Komatiites: From Earth’s Geological Settings to Planetary and Astrobiological Contexts

Delphine Nna-Mvondo¹ and Jesus Martínez-Frias¹

¹ Planetary Geology Laboratory, Centro de Astrobiologia (CSIC/INTA), associated to NASA Astrobiology Institute, Ctra. De Ajalvir, km 4. 28850 Torrejon de Ardoz, Madrid, Spain.

Correspondence:

Laboratorio de Geología Planetaria, Centro de Astrobiología (CSIC/INTA), associated to NASA Astrobiology Institute, Instituto Nacional de Técnica Aeroespacial, Ctra. De Ajalvir, km 4. 28850 Torrejón de Ardoz, Madrid, Spain.

Phone: +34 915206434
Fax: +34 915201074
E-mail: nnamvondod@inta.es
ABSTRACT

Komatiites are fascinating volcanic rocks. Up to date, they represent the most ancient lavas of the Earth. This fact, linked to their particular features (high magnesium content, high melting temperatures, low dynamic viscosities, etc.), has attracted the community of geoscientists since their discovery in the early sixties, who have tried to determine their origin and understand their meaning in the context of the terrestrial mantle evolution. In addition, it has been proposed that komatiites are not restricted to our planet, but they could be found in other extraterrestrial setting in our Solar System (particularly in Mars and Io). It is important to note that komatiites may be extremely significant in the study of the origins and evolution of Life on Earth. They not only preserve essential geochemical clues of the interaction between the pristine Earth rocks and atmosphere, but also may have been potential suitable sites for biological processes to develop. Thus, besides reviewing the main geodynamic, petrological and geochemical characteristics of komatiites, this paper also aims to widen their investigation beyond the classical geological prospect, calling attention to them as attracting rocks for research in planetology and astrobiology.

Keywords: astrobiology, Earth, geology, komatiites, origins and evolution of Life, Planetary bodies, ultramafic, volcanic rocks.

Abbreviations: BGB: Barbeton Greenstone Belt; GI: Gorgona Island; HSE: High Siderophile Element; LREE: Light Rare Earth Element; PGE: Platinum Group Element; PH: Pyke Hill; REE: Rare Earth Element; VB: Vetreny Belt
1. Introduction

Astrobiology is a quickly evolving, interdisciplinary field of science. Among the research for understanding how life began and evolved on Earth, various studies have increased evidence that early life may have been connected to volcanic settings. Hence, it is important to study and constrain the volcanic environment and rocks.

In the early days of Earth, many evidence show that the planet had much more energetic activity than today (as it is the case in other terrestrial planets). A natural consequence of this state would have been a higher mantle temperature and higher degree of melting, leading to the production of lavas with compositions closer to the bulk mantle chemical structure than those today. In this idea, “primitive” lavas have been considered as those formed at the highest temperatures. Such odd lavas do exist in the terrestrial geological record and are identified as komatiites. Komatiites were first recognized in the late 1960s in the Barberton Mountainland greenstone belt in South Africa (Viljoen and Viljoen, 1969a, 1969b) and were named from their type locality along the Komati River. In the beginning, it was thought that komatiite eruptions appeared mainly in the
Archean. Nonetheless, this assumption is incorrect as some have been dated to the Paleozoic and Mesozoic ages. Also it is hypothesized that, in the late Archean, komatiite volcanoes would have built edifices on the surface forming ocean islands over hotspots, like giant flat Hawaiis, but much more lower and of a larger diameter (~1000 km). Wide islands, would have even had an extensive land. Earlier in the Archean (4.0 – 4.2 Ga), mid-ocean ridges themselves may have been komatiitic. As time went on, the ridges changed to erupting basalt, as they do today, but the hotspots continued to produce komatiites until the end of the Archean (Shock, 1996).

Komatiites are petrologically defined as old ultramafic extrusive volcanic rocks, which derived from highly magnesian magmas. Their MgO contents exceed 18 wt% compared to 10 - 15 wt% for the most mafic mid-ocean ridge basalts or ocean-island basalts. Also, they are noted for their low dynamic viscosities (0.1 to 1 Pa·s), high liquidus temperature (~1600 °C) and great potential for turbulent flow and thermal erosion of their underlying substrates. Although their origin is still controversial, it is generally accepted that komatiites were generated most probably at depth of 150 to 200 km by massive partial melting of the Archean mantle (Takahashi and Scarfe, 1985) and that the ancient lava flows erupted at
high temperatures of 1400 - 1700 °C (Arndt et al., 1979; Huppert et al., 1984). In comparison, typical basaltic lavas have today eruption temperatures of about 1100 °C. Komatiites are exceptional and it can be said that, as a whole, they have no modern analogs.

The origin of this particular komatiitic Archean volcanism has also been discussed, considering a possible association with meteorites and meteoritic impacts. Such assumption is another argument that supports the plausible scenario of the supply of extraterrestrial material in the primitive Earth and perhaps also in other planets and satellites of our solar system (Fodor and Keil, 1976; Bairds and Clark, 1981; Williams et al., 2000a, b; Kargel et al., 2003; Rosengren et al., 2004).

Until now, komatiites have been mainly studied for their singular geochemical and tectonic characteristics and significance. The volume of data collected in this field of investigation, particularly regarding their petrology, is quite impressive. An updated search on komatiites topic in the web of Science (of the ISI web of knowledge website), gives a result of more than 500 published papers in thirty years. And during these thirty years, the last 5 years have been the episode of the
largest number of publication per year showing the vigorous recent re-interest for komatiites. Recently, the study of komatiites has also been extended to planetary geology, as they could be of a great help to understand igneous processes outside the Earth in other planets and moons, where analog materials could exist (Venus, Mars, Io and lunar lavas). In this paper, we are synthesizing and discussing the information reported about komatiites, also stressing their possible occurrence in other extraterrestrial environments and their astrobiological significance.

2. Age

As previously defined, komatiites have mostly an early origin. Textural and chemical analyses of more than 20 000 rocks have revealed that peridotitic komatiite is at present unknown from modern environments and basaltic komatiite is rare (Brooks and Hart, 1974). Komatiites were produced most commonly during the Archean (>2.7 Ga) and late Archean. Few are found in the early Proterozoic and they were much less frequent in the Phanerozoic era. The prevalence of komatiite almost entirely in the Archean indicates fundamental differences between ancient and modern mantle conditions. One of the reasons for
the decline of the abundance from Archean to Phanerozoic is interpreted as a result of the decrease in the degree of melting due to secular cooling (up to 500 °C) of the mantle since the Archean (Parman et al., 2001; Grove and Parman, 2004). As a consequence, this interpretation makes komatiites as potential thermometers of the Earth’s cooling. It has also been proposed that the deep mantle sources that produced komatiites have undergone chemical changes over the geological time giving rise to more enriched magmas (Campbell, 1998).

In Table 1, are reported the age of komatiites at representative selected locations. Komatiites are encountered in a number of places around the world: Canada, Southern African, Australia, Baltic Shield, Colombia, and Vietnam, among others. Geochronologic dating shows the Barbeton komatiites in South Africa to be 3.6 - 3.2 billion years old, which represents the oldest ultramafic rocks found on Earth. Such “timing” fits nicely with the concept of a hot early Earth taking into account the high temperatures inferred for the komatiite source region. Then it is observed a prevalence of komatiites around 2.7 Ga, most of them located in Canada and Australia. Munro Township, Ontario, Canada is the best preserved komatiite location in the world. Although komatiites occur in Proterozoic formations (e.g. Finnish Lapland), they are not as common as in Archean
greenstone belts. Komatiites are very rare in the Phanerozoic geological record. The most prominent representatives are the Mesozoic komatiites from Gorgona Island in Colombia associated with the Caribbean oceanic plateau (Echeverria, 1980; Arndt et al., 1997). They are the youngest known komatiitic lavas (89 Ma) and their existence indicates unusually high temperatures in the mantle during the Upper Cretaceous. The occurrence of younger komatiites is less common than the Barbeton and Munro-types. One of the explanations has been related to a progressive dehydratation of the upper mantle in the mid- to late-Archean. In this assumption, Mesozoic komatiites appearance may be due to local hydratation of the upper mantle after dehydratation of hydrous phases (Inoue et al., 2000).

[TABLE 1]

3. Origin

The origin of the anomalously high-temperature komatiitic materials has been debated for many years because of the implications for the thermal structure and composition of the Archean Earth mantle. It is a very controversial issue and
many hypotheses have been proposed and discussed since their first recognition in the late 1960s, trying to find a model which best fits komatiites.

Komatiites were primary explained as the first crust formed on Earth as a result of catastrophic melting event triggered by convective overturn during core formation (Viljoens and Viljoens, 1969a). However, this idea has been rapidly excluded, at least in the sense with which it was put forward.

Later on, a second scenario was proposed arguing a meteoritic impact origin. Spinifex (see next chapter) komatiites were long ago suggested to be an impact melt in chondritic meteorites; in this sense, it is important to note that cosmic spherules also feature spinifex olivine (Green, 1972; Jones, 2002). In such case, ultramafic liquids from some Archean greenstone belts are interpreted as products of 60 - 80% melting of their mantle source composition. This would imply more catastrophic conditions of mantle melting than in Phanerozoic mantle dynamics, as a possible consequence of major impacts on the early Earth’s surface. Therefore, following this hypothesis, Archean greenstone belts could correspond to very large impact scars, initially filled with impact-triggered melts of ultramafic to mafic composition and thereafter evolving with further magmatism,
deformation and metamorphism (Green, 1972). Although this meteorite impact-related origin of komatiites still remains controversial, it has been recently reassessed and more strongly supported (Abbott, 2000; Abbott and Isley, 2002). A temporal relationship between large impacts on early Earth and Moon and mantle plumes activities has been suggested by spectral analysis of time series of mantle plume rocks and impacts over the last 3.8 Ga (Abbott, 2000). Similarities between spectra derived from the impacts and the plume material could be due to strengthening of existing plume by the seismic energy released during impacts (Abbott and Isley, 2002). Such speculation could help to explain, for instance, why komatiites are not always plume tails and why there were more abundant during the Archean when large meteorites were frequently bombarding the early Earth. In this context, large meteorite and cometary impacts would have increased the amount of volcanism from already active mantle plumes.

The most widely accepted hypothesis about komatiite origin states that they were formed in an Archean plume-dominated environment (Fyfe, 1978; Arndt and Nisbet, 1982). Campbell et al. (1989) have argued from fluid-dynamics calculations that both basalts and komatiites could have been produced by a same starting thermal plume rising in a warmer Archean mantle. In such scenario,
komatiites could form by melting in the hot axial jet of the starting plume, whereas basalts would be produced by melting in the large head of the plume in which cooler mantle is entrained. Komatiitic magmas generated by mantle plume activities could contribute to the formation of Archean oceanic plateaux which, in some cases, could be later on buried in the mantle via subduction zone (Polat et al., 1998; Kerrich et al., 1999; Puchtel et al., 1999; Polat and Kerrich, 2000). They could also erupt on the continental crust as in the case of Zimbabwe komatiites (McDonough and Ireland, 1993), or interact with an island arc subduction environment (Wyman and Kerrich, 2002).

Nonetheless, recent melting experiments of representative mantle composition under hydrous conditions (Inoue et al., 2000) have demonstrated that Al-depleted Barberton-type komatiites are formed under relatively low pressures (< 8 GPa) and low temperatures (~1300-1500 °C) in the solidifying hydrous magma ocean. Such result contradicts the idea of a warmer Archean mantle suggested for the origin of komatiites.

Another strongly supported scenario for komatiite source is the generation in a subduction zone. Brooks and Hart (1972, 1974) first pointed out that the major
element chemistry of many of the komatiites and related magmas (komatiites basalts) were more similar to modern mafic subduction magmas than to any magma thought to be produced by a modern plume. The first strong evidence for a subduction origin for komatiites was exposed from a study of the Nondweni komatiites (Wilson and Versfeld, 1994). This komatiites have much higher SiO$_2$ than the Munro or Gorgona rocks and show some similarities to modern mafic subduction magmas (boninites). High SiO$_2$ does not match with the plume scenario as SiO$_2$ contents of magmas generally decrease as the pressure of melting increases. Boninites have high SiO$_2$ at high MgO contents because they are high degree melts that are formed at shallow depths. Such melting can occur at shallow depth because it is caused by high contents of water (Crawford et al., 1989). Boninites form by hydrous melting of metasomatized mantle above a subduction zone. For the Barberton komatiites and basaltic komatiites, it has been also proposed a subduction zone origin because it appears to be more consistent with the available trace element data. Moreover plume-based models that appeal to majorite garnet fractionation cannot produce the low Ti/Zr ratios of komatiites or their wide variation in La/Sm (Parman et al., 2003).
Because of the similarities with boninites, the old model (Allègre, 1982) of the production of komatiites by hydrous melting processes in the upper mantle has been reconsidered (Parman et al., 2001). Hanski (1992) discovered pargasitic amphibole in Fe-rich komatiites in Finland. Stone et al. (1997) also found this hydrous amphibole in a komatiite. This mineral was probably the first and most significant evidence for high H₂O contents. Nevertheless, there are more proofs suggesting that the Barbeton-type komatiites were formed under the presence of water (see for instance Stone et al., 1995, 1997; Parman et al., 1997). Subduction origin focuses on the high SiO₂ content in komatiites whether plume model implies low SiO₂. A very detailed geochemical analyses (major and trace elements) comparing basaltic komatiites and modern mafic magmas was performed by Parman et al., (2001, 2003). Their results confirm that, excluding the Mg content, the compositions of the basaltic komatiites are very close to modern boninites and much more similar than any ocean islands basalts. With such geochemical resemblances, komatiites are strongly supposed to be produced by similar melting processes as for modern boninites but under hotter mantle temperature since one assumed that the Archean mantle was 100 - 500 °C hotter than the modern mantle (Parman et al., 2001). Experimental data indicates that the Archean sub-arc mantle needs only to be 1500 - 1600 °C to produce
hydrous komatiitic melts (Parman et al., 2001). This is considerably cooler than estimates of mantle temperatures assuming an anhydrous, plume origin for komatiites (up to 1900 °C).

It is still unclear whether the water found in komatiites is produced in a subduction zone or whether originated from a hydrous plume. For this reason, the water content of komatiites still remains a debated issue. Arndt et al. (1998) have compiled all the information regarding the hydrous/anhydrous origin debate for komatiites in an excellent review. In short, arguments supporting the hypothesis of the formation of komatiites by hydrous melting are the following: a) the presence of water in the mantle source of komatiites reduces the melting temperatures from very high to lower values (Allègre, 1982; Inoue, 1994; Kawamoto et al., 1996); b) the pyroclatiscity and vesicles containing features of some komatiites are characteristic of magmatic volatiles (de Wit et al., 1983, 1987; Parman et al., 1997), and c) experimental studies of peridotite melting argue that the chemical composition and the spinifex textures of komatiites require hydrous conditions (Inoue, 1994; Grove et al., 1996; Ohtani et al., 1997; Parman et al., 1997). On an other hand, the scenario of melting by hydrous mantle is counterargumented by: a) when hydrous komatiites may be close to the surface, the loss of volatiles should imply degassing of their structures and textures which
is rare in komatiites, and b) chemical and isotopic compositions of most komatiites indicate that their mantle source became depleted in incompatible elements soon before the formation of the magma, which may remove water. The existing experimental data are not yet conclusive, therefore until further work one first may assume that most komatiites form in unusually hot and dry parts of the mantle, and only some rare komatiites may be hydrous (Arndt et al. 1998).

4. Petrology and geochemical characteristics

Komatiites exhibit compositional differences, stratigraphic and secular variations in major, minor and trace elements geochemistry depending on their location, their assemblage inside a location, and their age. The variety of data is impressive. For this reason, we have synthesized, summarized them and decided to report the main compositional information for four selected komatiitic locations corresponding to typical eras of the geological time-scale when the variety of komatiites is found, i.e at ~3.5 Ga (Archean Barberton Greenstone belt, BGB), ~2.7 Ga (Archean Pyke Hill, Abitibi greenstone belt, PH), 2.4 Ga
(Paleoproterozoic Vetreny Belt, VB) and 89 Ma (Mesozoic Gorgona Island, GI).

This compilation is regrouped in Tables 2, 3, and 4.

Komatiites often exhibit textural and compositional layering within individual flows which result from their unique fluid properties and composition (Huppert and Sparks, 1985). Many komatiites show unusual and spectacular textures, known as spinifex textures. Such textures are defined by large skeletal, plate-like olivine crystals in a finer-grained groundmass (generally of clinopyroxene, chromite, and glass). The crystals display parallel or randomly oriented grouping. The texture is explained by a magmatic quench crystallization effect promoted by rapid cooling of melt with low nucleation rate and high growth rate of crystals at large degree of supercooling (Donaldson, 1982).

Komatiitic basalts are dominated by pyroxene, with less plagioclase and olivine is only present where MgO is more than 12 wt. % (Arndt and Nisbet, 1982). Ultramafic komatiites are composed mainly of olivine, with interstitial pyroxene and a little or no feldspar. Pyroxenes are augite, magnesian pigeonite and bronzite (Arndt et al., 1977). On the Earth, magnesian pigeonite is common only in komatiite lavas and may be a defining characteristic.
Komatiite compositions are closer to that of the mantle than that of the basalt (Table 2). Komatiites are classified into two main types distinguished by their major and trace element contents. The high-magnesian and aluminium-depleted komatiites found only in the oldest records like Barberton (~3.5 Ga), and the less-magnesian and aluminium-undepleted komatiites of late Archean (e.g. Munro-type, Pike Hill, 2.7 Ga) and Mesozoic age (e.g. Gorgona Island, 60 - 87 Ga). Nonetheless, some komatiites of the Barbeton formation present Al-undepleted compositions. The Al-undepleted barberton komatiites are characterized to be chondritic-like with \( \text{Al}_2\text{O}_3/\text{TiO}_2 \) of ~15 - 18 and \( \text{CaO}/\text{Al}_2\text{O}_3 \sim 1.1 - 1.5 \) (Chavagnac, 2004 - refer to Table 2), whereas the Al-depleted have low \( \text{Al}_2\text{O}_3/\text{TiO}_2 \) ratios (~ 8 - 11) and high \( \text{CaO}/\text{Al}_2\text{O}_3 \) ratios (~ 1.1 - 1.6). Munro-type presents also higher, near chondritic \( \text{Al}_2\text{O}_3/\text{TiO}_2 \). Barberton-type komatiites have moderately high levels of incompatible trace elements, whereas Al-undepleted komatiites (Munro-type and the Cretaceous komatiites from Gorgona Island) are typically depleted in incompatible trace elements. Rare Earth element (REE) patterns show depletion of the heavy REE (high Gd/Yb) for Barberton type komatiites, while Munro-type are depleted in lighter elements and have near-chondritic ratios of the middle to heavy elements (Arndt, 2003, and see Table 3).
Other peculiar compositional characteristics of komatiites are: a) their low Al/Si ratios. This indicates as well a more chondritic composition for the Earth’s early Archean mantle (Francis, 2003); b) their excess in tungsten. For instance, komatiite samples from Phanerozoic (Gorgona Island) and Archean terrains (Boston Creek, Canada; Belingwe, South Africa, 2.7 Ga) were analyzed for tungsten concentrations. Samples from all three locales show high W (516 to 2643 ppb), with most samples containing near 700 ppb. This enrichment could result from shallow-level alteration processes via W-rich fluids and other fluid mobile elements from crustal rocks (Becker et al., 2004) and c) they show high $^{3}\text{He}/^{4}\text{He}$ ratios. For instance, Archean komatiites (e.g. Abitibi greenstone belt, Alexo) show high $^{3}\text{He}/^{4}\text{He}$ ratios, of about 30 Ra (where Ra denotes the atmospheric $^{3}\text{He}/^{4}\text{He}$ ratio) (Matsumo et al., 2001, 2002).

4.1. Komatiites and ore forming processes
Other interesting aspect related with komatiite magmas is their importance in ore forming processes. They are among the few mafic/ultramafic lavas types that are S-undersaturated at the time of magma formation and do not reach S-saturation until a late stage in their ascent from the mantle. This S-undersaturation is due to the high temperature of these magmas produced by large degrees of partial melting of upper mantle source regions that were already depleted in S through earlier partial melting events. S-saturation of magmas lead to depletion in the chalcophile metals, in contrast komatiitic magmas retain the full complement of chalcophile elements (including Fe, Co, Ni, Au, Cu, Tl, Bi and PGEs) that the magma derived from the mantle source. When they become S-saturated they may form sulphides, strongly enriched in Ni, Cu, Au, PGEs and other chalcophile elements, which may accumulate to form ore deposits directly or dispersed in komatiites (Keays, 1995). Platinum-group element (PGE) abundances including Os, Ir, Ru, Pt, Pd have been reported in komatiites (Table 4). PGEs are present at higher levels in komatiites than in basalts making komatiites better probes of mantle PGE abundances (Puchtel and Humayun, 2000). In accordance with these authors, the spinifex-textured (MgO = 25 - 28%) and cumulate (MgO = 34 - 37%) komatiites are moderately enriched in Pt and Pd relative to Os and Ir with (Pt/Os)N = 2.5±0.4, and exhibit chondritic (Os/Ir)N = 0.98±0.06 ratios. Generally
it is observed that, in ultramafic magmas, PGEs are very strongly and roughly equally enriched in any sulphide or metallic minerals that are present. They can provide unique information on the important role that sulfur plays during magmatic processes, a role still ignored by most petrochemists. It has been observed in many geological shields (e.g. Yilgarn, Perseverance, Pilbara, Zimbabwe, Kambalda, Abitibi terrains) that abundant komatiites host magmatic sulphide deposit rich in nickel (Barnes et al., 1995; Moore et al., 2000; Lahaye et al., 2001; Barnes, 2004; Hill et al., 2004;) and show high content of Ni. Mostly all largest known concentrations of komatiite-hosted Ni sulfide deposits (but also Fe-Cu-PGE deposits) are regrouped during the Archean. However, some komatiites of Permian-Triassic age (Northwestern Vietnam) as well have been described to be associated with Ni-Cu-(PGE) bearing deposits (Glotov et al., 2001). Magmatic Ni-Cu sulphides strongly influence the precious metal contents of komatiites because they are greatly enriched in these metals relative to crustal rocks (Keays, 1982). Most komatiite-associated magmatic Ni-Cu-(PGE) sulfide deposits formed from sulfide undersaturated magmas and are interpreted to have formed in dynamic lava channels or magma conduits by incorporation of crustal sulfur. They commonly exhibit geochemical and isotopic evidence of crustal contamination (e.g., Th-U-LREE enrichment, negative Nb-Ta-Ti anomalies) and
chalcophile element depletion on the scale of individual cooling units (Lesher et al., 2001). Thermal erosion and incorporation of sulphur-rich sea-floor sediments have been proposed as a mechanism by which the komatiites were brought to sulphide saturation (Huppert et al., 1984; Groves et al., 1986; Lesher and Groves, 1986).

Among the chemical analyses for determining PGE abundance in komatiites, Osmium has been studied in detail, particularly its isotopic composition. As with modern plumes, the sources of Archean and Proterozoic komatiites exhibit a large range of initial $^{187}\text{Os}/^{188}\text{Os}$ ratios. Most komatiites are dominated by sources with chondritic Os isotopic compositions (e.g. Song La, Norseman-Wiluna, Pyke Hill, Alexo), though some (e.g. Gorgona) derive from heterogeneous sources (see Table 4). Some komatiites are enriched in $^{186}\text{Os}$ and $^{187}\text{Os}$ (Brandon et al., 2003; Gangopadhyay et al., 2003). The coupled enrichments of $^{186}\text{Os}/^{188}\text{Os}$ and $^{187}\text{Os}/^{188}\text{Os}$ are very similar to those displayed by the Hawaiian and Siberian plumes. Such enrichments could originate from the addition of ancient hydrothermally altered or metalliferous sediments into the source of plumes (Ravizza et al., 2001). But this is contradicted by mixing models and another explanation for the Os isotopic variations which involves Os transfer from the
outer core to the lower mantle in the late Archean (Puchtel et al., 2001; Brandon et al., 2003).

TABLE 4

Finally, one of the last attractive discoveries about komatiites has been the report of diamonds (Capdevila et al., 1999). Abundant diamonds ranging from microdiamonds size up to 4 mm were found in a pyroclastic komatiite from the Proterozoic Dachine island arc in French Guiana, South America. This recent discovery was quite unexpected as the tectonic setting is distinct from that of all other currently exploited diamond deposits. And it places significant constraints on the origin of komatiite magmas and the manner in which they interact with hydrated mantle in subduction zones. Capdevila et al. (1999) proposed that primary, anhydrous komatiite magma formed by deep melting, then penetrated hydrated lithosphere beneath the ancient island arc where it collected both water and diamonds. As komatiite magma interacted with relatively cool hydrated base of the mantle wedge, it become hydrous, its temperature and density decreased dramatically and it was ejected to the surface, bringing with it diamonds. The discovery implies also that some komatiites must have originated deep within
levels (~250 km or greater). It has been proposed that diamonds can be natural time capsules, preserving information about the cycling of sulfur between Earth's crust, atmosphere, and mantle some 3 billion years ago (Farquhar et al., 2002). These authors report that diamonds from a region in Botswana, Africa contain a distinctive ratio of three forms, or isotopes, of sulfur. The signature presence of this ratio indicates that the sulfur in these diamonds went through a nearly complete geochemical cycle. Thus, diamonds are valuable crystals through which geologists and atmospheric chemists can peer to gain insights into the Earth's atmosphere as it existed billions of years ago.

Whereas the petrological features of komatiites have been the purpose of a wide range of studies, their volatile abundances remain largely unknown because of significant alteration of rocks and lack of fresh glasses.

5. Komatiite in the Solar System

As previously described, komatiites are defined as the primitive volcanic material of the early Earth, mainly representative of the Archean era. However, the direct
existence of komatiites (or rocks with komatiite-like compositions) has also been proposed in other planetary bodies of our Solar System, as it is briefly shown in the present review.

5.1. The Moon

The sinuous rilles exposed on the Moon's surface are erosive valleys produced by komatiite lava flows, contemporaneous with the ancient eruption of similar lavas on Earth (Williams et al., 2000b). On the basis of previous experimental studies on synthetic lavas derived from the composition of Apollo 11 basalts, these authors studied the liquid viscosities of several lava compositions. The viscosity of lunar lavas is up to two orders of magnitude lower than that of modern, terrestrial tholeiitic basalt lavas, more similar to ancient Precambrian komatiitic lavas.

In addition, coexisting pyroxenes, pigeonite and augite, have been found in ~12 categories of lunar mare basalts as well as in Apollo 12 pigeonite basalts. These basalts are also magnesium-rich and therefore it is argued that these coexisting pyroxenes may have formed by rapid metastable crystallization of a supercooled liquid, a similar mechanism of komatiites formation on the Earth (Reyes and Christensen, 1994).
It has been observed moreover that the lunar crust at the Apollo 16 highland breccias contains a primitive component which has been found to be a komatiite compositionally similar in major and minor elements to terrestrial komatiites (Ringwood et al., 1987; Wentworth and McKay, 1988). It strongly implies a corresponding similarity between the source regions of komatiites in the lunar interior and the Earth’s upper mantle.

5.2. Mars

SNC meteorites have been observed to present similarities to komatiites. SNC meteorites, as Earth meteoritic debris dated of 1.3 Ga, have been classified as martian suspects (McSween, 1985). Analysis of their mineralogy and MgO contents have shown that Shergotty, Nakhla and Chassigny meteorites resemble a lower-Mg komatiitic basalt, a higher-Mg komatiitic basalt and a peridotitic komatiite, respectively (Reyes and Christensen, 1994). Shergotites have coexisting augite and pigeonite like many mafic komatiites, Nakhla and Chassigny have coarse cumulate textures common to the basal portions of terrestrial komatiites (Treiman, 1988). Certain shergotites may be actually extrusive lavas or near surface intrusions (McSween and Jarosewich, 1983). Those extrusive shergotites would be ultramafic pyroxene-rich lavas with
coexisting pigeonite and augite, like komatiitic basalts, making early Precambrian basaltic komatiites on Earth as a good candidate for an analog of Martian lavas (Reyes and Christensen, 1994). Other works have also stressed this possibility (Baird and Clark, 1981; Mustard and Sunshine, 1995).

It is important to note that the degree of ease with which fluid komatiite lavas may be generated on Earth and Mars is different: on Earth, melting 40% of the mantle to get komatiite lavas is a difficult exercise because very high temperatures are needed (1450 °C to 1700 °C) to achieve such high melting ratios. It was mainly in the first half of Earth History, when the mantle was arguably hundreds of degrees hotter than today’s, that komatiite lava was produced. However, on Mars, komatiite could be much more widespread: if Mars mantle is indeed much richer in iron, this type of magma would be produced at lower melting ratios than on Earth, i.e. at lower mantle temperatures. Komatiites might then be the dominant lava type we see at the surface, rather than its close cousin basalt (Frankel, 1996).

Observations and data from the Phobos 2 Imaging Spectrometer (ISM) for Mars (Baird and Clark, 1981; Mustard et al., 1993; Reyes and Christensen, 1994)
appear to support this hypothesis. The chemical and mineralogical composition of Martian fines indicate derivation from mafic to ultramafic igneous rock, probably rich in pyroxene (Baird and Clark, 1981). Also, according to Mustard et al. (1993), the Syrtis Major volcanic materials analyzed by ISM are dominated by pyroxene, may contain both pigeonite and augite, and have little olivine, which is consistent with terrestrial komatiitic lavas (Reyes and Christensen, 1994). Komatiitic lavas could erode channels on Mars (Baird and Clark, 1984). Most of the objections to lava as the main erosive agent on Mars are based on the observed characteristics of basalt (eruption at ~1200 °C and high viscosity). However, Huppert et al. (1984) demonstrate that terrestrial Precambrian komatiitic lavas, erupting as very hot, highly fluid, turbulent flows, may be capable of eroding deep channels, melting and assimilating rocks over which they flowed. Therefore if lavas on Mars had a komatiitic origin, a water like fluid would have been available and would explain the channel formation and the lateral extent of Martian flows, and the absence of apparent outflow sediments deposits in the basins into which the large channels discharge (Baird and Clark, 1984).
5.3. Venus

As Ghail (2001) states “Venus might have the key to understand what the early Earth was like during the late Archaean and early Proterozoic”.

Volcanic terrains are abundant on Venus. 80 to 90 % of the Venusian surface is covered by volcanic plains and edifices. Venus hosts ~400 - 500 quasi-circular features called coronae. Coronae, which range in diameter from 60 to 1060 km (200 km median diameter), reflect both magmatic and tectonic processes. Coronae may be responsible for significant heat transfer from the mantle. Coronae are so large, complex, and contain such diverse range of volcanic phenomena that it is hard to characterize them straightforwardly. At present, it seems probable that they are the surface manifestations of large mantle plumes. Their diversity of volcanic structures probably reflects variations in temperature and composition of the erupted products: hotter, more primitive basalts, and komatiites may be present at the center, while tholeiites may be erupted from the cooler margins of the plume (Francis and Oppenheimer, 2004).

In accordance with the geological and geochemical information about Venus compiled by McMillan (2005), analyses obtained by the Venera 13 and 14 craft on the plains east of Phoebe Regio showed smooth surfaces and curved edged
surface features, which resembled pahoehoe lava similar to that of the basalts of the Hawaiian shields or the slab pahoehoe surfaces seen in the Snake River plains. Color corrected images showed the features as dark grey indicating mafic, unoxidized lava. The Venera 14 site had a tholeiitic basalt composition, similar to that of Mid Ocean Ridge basalts, while the Venera 14 site had subalkaline basalt composition (leucitic basalt) as found on the slopes of Vesuvius. These tholeiitic analyses matched orbital imagery of the Venusian plains; compositions such as lamprophyre, trachyte or subalkaline basalt are associated with more unusual surface forms. Lava flows on Venus have apparently a very low viscosity like lunar basalts and terrestrial komatiites. Over fifty major flow fields have been recognized such as Mylitta Fluctus which covers an area of approximately 300 000 km². The morphology and extent of the lava flows are consistent with a basaltic composition and may be of a komatiite or carbonate rich type. The mobility of lava of basaltic composition would be enhanced by the high surface temperature and pressures found on Venus. A number of candidates lava types have been considered which could form the Venusian canali. The ESA mission, Venus Express, whose one of the scientific objectives is to study the Venusian surface properties, will supply scientific data that could shed light on the ambiguity regarding the lava type on Venus. Specifically, the VIRTIS instrument,
a visible infrared thermal imaging spectrometer, will provide unique information on surface temperature, mineralogy, chemical weathering, recent volcanic activity and earthquakes occurrence (Marinangeli et al., 2004).

5.4. Io

Among many discoveries about Io, one of the most astonishing reported from the Galileo spaceprobe data of active volcanoes on Jupiter’s moon, is that some Io’s lavas possess eruption temperatures of 1430 - 1730 °C (Keszthelyi and McEwen, 1997; McEwen et al., 1998) greater than any lavas erupted on Earth today and possibly since the start of Earth’s geologic history.

One of the interpretations of high-temperatures hotspots on Io is the occurrence of ultramafic materials similar to terrestrial Precambrian komatiites. Indeed, because of its orthopyroxene spinifex and high MgO content resulting in high liquidus temperature of 1611 °C, the 3.3 Ga komatiite in the Commondale greenstone belt of South Africa has been proposed (Williams et al. 1999) as a useful terrestrial analog for the Ionian lavas. Eruptions on Io have been modeled applying komatiitic analogs and terrestrial ultramafic flow model (Williams et al., 2000a). And the model revealed that the komatiites of the Commondale greenstone belt,
South Africa, are consistent with available Galileo data on the temperatures and composition of potential Ionian ultramafic materials.

If the assumption of superheated ultramafic melts on Io is further corroborated and confirmed, then one might reevaluate the idea that a hot Archean mantle may have generated superheated melts (Williams and Lesher, 1998).

5.5. Chondritic bodies

It has been noted earlier in this paper, komatiites present similarities in composition with chondritic material, which rises the assumption of a meteoritic source for the production of komatiites.

For instance, many Os isotopic compositions (\(^{187}\)Os/\(^{188}\)Os ratios) and Re-Os ratios (\(^{187}\)Re/\(^{188}\)Os) are comparable to ratios found in ordinary chondrites (Puchtel et al., 2004a). Also in some komatiites, high siderophile element (HSE) occur in relative proportions similar to those found in average enstatite chondrites (Puchtel et al., 2004a), which could be consistent with one model of the accretion arguing that the HSE abundances in the terrestrial mantle were inherited from chondritic material of a late veneer.
Komatiites exhibit also Rb/La, Sr/Sm ratios near-chondritic values (Arndt, 2003) and the low Al/Si ratios found in some komatiites may as well indicate a chondritic composition for the Earth’s early Archean mantle (Francis, 2003).

6. Komatiites and implications in Astrobiology

It is quite evident that komatiites may have represented a major rocky component of the primitive environments where early life on Earth emerged and evolved and may have played a significant role in the evolution of the primitive atmosphere and the change in the compositions of the hydrosphere.

Molecular evidence is increasingly strong that the first living organisms existed around (or were related to) a hydrothermal system. This “hydrothermal” hypothesis is supported by a wide variety of arguments. The most accepted is that all the deepest branches of life share a common hyperthermophile character (Kandler 1992, 1994) existing at temperatures of 80 - 110 °C. Also, many of the most ancient proteins appear to have a hydrothermal origin and key elements that make possible the existence of living communities. S, Fe, Mn, Zn, Mo and
perhaps P, Ni and Mg may have entered into life processes from an early hydrothermal or volcanic substrate, or from fluids in a volcanic ambiance (Nisbet and Flower, 1996). From this reasoning, early life on the Archean Earth may have colonized a wide variety of hydrothermal environments which would have included hydrothermal systems on mid-ocean ridges, around komatiite plume volcanoes and in shallow water settings. On the continents, plume komatiitic volcanism (comparable to Hawaii but lower and much larger) would have created wide low shields.

Inorganic components of life as sulphur, iron, manganese and magnesium, all characteristic of hydrothermal environments, play crucial roles in many functions of life, such as photosynthesis (Barber and Anderson, 1994). Komatiite eruptions as other hydrothermal systems like submarine basalt may have first supplied these elements to life. A wide variety of trace elements like Zn, Cu, Mo, Se and rare elements also used in essential processes of life, not easily accessible to the early unskilled biosphere, would have been introduced to living organisms most likely by hydrothermal systems and possibly around komatiite plume volcanoes (Nisbet and Fowler, 1996).
A particular astrobiological interest in komatiites may be related to its ability to host large sulphide deposits (Barnes, 2004; Hill et al., 2004) accumulating along the bases of the flows and potentially exposed on active volcanoes by erosion or earthquakes. In some cases, hydrothermal penetration of nickel sulphide deposits in komatiite flows may have provided local Ni-rich fluids. Environmentally, Ni is a relatively rare element, not especially concentrated even in most hydrothermal fluids, and it is quite difficult to imagine how the primitive organisms may have obtained it. One possibility is that nickel had a meteoritic origin but it may have also derived geologically in large komatiitic plume volcanoes. Such volcanoes would form a huge shield structure and would produce enormous lava flows, flowing widely and then cooling with vigorous and shallow hydrothermal systems. Many key proteins are Ni-based, for example, urease, a key part of the nitrogen cycle, is built around Ni. Given that early cells were probably not highly skilled at extracting metals from the environment, it is possible that Ni-enzymes used in basic cellular housekeeping evolved in a setting where Ni sulphides were abundant and obtruded into early cells, perhaps serving as sites for the first Ni-metal proteins. It is plausible to imagine that such settings would have been around komatiite hydrothermal systems that penetrated Ni sulphide deposits in komatiite flows. Nickel sulphide layers would have provided substrates for
bacteria. One can also propose that urease may have had a komatiite-based history (Nisbet and Fowler, 1996). Urease may have evolved in the presence of abundant carbon dioxide as CO$_2$ is required for the assembly of the nickel metallocentre (Park and Hausinger 1995). One possibility of encountering such conditions could have been around an exposed nickel-sulphide substrate in an eroded or fault broken lava flow on the flanks of an extensive komatiite plume volcano (Nisbet and Fowler, 1996).

The ultramafic character of komatiites would have favored conditions for an early Earth’s environment suitable for life. Among the hypothesis for the origin of life on Earth, one strongly argues that life arose in aqueous solution as in lagoons, lakes and oceans. In order for life to being able to emerge and develop in such solutions, particular chemical conditions would have been required, like non acidic composition (avoiding for instance the hydrolysis of proteins), non-oxic solution (avoiding a rapid oxidation of the organic matter) and low Ca$^{2+}$ concentrations (for correct biochemical functioning of proteins, avoiding protein denaturation and avoiding the reduction of the phosphate concentration for the production of ATP) (Kempe and Kazmierczak, 2002). Therefore, alkaline environments could be better promising sites to biogenesis. It is proposed that the
presence of komatiites during weathering by H$_2$CO$_3$, HCl and H$_2$SO$_4$ acids could have promoted alkaline solutions (Kempe and Kazmierczak, 2002). Indeed, dissolution experiments with pulverized komatiites in water exposed to ambient CO$_2$ pressure during several weeks (Kempe and Kazmierczak, 2002) or komatiites in standard seawater at different temperatures (MacLeod et al., 1994) show a decrease of Ca$^{2+}$ concentration and an increase of the alkalinity of the resulting solution.

In addition, the predominance of high-temperature mafic (e.g. picrites) and ultramafic (e.g. komatiites) lava on early Earth would have favor effusive eruptions with high H$_2$ and CO contents in volcanic gases owing to CO - CO$_2$ and H$_2$O - H$_2$ equilibria in magmatic gases. In addition, the amounts of CO and H$_2$ (and NH$_3$) increase if magmas were more reduced (fO$_2$ down to C$^0$ - , Fe$^0$ –bearing buffers) than on the present Earth. These buffers provide significant thermodynamic drive to form hydrocarbons below ~400°C. The best conditions for organic synthesis on early Earth is achieved in submarine Hawaiian-type eruptions of high temperature and/or reduced magmas. The hydrocarbons might be formed by Fisher-Tropsch type synthesis catalyzed by magnetite and/or Fe$^0$ present in solid volcanic products (Anderson, 1984). Fisher-Tropsch type reactions may have produced
hydrophobic compounds. Such hydrophobic material would have formed a hydrophobic layer on the surface of the sea, which would have provided an environment thermodynamically more suitable than water for the concentration and polymerization of organic molecules fundamental to life, particularly amino acids and pyridine bases.

To examine the possible role of komatiites in the production of H₂ and in the consequent production of hydrocarbons, Richard (2005) has studied thermodynamically the hydrothermal alteration of ultramafic rocks in slow-spreading mid-ocean ridges. The results of the calculations indicate that H₂ is produced in sufficient amounts to lead to detectable amounts of organic according to the Fisher-Tropsch type reaction. Therefore, as the author concludes, in Archean environments, the alteration of komatiites could also have led to important production of H₂ and abiogenic organic carbon, part of which may have been preserved as residual carbonaceous material in the hydrothermal cherts overlying the komatiites.

Also elemental phosphorus or phosphorus-containing compounds (such as phosphite) deriving from volcanic eruptions would have ended up raining down into the hydrophobic layer, accumulating. Phosphorus-containing compounds
might have interacted with hydrophobic molecules in the layer giving rise to polymers. In particular, phosphite might have reacted with the hydrophobic amino acids, giving rise to phosphoamino acids, which, in turn, might have interacted with pyrimidine bases (relatively abundant in the layer) giving rise to peptides and oligonucleotide-like polymers (Morchio and Traverso, 2005).

Finally, there is a significant and exciting relation of early Earth komatiites with copper mineralization, regarding the origin of life and the "peptide world". In accordance with Planckensteiner et al. (2004) the availability of copper(ii) ions in a prebiotic scenario would enable the formation of peptides and proteins, which are the basic components of living organisms. As previously defined, Cu is an element which is retained in komatiitic magmas. The recently discovered Collurabbie Ni-Cu-PGE prospect in the northeast Yilgarn Craton (Western Australia) is an unusual, PGE-enriched nickel sulphide komatiite deposit (Jaireth et al., 2005) and the Permian-Triassic komatiite basalt complex in the Song Da rift, northwestern Vietnam, occurs in the axial part of this structure and includes komatiites, komatiitic basalts, olivine basalts, and subvolcanic bodies of dunite and plagioclase-bearing wehrlite hosting NiCuPGE sulfide ores (Glotov et al., 2001).
7- Summary

The unique character and origin of komatiites make them excellent indicators of the early composition and development of the Earth’s mantle. Considered as “primitive” lavas and therefore as a significant constituent of the Archean crust, komatiites are important for understanding the evolution of the early Earth. Komatiites are not only important for understanding the evolution of the early Earth, but also for the astrobiological exploration (i.e. early Mars) (Nna-Mvondo and Martinez-Frias, 2005). Komatiites are not exclusively related to the early Earth, as they may be part of the geological features of other planetary bodies of the Solar System. Such prospect opens the idea that komatiites might be more common in the Solar System and also that the definition of komatiites as Archean rocks could further be extent more largely to planetary volcanic material. Komatiites have been observed to present chondritic-like compositional characteristics, as some meteorites have been reported to be similar to komatiites for specific features in their structure and geochemistry. And so far it has been suggested an extraterrestrial impact origin for komatiites. But this impact
hypothesis is based on theoretical models, and clearly need to be further explored to better assign such origin. This is of particular interest as meteorites are proposed to be the building blocks from which all planets are made and because they tell us a great deal about the primary mineral planetary composition. Undoubtedly, the connection between (large) impacts and komatiites genesis needs to be further explored.

We tend to forget the importance of rocks and mineral in bio/geochemistry and consequently in the early life on Earth. Volcanic rocks as komatiites could be a habitat for early microbial life since on the beginning of Earth’s history, komatiite plume volcanoes provide possible sites for the evolution of various biological processes. For instance, perhaps metals like nickel could have been incorporated into biochemistry around a komatiite volcano. Recently, it has even been documented evidence of ancient microbial activity within Archean pillow lavas of the Barberton Greenstone Belt (Furnes et al., 2004). These pillow lavas are predominantly komatiitic and basaltic. Such modern view makes komatiites much more attractive rocks that may offer new perspectives in the astrobiological Sciences (Nna-Mvondo and Martinez-Frias, 2005). In this context, their investigation should extend well over the geological, geochemical field, as well as the understanding of their significance should not be restricted to the early Earth
history but studied and interpreted as well for other planets and planetary bodies of the Solar System.

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**References**


Gangopadhyay, A., Walker, R.J., Sproule, R.A.: 2003, Major and trace element geochemistry and Os isotopic compositions of komatiites from Dundonald Beach, Abitibi Greenstone Belt, Canada, American Geophysical Union, Fall Meeting 2003, abstract V42C-0374.


Table 1. Age of komatiites for different locations (listed in the descending order).

<table>
<thead>
<tr>
<th>Age (Ga)</th>
<th>Geological terrain</th>
<th>Location</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6 - 3.2</td>
<td>Barbeton Greenstone Belt</td>
<td>South Africa</td>
<td>Byerly et al., 1996; Lowe and Byerly, 1999</td>
</tr>
<tr>
<td>3.5 - 3.2</td>
<td>Commondale Greenstone Belt</td>
<td>South Africa</td>
<td>López-Martínez et al., 1992</td>
</tr>
<tr>
<td>3.47</td>
<td>Pilbara Craton, North Pole Dome</td>
<td>Western Australia</td>
<td>Brown et al., 2004</td>
</tr>
<tr>
<td>2.97</td>
<td>Rio Maria greenstone terrane</td>
<td>Southeast Pará, Northern Brazil</td>
<td>De Souza et al., 1997</td>
</tr>
<tr>
<td>2.9</td>
<td>Forrestania, southern Cross Province</td>
<td>Western Australia</td>
<td>Perring et al., 1996</td>
</tr>
<tr>
<td>2.8</td>
<td>Kostomuksha Greenstone Belt</td>
<td>Baltic Shield</td>
<td>Puchtel et al., 2001a</td>
</tr>
<tr>
<td>2.7</td>
<td>Belingwe Greenstone Belt</td>
<td>Zimbabwe</td>
<td>Nisbet et al., 1987</td>
</tr>
<tr>
<td>2.7</td>
<td>Abitibi Greenstone Belt (Munro, Alexo, Tisdale, Boston, Dundonald, Pyke Hill, Marbridge Townships)</td>
<td>Ontario, Canada</td>
<td>Puchtel et al., 2004b; Gangopadhyay and Walker, 2001; Arndt, 1976</td>
</tr>
<tr>
<td>2.7</td>
<td>Yilgarn Craton, (Black Swan, Perseverance complex in Norseman-Wiluna greenstone belt)</td>
<td>Western Australia</td>
<td>Barnes, 2004; Barnes et al., 1995</td>
</tr>
<tr>
<td>2.7</td>
<td>Kambalda</td>
<td>Western Australia</td>
<td>Lahaye et al., 2001</td>
</tr>
<tr>
<td>2.4</td>
<td>Vetreny belt</td>
<td>Southeastern Baltic Shield</td>
<td>Puchtel et al., 2001b, 1996</td>
</tr>
<tr>
<td>2.1</td>
<td>Dachine deposit, Inini greenstone belt</td>
<td>French Guiana</td>
<td>Capdevila et al., 1999</td>
</tr>
<tr>
<td>2.06</td>
<td>Central Lapland Greenstone Belt, (Finnish Lapland)</td>
<td>Finland</td>
<td>Hanski et al., 2001; Gangopadhyay, 2002</td>
</tr>
<tr>
<td>0.270</td>
<td>Song Da zone</td>
<td>Northwestern Vietnam</td>
<td>Hanski et al., 2004</td>
</tr>
<tr>
<td>0.089</td>
<td>Gorgona Island</td>
<td>Colombia</td>
<td>Echeverria, 1980; Arndt et al., 1997</td>
</tr>
</tbody>
</table>

* General dating error roughly ranges from ± 0.01 to ± 0.8.
Table 2. Major element abundances (wt.%) in komatiites located in different geological settings, in comparison with the earth’s undepleted mantle (UM) and primitive basalt abundances (PB).

<table>
<thead>
<tr>
<th>Location</th>
<th>SiO$_2$</th>
<th>MgO</th>
<th>Fe$_2$O$_3$</th>
<th>LOI</th>
<th>Al$_2$O$_3$</th>
<th>CaO</th>
<th>FeO</th>
<th>Na$_2$O</th>
<th>TiO$_2$</th>
<th>MnO</th>
<th>K$_2$O</th>
<th>P$_2$O$_5$</th>
<th>H$_2$O</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGB</td>
<td>47.2</td>
<td>31.4</td>
<td>—</td>
<td>—</td>
<td>3.4</td>
<td>5.6</td>
<td>11.2$^b$</td>
<td>0.07</td>
<td>0.3</td>
<td>0.2</td>
<td>0.04</td>
<td>0.02</td>
<td>—</td>
<td>(1)</td>
</tr>
<tr>
<td>PH</td>
<td>45.1</td>
<td>30.0</td>
<td>11.4</td>
<td>7.5</td>
<td>6.3</td>
<td>5.7</td>
<td>—</td>
<td>0.34</td>
<td>0.31</td>
<td>0.15</td>
<td>0.05</td>
<td>0.01</td>
<td>—</td>
<td>(2)$^c$</td>
</tr>
<tr>
<td>VB</td>
<td>45.4 – 53.6</td>
<td>6.8 - 26.1</td>
<td>10.8 – 13.4</td>
<td>0.2 – 5.3</td>
<td>7.2 – 13.8</td>
<td>7 – 11.6</td>
<td>—</td>
<td>0.4 – 2.5</td>
<td>0.4 – 0.8</td>
<td>0.16 – 0.19</td>
<td>0.1 – 0.7</td>
<td>0.06 – 0.2</td>
<td>—</td>
<td>(3)</td>
</tr>
<tr>
<td>GI</td>
<td>43.48</td>
<td>21.9</td>
<td>11.2</td>
<td>3.4</td>
<td>9.6</td>
<td>8.6</td>
<td>—</td>
<td>0.64</td>
<td>0.49</td>
<td>0.17</td>
<td>0.04</td>
<td>0.04</td>
<td>1.89</td>
<td>(4)$^e$</td>
</tr>
<tr>
<td>UM</td>
<td>45.1</td>
<td>38.1</td>
<td>—</td>
<td>—</td>
<td>3.3</td>
<td>3.1</td>
<td>8.0</td>
<td>0.4</td>
<td>0.2</td>
<td>0.1</td>
<td>0.05</td>
<td>—</td>
<td>—</td>
<td>(5)</td>
</tr>
<tr>
<td>PB</td>
<td>44.2</td>
<td>13.1</td>
<td>—</td>
<td>—</td>
<td>12.1</td>
<td>10.1</td>
<td>10.9</td>
<td>3.6</td>
<td>3.7</td>
<td>0.2</td>
<td>1.3</td>
<td>0.8</td>
<td>—</td>
<td>(6)</td>
</tr>
</tbody>
</table>

$^b$ Location: BGB (Barbeton greenstone belt), PH (Pyke Hill, Abitibi Greenstone belt), VB (Vetreny Belt), GI (Gorgona Island).

$^c$ All Fe were calculated as FeO.

$^d$ Data sources in Tables 2, 3 and 4: (1) Parman et al., 2003; (2) Puchtel et al., 2004a; (3) Puchtel et al., 1997; (4) Hanski et al., 2004; (5) Francis and Oppenheimer, 2004; (6) Basaltic Volcanism Study Project, 1981; (7) Puchtel and Humayun, 2000; (8) Puchtel et al. (2001b); (9) Kerr, 2005.

$^e$ Average data of the abundances of several analyzed samples.
Table 3. Minor and trace element abundances (ppm) in komatiites located in different geological settings

<table>
<thead>
<tr>
<th>Location</th>
<th>Cr</th>
<th>Ni</th>
<th>Zr</th>
<th>Y</th>
<th>Ga</th>
<th>Nd</th>
<th>Ce</th>
<th>Dy</th>
<th>Gd</th>
<th>Er</th>
<th>Yb</th>
<th>Sm</th>
<th>Nb</th>
<th>La</th>
<th>Eu</th>
<th>Th</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGB</td>
<td>2920</td>
<td>1611</td>
<td>19.1</td>
<td>6.8</td>
<td>—</td>
<td>2.5</td>
<td>3.2</td>
<td>1.08</td>
<td>0.9</td>
<td>0.6</td>
<td>0.6</td>
<td>0.8</td>
<td>1.05</td>
<td>1.2</td>
<td>0.3</td>
<td>0.1</td>
<td>(1)</td>
</tr>
<tr>
<td>PH</td>
<td>2600</td>
<td>1633</td>
<td>15.0</td>
<td>7.6</td>
<td>6.3</td>
<td>1.4</td>
<td>1.3</td>
<td>1.2</td>
<td>0.9</td>
<td>0.8</td>
<td>0.8</td>
<td>0.6</td>
<td>0.4</td>
<td>0.4</td>
<td>0.2</td>
<td>0.04</td>
<td>(2)</td>
</tr>
<tr>
<td>VB</td>
<td>283 - 3507</td>
<td>57 - 1138</td>
<td>34 - 71</td>
<td>9 - 17</td>
<td>—</td>
<td>5 - 12</td>
<td>9 - 24</td>
<td>1.5 - 3</td>
<td>1 - 3</td>
<td>0.9 - 2</td>
<td>0.9 - 2</td>
<td>1 - 3</td>
<td>1 - 3</td>
<td>4 - 11</td>
<td>0.4 - 0.9, 0.7 - 3</td>
<td>(3)</td>
<td></td>
</tr>
<tr>
<td>GI</td>
<td>2323</td>
<td>997</td>
<td>19.2</td>
<td>12.3</td>
<td>2.1</td>
<td>2.1</td>
<td>2.0</td>
<td>1.5</td>
<td>1.3</td>
<td>1.3</td>
<td>0.9</td>
<td>0.6</td>
<td>0.8</td>
<td>0.4</td>
<td>&lt;0.5</td>
<td>(4)</td>
<td></td>
</tr>
</tbody>
</table>

Notes b, d and e are the same as in Table 2.

Table 4. PGE abundances (ppb) in komatiites located in different geological settings

<table>
<thead>
<tr>
<th>Location</th>
<th>188Os/187Os</th>
<th>Os</th>
<th>Ir</th>
<th>Ru</th>
<th>Pt</th>
<th>Pd</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>BGB</td>
<td>—</td>
<td>0.792</td>
<td>1.23</td>
<td>4.30</td>
<td>5.83</td>
<td>5.51</td>
<td>(7)</td>
</tr>
<tr>
<td>PH</td>
<td>0.1099±0.0019</td>
<td>2.38</td>
<td>2.13</td>
<td>5.31</td>
<td>11.1</td>
<td>10.6</td>
<td>(2)</td>
</tr>
<tr>
<td>VB</td>
<td>0.1099±0.0016, 0.1110±0.0013</td>
<td>0.04 - 0.8</td>
<td>0.06 - 1.7</td>
<td>0.9 - 5.5</td>
<td>7.8 - 11</td>
<td>7.3 - 13.8</td>
<td>(7), (8)</td>
</tr>
<tr>
<td>GI</td>
<td>0.12506±0.00041</td>
<td>1.4 - 7.0</td>
<td>2.05</td>
<td>3.3</td>
<td>14.1 #</td>
<td>12</td>
<td>(4), (9)</td>
</tr>
</tbody>
</table>

Notes b, and d are the same as in Table 2.