chamber, it will fractionally crystallize and lose its ultramafic character. For komatiite to reach the surface it must flow rapidly and continuously, without pausing on its way. Komatiite is also a relatively dense magma. Anhydrous komatiite containing 28% MgO has a density of about 2800 kg m⁻³, significantly higher than that of many rocks in the upper crust. For komatiite to reach the surface and erupt, it must fill a continuous liquid column within rocks whose average density is greater than that of the komatiite itself. This would be the case when komatiite erupts in an oceanic setting where solidified basalt near the surface has a density similar to that of the komatiite liquid, and the cumulates or other intrusive rocks at deeper levels have higher densities. However, when komatiite traverses or erupts onto a granitic substrate, as in the Kambalda area in Western Australia, the high density of mantle rocks lower in the liquid column must counterbalance the low density of the granites.

We have very little idea how a komatiite behaves during eruption. The best analogue is probably the sheet flows of continental flood basalt sequences. On this basis, we can predict that komatiites probably erupted initially along fissures, as a series of lava fountains. The violence of this fountaining is difficult to judge. It will be enhanced by the low viscosity of the silicate liquid but mitigated by the high density. The primary control, however, is the volatile content in the komatiite magma, which probably is low in most komatiites.

We know from work in areas of good outcrop that once komatiites escape the vent they form highly mobile flows (Arndt et al. 1977; Leshner et al., 1984; Barnes et al. 1988; Hill et al. 1995). The maximum length of a komatiite flow is unknown, our knowledge being limited by the quality and continuity of outcrop. However, in some parts of Canada, individual flows can be traced for several kilometers (Arndt et al. 1977), and in Australia, komatiitic units are continuous for many tens of kilometers (Leshner et al., 1984; Barnes et al. 1988; Hill et al. 1995).

Thick, massive, olivine-rich units are present in most regions where komatiite lavas are abundant. These are interpreted as channels through which the lavas passed during their passage from vent to flow front (Leshner et al. 1984, 1989; Hill et al. 1995). Flowage through these channels may have been very rapid and turbulent (Huppert and Sparks 1985). Most of the komatiite flows preserved in greenstone belts represent lateral facies — small sheets or lobes of lava that spread out from central feeder. These small pulses of lava may never have

moved far from the feeder channel before ponding and crystallizing beneath a thin elastic crust

The characteristic layering of komatiite flows is produced during crystallization of ponded lava. Polyhedral olivine grains, which were present before eruption or crystallized during flowage, settle to the base of the flow or crystallize in situ to form the lower cumulate layer (Fig. 6). At the same time, the spinifex-textured upper part of the flow crystallizes through downward growth of crystals from the crust of the flow. Faure et al. (2002) have shown that the presence of a thermal gradient, such as exists at the margin of every flow and high-level intrusion, is instrumental in the formation of spinifex texture. The texture forms as a result of constrained, in-situ crystallization of olivine or pyroxene during moderately rapid cooling of low-viscosity ultramafic liquid.

Melting and segregation of komatiite liquids

During mantle melting, if certain conditions are met, the silicate liquid segregates efficiently from its source even at low degrees of melting. The conditions are (1) the viscosity of the liquid is low, (2) the solid matrix is deformable, and (3) the density of the liquid is less than that of the unmelted residue. Although this is the normal situation for melting at low pressures where basaltic magmas are produced, it may not always be the case for komatiites. (Agee and Walker 1988; Ohtani et al. 1998; Rigden et al. 1984) have shown through experimental studies that because silicate liquid is more compressible than solid silicate minerals, the density contrast between solid and liquid *decreases* as pressure increases. At pressures greater than about 8 GPa, which correspond to a mantle depth of about 250 km, the density of an ultramafic komatiite liquid exceeds that of olivine. It remains less, however, than that of garnet, the densest upper-mantle mineral. (Herzberg and Ohtani 1988; Ohtani 1984) have shown that at 8 GPa, komatiite magma forms through 30-50 % melting, leaving a residue of olivine and majorite garnet. The density of the liquid is slightly less than that of the olivine-garnet residue. Although under static conditions there would be little impetus for the liquid to segregate from its source, mantle melting is normally due to adiabatic decompression in an ascending source, as in a mantle plume. As the source rises, the pressure decreases and the density difference between melt and solid increases. Eventually the density contrast becomes sufficiently large that komatiite of the Al-depleted Barberton type escapes from its source, probably in a single batch of high-degree mantle melt. This type of komatiite is probably one of the rare types of magma that forms through batch melting of the mantle.

Al-undepleted or Munro-type komatiites lack the geochemical signature that signals melting in equilibrium with garnet (Nesbitt et al. 1979; Green, 1981; Herzberg and Ohtani, 1988). This does not necessarily require that the source was garnet-free; only that when the komatiite magma separated from its source, garnet was absent in the solid residue. Three processes can contribute to the elimination of garnet: low pressure, which destabilizes garnet; a high degree of melting, which eliminates low-temperature phases; and fractional melting, which preferentially removes the first-melting garnet-rich component from the source. In a rising mantle plume, all three processes may operate together.

Al-undepleted Munro-type komatiites are characterized by relative depletion of the more incompatible trace elements such as the light rare-earth elements (LREE), Nb and Th. In some cases, notably for the Cretaceous Gorgona komatiites (Aitken and Echeverria 1984; Echeverria and Aitken 1986), the extent of LREE depletion varies widely within a suite of

rocks of constant Nd isotopic composition. This pattern is a clear signature that the rocks formed through fractional melting. The source apparently started to melt at pressures lower than those that produced Barberton-type komatiites (Herzberg 1992; Nisbet 1993). Under these conditions the komatiite liquid is less dense than the residual solid — perhaps the source initially contained a small water content, which entered the melt and lowered its density. This melt then escaped from the source, taking with it a high proportion of the incompatible elements or low-temperature components, including garnet, and the komatiites then formed through more advanced melting of the now-depleted source.

Wet komatiites?

Grove et al. (1999) and Parman et al. (2001) have proposed that Barberton komatiite is a hydrous magma that forms by partial melting of metasomatised mantle above a subduction zone. In their model, the komatiite magma did not erupt as lava flows but crystallized in high-level sills. Arguments in support of the model are as follows. (1) The presence of water in the mantle source reduces the melting temperatures to “reasonable” levels. (2) The morphologies of olivine crystals in spinifex texture are best explained by crystallization in magmas that either contained a significant water content, or had recently exsolved water. (3) The compositions of augite in spinifex-textured komatiites from the Barberton region resemble those of pyroxene in moderate-pressure hydrous experiments (Parman et al. 1997). (4) Analyses of melt inclusions in chromite in komatiites from Zimbabwe suggest that the parental komatiite contained about 0.9% water (Shimizu et al. 1997). (5) Komatiites from the Boston Creek in Canada and in some other areas (Stone et al. 1997), Beresford et al. (2000) and Dann (2001) contain vesicles and minor amounts of magmatic amphibole. (6) The trace-element compositions of some komatiitic basalts resemble those of modern boninites (Parman et al. 2001).

Many other geologists and geochemists believe that most komatiites are essentially anhydrous and that only some rare examples (excluding the Barberton komatiites) contain moderate water contents. The principal arguments are: (1) The Archean mantle probably was hotter than the modern mantle because of higher heat production from more abundant radioactive elements, release of accretion energy and core formation. In this context, the $\sim 1600^{\circ}\text{C}$ liquidus of anhydrous komatiite is not “unreasonably” hot. (2) Spinifex texture has been reproduced in anhydrous experiments (Faure et al., 2002). (3) Recent mapping has shown that Barberton komatiite, like komatiite in other regions, erupted on the surface as highly mobile, long-lived, non-explosive lava flows. This corresponds to the eruption behaviour of anhydrous magma. (4) The extrusive setting of Barberton komatiite casts doubt on the interpretation of pyroxene compositions. (5) Melt inclusions in komatiitic olivine have low water contents (McDonough and Danyushevsky 1995; McDonough and Ireland 1993). (6) The trace-element compositions of most komatiites are very different from those of boninites (Arndt, 2002). (7) The major and trace-element contents of komatiites indicate that they formed at depths far below those of subduction zones (Herzberg, 1992; Arndt, 2002) (Fig. 4b).

Ni-Cu-(PGE) Mineralization

Because they have relatively high Ni, Cu and platinum-group element (PGE) contents and are capable of eroding S-rich crustal rocks, komatiites are capable of forming Ni-Cu-(PGE) sulfide deposits (Gresham and Loftus-Hills, 1981; Leshner, 1989; Leshner and Keays, 2002). The best-known examples, of Archean age, are in the Kambalda region of Western Australia.

These deposits are localized in the lower parts of thick dunitic units that are interpreted as lava channels. Komatiite lava flowing turbulently through the channels thermally eroded and melted S-rich floor rocks, leading to the segregation of Ni-Cu-PGE-rich immiscible sulfide liquids that accumulated at the base of the units to form the ore deposits. Proterozoic deposits, such as those of the Cape Smith Belt in Canada, formed by a similar process within invasive lava channels (Leshner et al., 1999)

Figure captions

- Fig. 1. a. Spinifex-textured komatiite in outcrop (sample from Munro Township, Canada). The bladed habit of large parallel olivine crystals is clearly visible. b. Spinifex-textured komatiite in thin section. Sample from the Belingwe Belt, Zimbabwe. Skeletal olivine crystals lie in a matrix of clinopyroxene and altered glass. c. The upper spinifex-textured portion and the upper part of the olivine cumulate of a layered komatiite flow from Munro Township, Canada. The curved contact between the spinifex and cumulate zones is unusual; in most flows this contact is horizontal.
- Fig. 2. Variation diagrams illustrating the range of compositions of the main types of komatiite. The limit at 18% MgO separates komatiitic basalt from komatiite; the limit at 30% MgO indicates the probable maximum MgO content of komatiitic liquids. Rocks with more than 30% MgO are olivine cumulates.
- Fig. 3. Al_2O_3/TiO_2 vs Gd/Yb showing the main types of komatiite. The high Gd/Yb and low Al_2O_3/TiO_2 of Barberton-type komatiite indicates that garnet was retained in the residue of melting and that the magmas formed at extreme mantle depths.
- Fig. 4. Melting behaviour of mantle peridotite and the formation of ultramafic magmas. (a) Anhydrous conditions – phase relations from (Herzberg 1999). The grey lines show the paths taken by mantle that undergoes partial melting. MORB forms from ambient, low-temperature mantle. Much high source temperatures, as in mantle plumes, are required to produce komatiites. The plumes intersect the solidus at great depths. The source of Munro-type komatiite starts to melt at about 200 km depth and it undergoes fractional melting. The relatively low pressure and the fractional melting process eliminates garnet from the source of these magmas. Barberton-type komatiites start to melt at greater depths — their source may have been molten as it transited the transition zone. These komatiites are formed by about 30% batch melting at depths greater than 200 km. (b) Hydrous conditions – phases relations from (Asahara et al. 1998). The position of the solidus is very uncertain but its location is less important than that of the 30% melting curve, which corresponds to the conditions under which Barberton-type komatiites form. Pressures greater than about 6GPa are needed to stabilize garnet in the residue of a 30% partial melt. In contrast, the subduction-zone komatiite of Grove et al. (1999) (shown as a star) forms at much shallower depths. Under these conditions garnet is not stable in the residue of fusion and the melt does not have the geochemical characteristics of Barberton komatiite.
- Fig. 5. Concentrations of Ce and Zr in komatiites, normalized to 25% MgO by subtracting or adding olivine. The average compositions of the two groups are shown, together with calculated percentages of mantle melting. These were calculated assuming a

primitive source for Barberton komatiites (1.6 ppm Ce and 9.7 ppm Zr) and a depleted source for Munro (1.3 ppm Ce and 9.7 ppm Zr). Residual mineralogy: ol - 50; opx - 30; cpx - 10; gt - 10. Partition coefficients are from Green (1994). Principal sources of komatiite data: (Sun and Nesbitt, 1978; Bickle et al., 1993; Jahn et al., 1983; Lahaye et al., 1995; Lahaye and Arndt, 1996; Lesher and Arndt, 1995).

Fig. 6. Diagram illustrating the crystallization of a layered spinifex-textured komatiite flow.

Fig. 7. Classification of komatiitic flows and sills on the basis of the relative degrees of olivine enrichment and differentiation in situ (modified from Lesher et al., 1984). UN = undifferentiated non-cumulate (massive, pillowed, or volcanoclastic), DN = differentiated non-cumulate, UC = undifferentiated cumulate, DC = differentiated cumulate. illustrating the crystallization of a layered spinifex-textured komatiite flow.

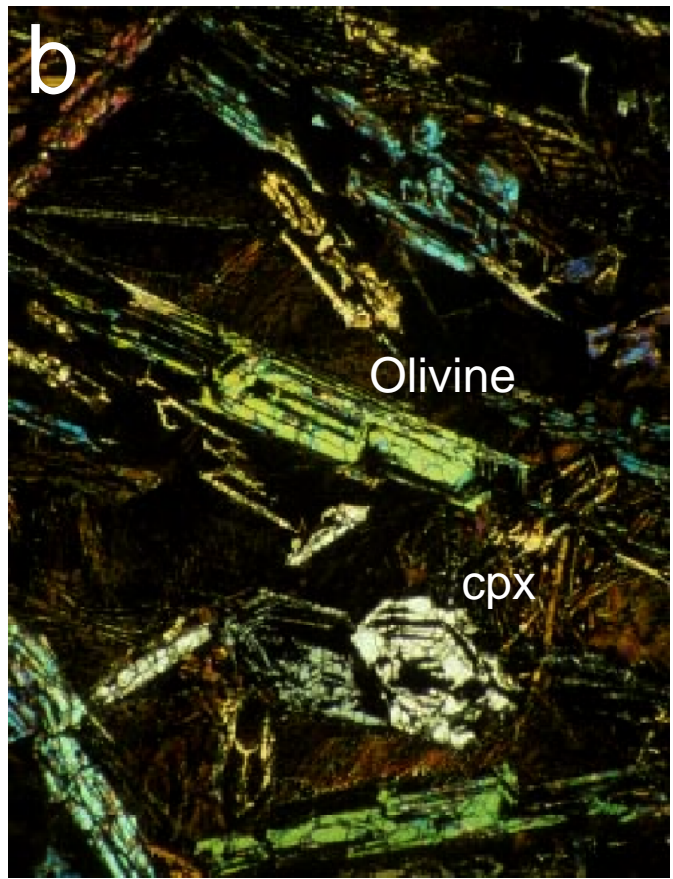
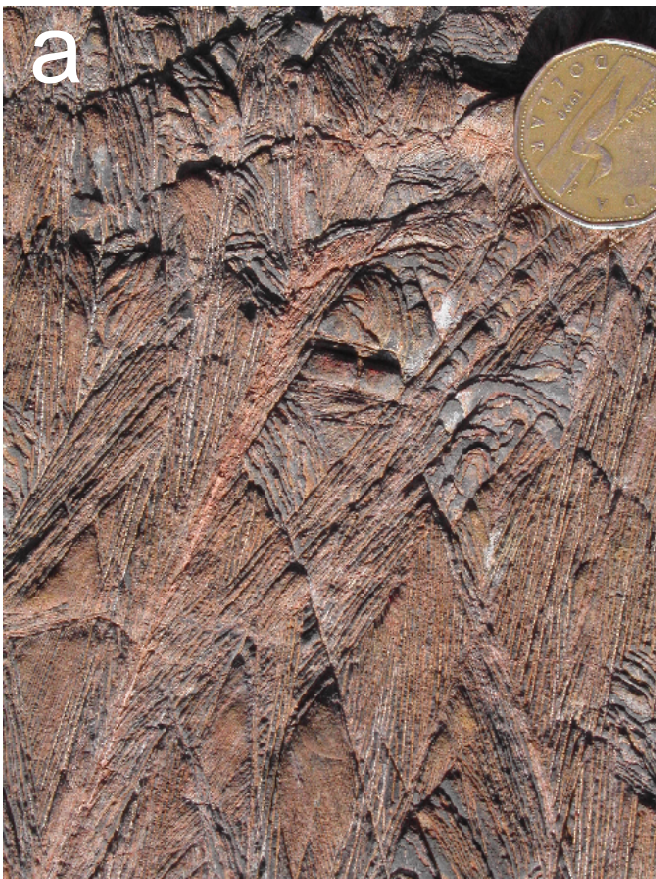
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top of flow
upper chilled zone

spinifex zone

olivine cumulate

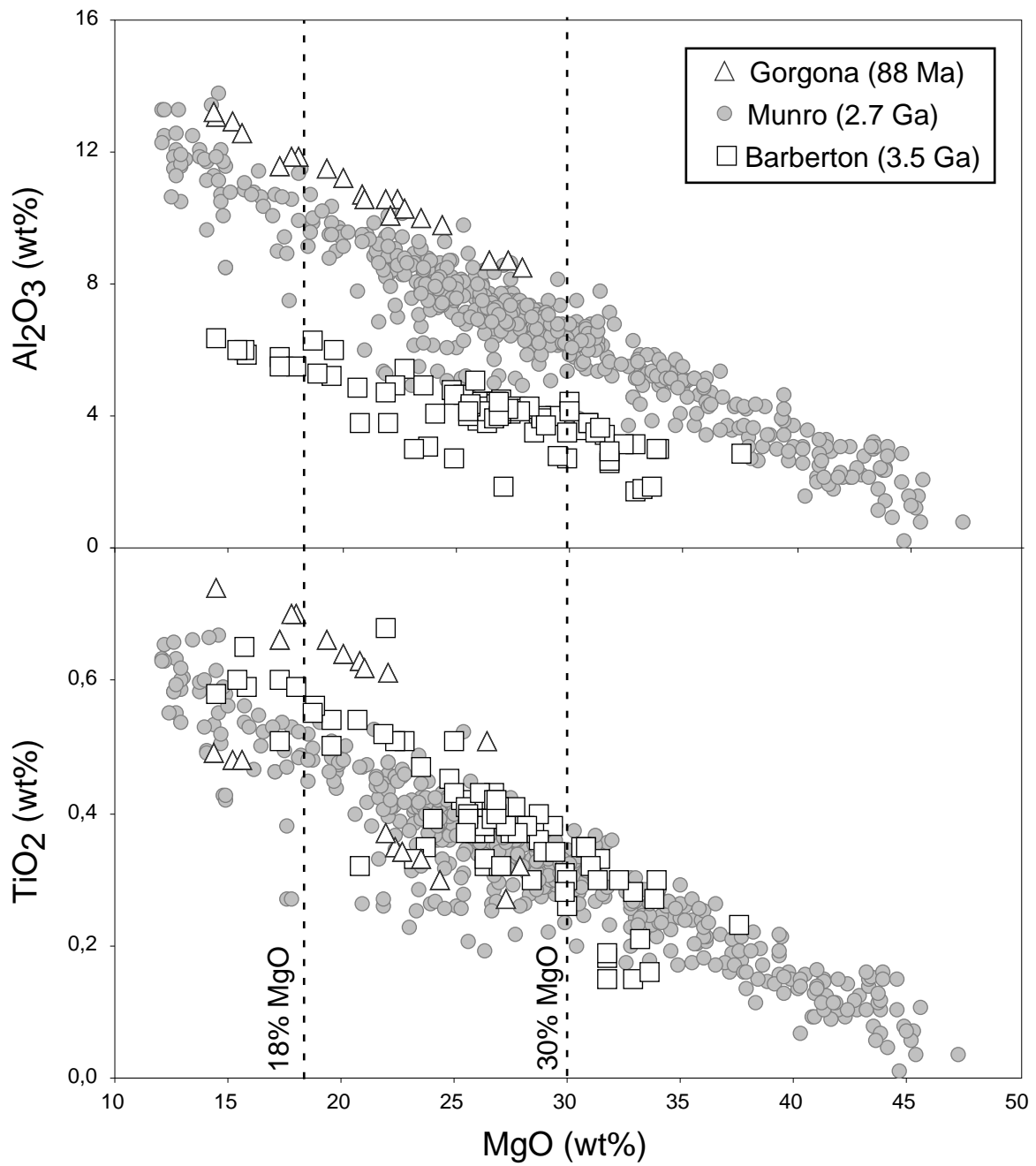
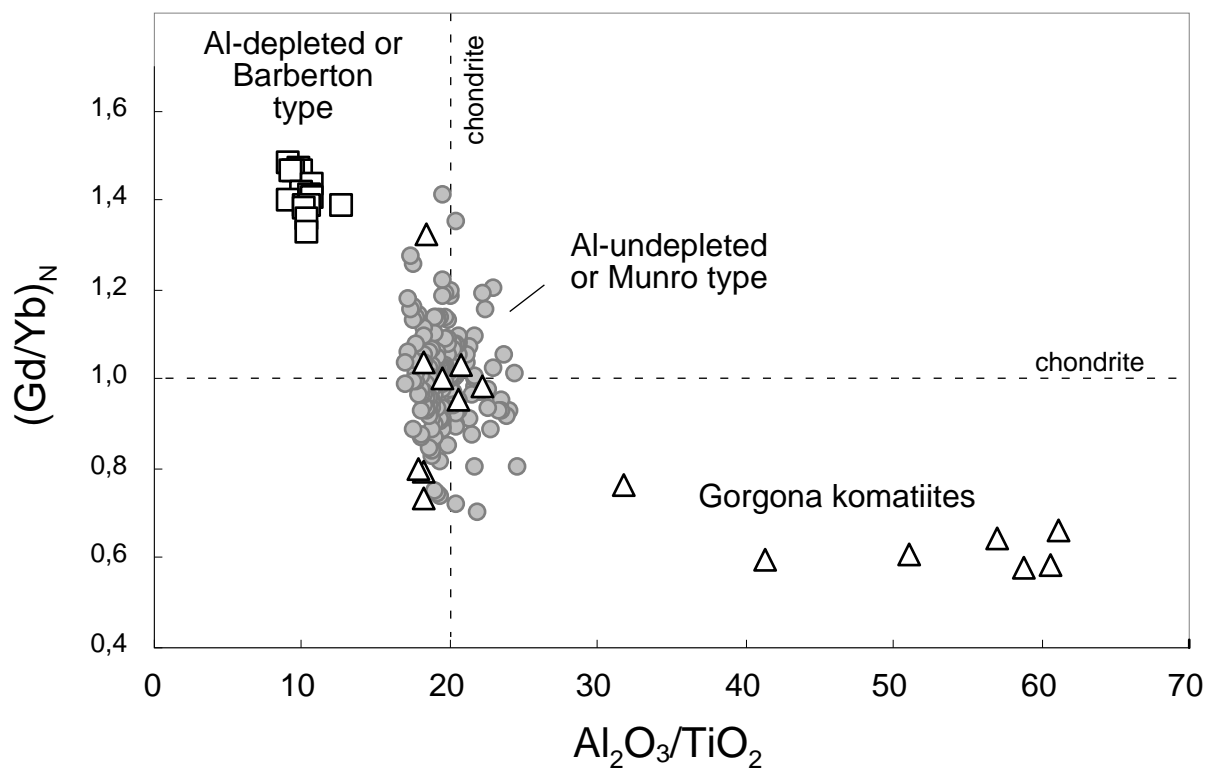
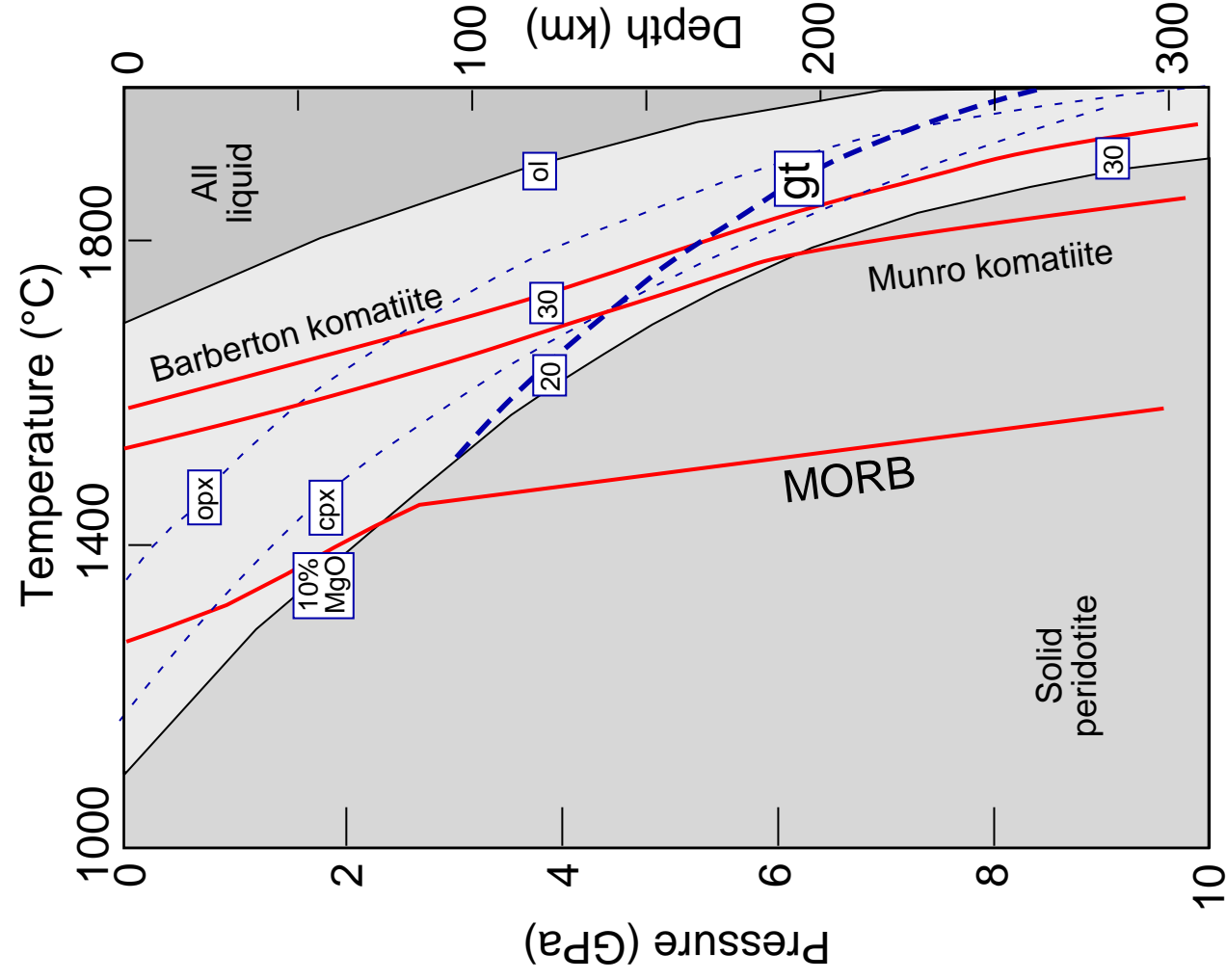
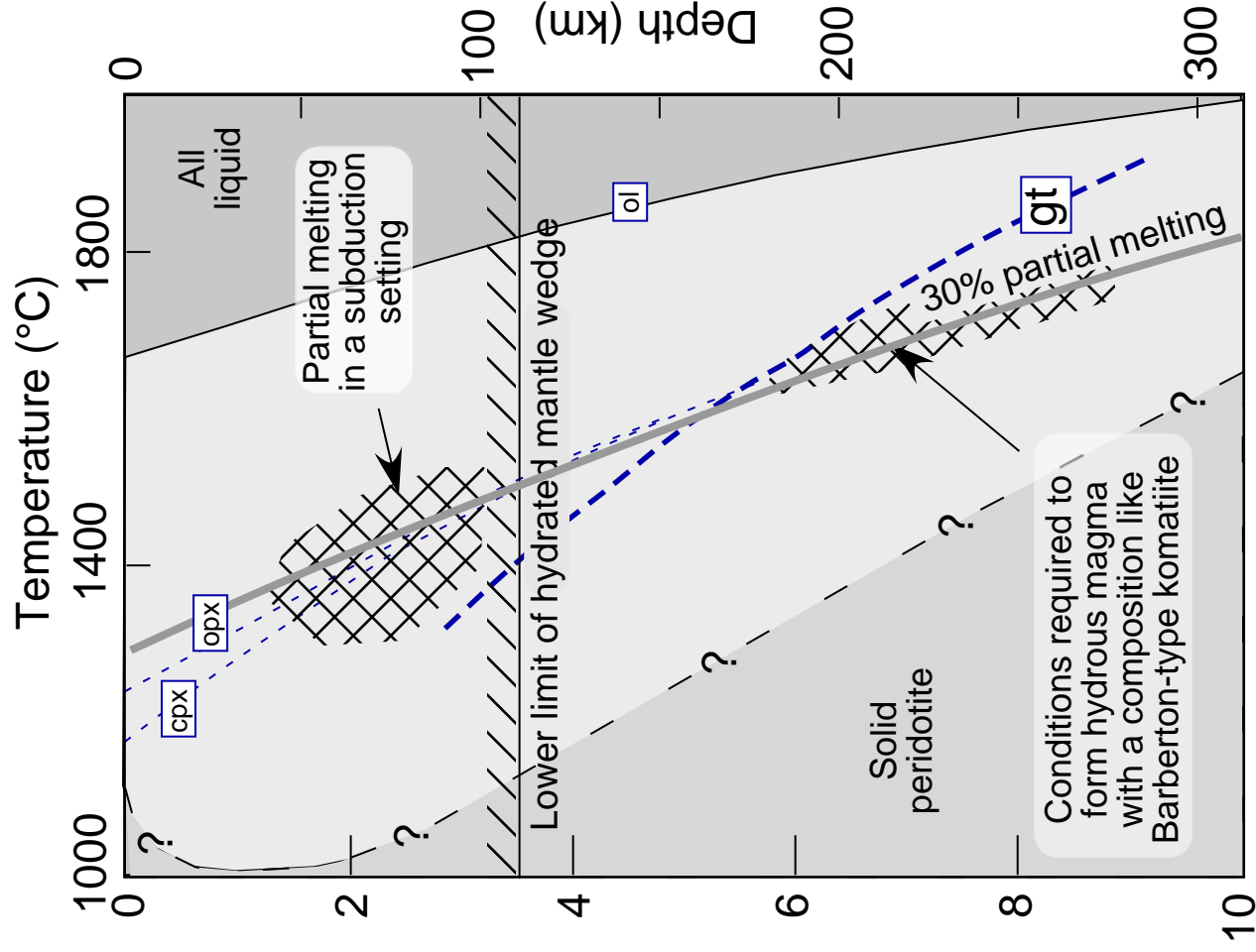


Fig. 2: Variation diagrams illustrating the range of compositions of the main types of komatiite. The limit at 18% MgO separates komatiitic basalts from komatiites; the limit at 30% MgO indicates the probable maximum MgO content of komatiitic liquids. Rocks with more than 30% MgO are olivine cumulates.

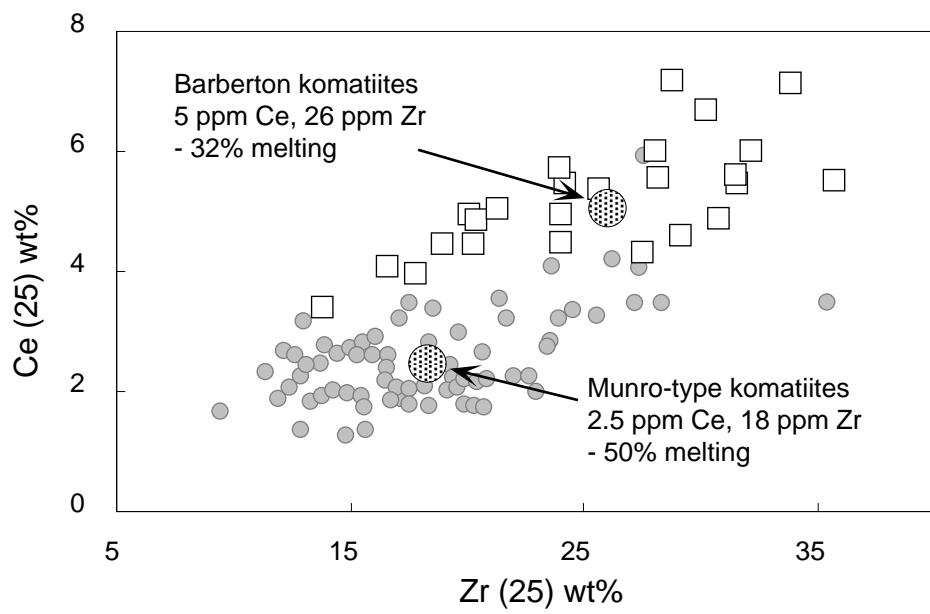




(a) anhydrous conditions



(b) hydrous conditions
(~2% water)



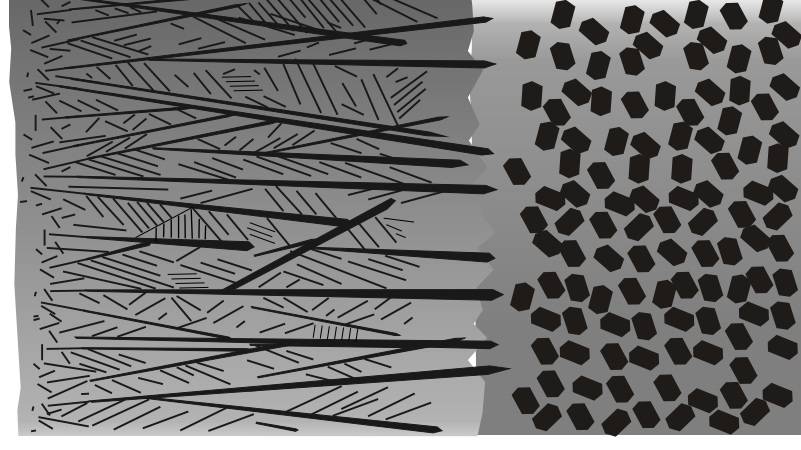
(a) during eruption



(b) initial growth of crust and downward sedimentation of olivine grains



(c) continued growth of spinifex layer



continued growth results in preferred orientation of spinifex olivine grains perpendicular to the flow top

continued accumulation and in-situ growth of polyhedral olivine crystals

Compositional Facies in Komatiitic Flows and Sills

