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Part I

Background information – description of the field characteristics, mineralogy and geochemistry of komatiites

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1

A brief history of komatiite studies and a discussion of komatiite nomenclature

1.1 The discovery and early investigations of komatiite

A review of reports written by field geologists in the early twentieth century reveals many references to ultramafic volcanic rocks. These rocks were identified as extrusive because of their volcanic textures and structures, and they seem to have been accepted as a normal component of Archean volcanic successions. Then, between 1920 and 1930, as Bowen and other petrologists conducted the experimental studies that led them to question the very existence of ultramafic magma (Bowen, 1928), and as the influence of these petrologists spread, descriptions of ultramafic volcanics virtually disappeared from the geological literature. There were sporadic reports of serpentinite flows in younger terranes, as reviewed by Bailey and McCallien (1953), and argument persisted about the nature and origin of 'alpine peridotites', but references to ultramafic lavas in Archean areas became rare. In a few Canadian papers, the texture we now know as spinifex was described, and the rocks containing these textures were interpreted as volcanic (Berry, 1940; Prest, 1950; Abraham, 1953). Similar reports appeared of ultramafic lavas in various parts of the (then) Rhodesian craton (Keep, 1929; Wiles, 1957). More commonly, however, the ultramafic rocks were interpreted as intrusive, in most cases as the lower cumulate layers of differentiated sills. This is the case for two type areas of komatiite, Barberton in South Africa and Munro Township in Canada. The ultramafic rocks of the Barberton greenstone belt were originally interpreted as the intrusive component of the 'Jamestown Igneous Complex', described as an association of magnesium-rich intrusive rocks subsequently converted to serpentinites and schists (Hall, 1918; Visser, 1956; de Wit *et al.*, 1987). Satterly (1951b) produced a detailed geological map of Munro Township in Ontario. Satterley's maps are remarkably accurate and the distribution of ultramafic units is shown in detail. Even spinifex texture was identified and carefully

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mapped. However, instead of interpreting it as volcanic, Satterly attributed the texture to metamorphism that had preferentially affected the margins of ultramafic sills.

The changes that were to come were foreshadowed by Naldrett and Mason (1968), who described in detail skeletal olivine crystals in ultramafic lenses from Dundonald Township, not far from Munro. Naldrett, in his Ph. D. thesis (Naldrett, 1964b), had noticed the similarity between the morphology of these crystals and those of olivine in rapidly cooled experimental mafic liquids, and he argued for the existence of ultramafic liquids. In their paper, Naldrett and Mason (1968) concluded that the ultramafic units were high-level sills or perhaps lava flows that had formed from highly magnesian magmas.

The honour for the discovery of komatiites goes to Morris and Richard Viljoen, twin brothers who, in the course of their detailed mapping and subsequent petrographic and chemical studies of ultramafic units in the Barberton greenstone belt of South Africa, concluded that these units were indeed ultramafic lava flows. In a series of papers published as part of South Africa's contribution to the 1969 Upper Mantle Project (Viljoen and Viljoen, 1969b, c), they presented convincing arguments to support their conclusion. A feature that particularly impressed them was the manner in which the ultramafic units thinned sympathetically with the mafic lavas because this suggested that these units were part of the volcanic succession, and not younger intrusions. Other features such as chilled flow tops, hyaloclastite breccias and what they called 'crystalline quench texture' also pointed to a volcanic origin.

Viljoen and Viljoen (1969c) compared the chemical compositions of the Barberton komatiites with those of other types of ultramafic rocks, particularly alpine peridotites and mantle xenoliths and with other types of mafic lava. In this comparison, the komatiites were found to have lower MgO and higher SiO_2 contents than the ultramafic cumulates or restitic rocks, but were distinguished from the other volcanic rocks by high MgO, low SiO_2 contents and lower contents of TiO_2 and alkali elements. Perhaps the most distinctive chemical feature was the $CaO–Al_2O_3$ ratio, which was significantly higher than in the other rocks. These chemical characteristics were shared by mafic volcanics associated with the ultramafic lavas, and since these mafic rocks also contained crystalline quench textures, the Viljoens argued that they were part of the same magma series. It was for rocks of this ultramafic–mafic suite that the term komatiite was introduced.

In the following five years, komatiites were recognized in many other areas, notably in the Abitibi greenstone belt in Canada, the Yilgarn of Australia and the Belingwe belt in Zimbabwe. Following the studies of Naldrett (1964a) and Naldrett and Mason (1968), Pyke (1970) documented the existence of

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ultramafic lava flows in Langmuir and Blackstock Townships in the Abitibi greenstone belt, and later worked with Naldrett and Eckstrand in the investigation of the now classic outcrops in Munro Township (Pyke *et al.*, 1973). Eckstrand (1972) discussed the relationship between certain Canadian nickel sulfide deposits and ultramafic volcanic rocks.

McCall and Leishman (1971) published a description of ultramafic and mafic volcanic rocks in Western Australia and, at about the same time, Nesbitt (1971) introduced the term spinifex texture into the international geological literature and discussed how the texture might have formed. Subsequent papers by Williams (1972), Hallberg and Williams (1972) and Barnes *et al.* (1973) demonstrated that ultramafic volcanic rocks were a ubiquitous component of volcanic sequences throughout the Yilgarn belt of Western Australia. Interest in these rocks was heightened by the recognition that ultramafic volcanic rocks hosted the large and rich Ni-sulfide deposits that had been discovered in the mid-1960s in the Kambalda area. These discoveries led to an exploration boom that lasted for a decade and provided the impetus for numerous studies of komatiites and their ore deposits (Ross and Hopkins, 1975; Naldrett and Turner, 1977).

The study of komatiites of the Belingwe greenstone belt by Bickle *et al.* (1975, 1977), and the more detailed report by Nisbet *et al.* (1977) documented the general petrological features of the ultramafic and mafic volcanic rocks in this region, and also provided information about their tectonic environment that had been lacking in other areas. Brooks and Hart (1974) described several examples from Canada, revised the definition of the rock type and, perhaps most importantly, suggested that the rocks might have formed through melting under hydrous conditions. Nesbitt and Sun (1976) and Sun and Nesbitt (1978) undertook the first global investigations of the major- and trace-element geochemistry of komatiites and developed many important ideas concerning the origin of these rocks.

Subsequent reports have confirmed the presence of komatiite in almost all Archean terrains, as shown in Figure 1.1 and Table 1.1. The Proterozoic appears to be devoid of true komatiites, with the possible exceptions of the dunitic hosts of ore deposits at Thompson, Canada (Burnham *et al.*, 2003) and some very poorly preserved occurrences in Guyana (Gruau *et al.*, 1985; Capdevila *et al.*, 1999). Mg-rich basalts, some with spinifex textures, are known in parts of the Circum-Superior Belt in Canada (Baragar and Scoates, 1981), but ultramafic lavas appear to be absent. The only definite example of Phanerozoic komatiite ('dinkum komatiite', to use the expression of Lina Echeverría, who undertook the definitive study of these rocks) are on Gorgona Island off the coast of Colombia. Gansser *et al.* (1979) first reported the existence of these ultramafic lavas, and Echeverría

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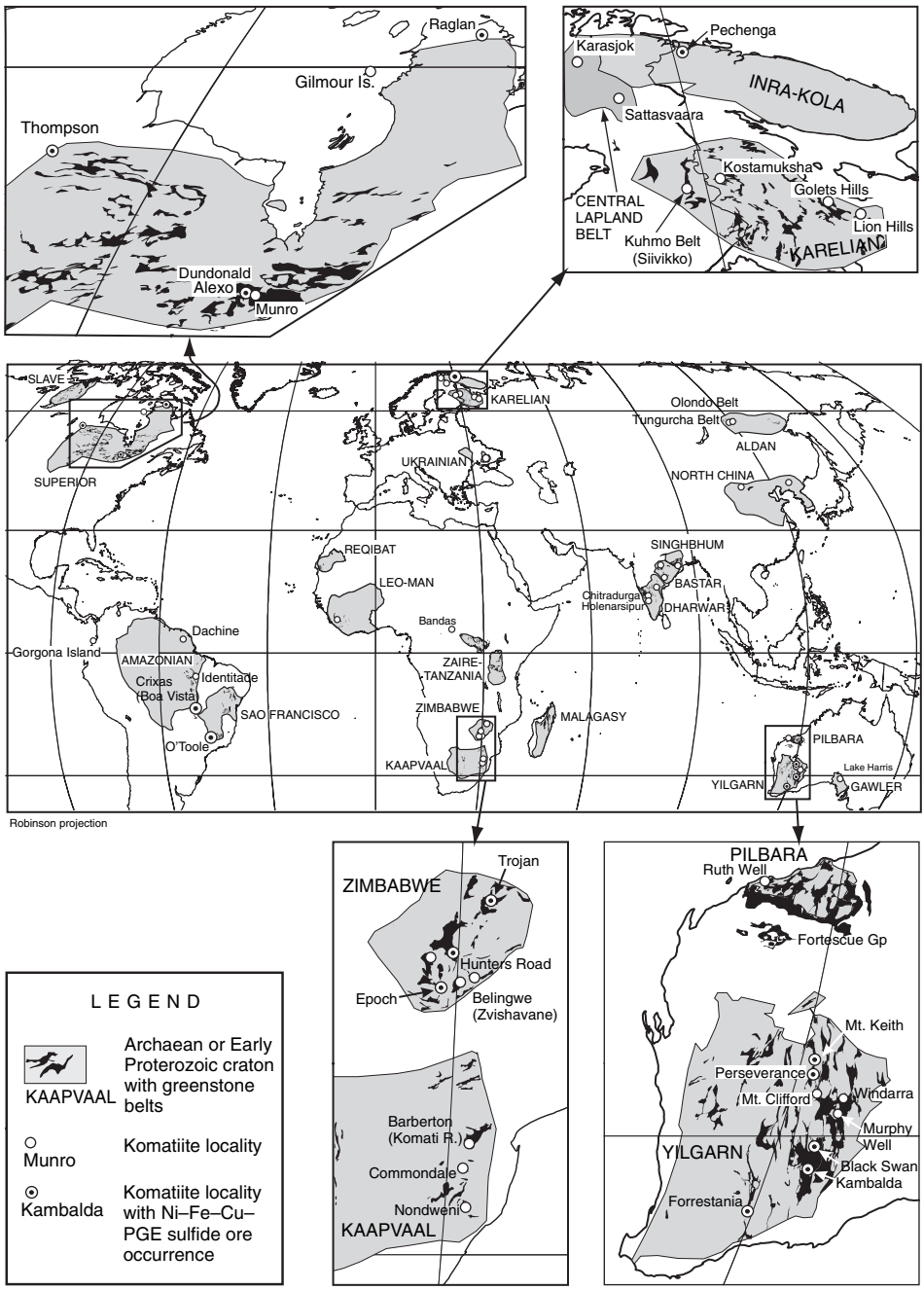

Fig. 1.1. World map showing Archean and older Proterozoic cratons, greenstone belts, principal komatiite localities and major associated nickel deposits. Localities and principal references are listed in Table 1.1.

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Table 1.1. *Localities of worldwide komatiite occurrences shown in Figure 1.1*

Country	Locality	Belt	Lat	Long	Reference
Australia	Digger Rocks	Forrestania–Lake Johnston–Ravensthorpe	−32.72	119.81	Perring *et al.*, 1995, 1996.
Australia	Warrawoona Group	Pilbara Craton	117.40	−22.66	Arndt *et al.*, 2001.
Australia	Lake Harris greenstone belt	Lake Harris	−30.78	134.50	Hoatson *et al.*, 2005.
Australia	Kambalda	Norseman–Wiluna	−31.20	121.67	This volume, Chapters 2 and 10
Australia	Mt Keith	Norseman–Wiluna Agnew–Wiluna	−27.24	120.54	This volume, Chapter 10
Australia	Perseverance	Norseman–Wiluna Agnew–Wiluna	−27.81	120.70	Barnes *et al.*, 1988; Barnes 2006.
Australia	Windarra	Norseman–Wiluna East	−28.61	122.24	Marston 1984.
Australia	Black Swan	Norseman–Wiluna Kalgoorlie Terrain	−30.39	121.64	Hill *et al.*, 2004; Dowling *et al.*, 2004; Barnes *et al.*, 2004.
Australia	Scotia	Norseman–Wiluna Kalgoorlie Terrain	−30.21	121.27	Page and Schmulian, 1981.
Australia	Ruth Well	Pilbara West (Karratha–Whim Creek)	−20.85	116.83	Nisbet and Chinner, 1981.
Australia	Fortescue basalts	East Pilbara			
Brazil	Boa Vista	Crixas greenstone belt	−14.16	−50.11	Costa *et al.*, 1997; Arndt *et al.*, 1989.
Brazil	O'Toole deposit	Quadrilatero Ferrifero (Rio das Velhas)	−20.90	−46.72	Brenner *et al.*, 1990.
Canada	Alexo	Abitibi greenstone belt	48.65	−80.81	This volume, Chapter 2, Chapter 10.
Canada	Dundonald	Abitibi greenstone belt	48.63	−80.83	Houlé *et al.*, 2007a; This volume, Chapter 3.
Canada	Munro Township	Abitibi greenstone belt	48.59	−80.20	This volume, Chapter 2.
Canada	Dumont Sill	Abitibi greenstone belt	48.87	−79.32	Duke 1986a,b.
Canada	Spinifex Ridge	Abitibi greenstone belt	48.23	−78.22	Gélinas *et al.*, 1977, Dostal and Mueller, 2001.

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Table 1.1. *(cont.)*

Country	Locality	Belt	Lat	Long	Reference
Canada	Donaldson	Cape Smith belt, Quebec.	61.67	−73.28	St Onge and Lucas, 1993b; Lesher 2007.
Canada	Katinniq	Cape Smith belt, Quebec.	61.68	−73.67	This volume, Chapter 10.
Canada	Gilmour Island	East Hudson Bay	59.75	−80.05	This volume, Chapter 2.
Canada	Lac Guyer	Superior Province, Quebec	53.42	−77.58	Stamatelopoulou-Seymour and Francis, 1980.
Canada	Thompson	Thompson	55.73	−97.80	This volume, Chapter 10.
Canada	Steep Rock	Wabigoon belt, Ontario	48.80	−91.60	Barnes and Often, 1990; Schaefer and Morton, 1991.
Colombia	Gorgona Island	Gorgona Island	2.95	−78.20	This volume, Chapter 2.
Finland	Sattasvaara	Kittila (Sattasvaara)	67.61	26.68	Hanski *et al.*, 2001.
Finland	Kuhmo Belt (Siivikko)	Kuhmo	64.23	29.09	Sorjonen-Ward *et al.*, 1997; Gruau *et al.*, 1992.
Guyana	Dachine	Gyr-Inini	3.35	−53.30	Capdevila *et al.*, 1999.
Norway	Karasjok	Karasjok	69.10	25.00	Barnes and Often 1990.
Russia	Pechenga	Inari-Kola Craton	69.54	30.53	Hanski 1992; Hanski and Smolkin, 1989; Skufin and Theart 2005.
Russia	Kostamuksha	Kostamuksha-Gimola	64.65	30.75	Puchtel *et al.*, 1997.
Russia	Olondo Belt (Red Hill Massif)	Olondo greenstone belt	56.94	119.33	Puchtel and Zhuralev, 1989.
Russia	Tungurcha Belt	Tungurcha	57.20	120.90	Puchtel *et al.*, 1991.
Russia	Vetreny Belt (Golets Hills)	Vetreny belt	63.78	35.70	Puchtel *et al.*, 2001a,b.
Russia	Lion Hills	Vetreny belt	63.32	37.18	Puchtel and Humayun, 2001.
South Africa	Komati formation	Barberton greenstone belt	−25.95	30.79	This volume, Chapter 2.
South Africa	Commondale	Commondale	−26.90	30.60	Wilson *et al.*, 2003; Wilson, 2003.
Zimbabwe	Zvishavane	Belingwe greenstone belt	−20.33	30.03	Nisbet *et al.*, 1987; Bickle *et al.*, 1993.
Zimbabwe	Trojan	Bindura-Hamva belt	−17.33	31.27	Prendergast, 2003.
Zimbabwe	Epoch	Filabusi	−20.43	29.28	Prendergast, 2003.
Zimbabwe	Hunters Road	Midlands-Chegutu	−19.15	29.78	Prendergast, 2003.

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(1980), Cameron and Nisbet (1982) and Aitken and Echeverría (1984) subsequently documented their petrology and chemical compositions, and convincingly demonstrated their origin as eruptive ultramafic magmas.

Viljoen and Viljoen (1982) provide a more detailed account of the early years of komatiite investigation in one of their contributions to the first komatiite book (Arndt and Nisbet, 1982a).

1.2 More recent studies

The cosy world of komatiite studies was upset when, in 1996, Grove, de Wit, Parman and Dann proposed that komatiites were hydrous magmas. In their view, as expressed in a long series of papers (de Wit and Stern, 1980; de Wit *et al.*, 1983, 1987; Grove *et al.*, 1994, 1996; Parman *et al.*, 1996; Grove *et al.*, 1997; Parman *et al.*, 1997; Grove *et al.*, 1999; Parman *et al.*, 2001, 2003; Grove and Parman, 2004; Parman *et al.*, 2004), the komatiites from the type area in the Barberton greenstone belt did not erupt as anhydrous lava flows but were intruded as hydrous magmas at depths of about 6 km in the basaltic lava pile. The idea that komatiites were hydrous was not new, having been mentioned by Brooks and Hart (1974) and Allègre (1982), but Grove and coinvestigators took the model much further and developed a series of petrological and geochemical arguments that persuaded a significant proportion of the geological community of the validity of the hypothesis. The history of the hydrous komatiite hypothesis and its current status are discussed in detail in Chapter 11.

Other important developments include the application of the inductively-coupled plasma mass-spectrometer (ICPMS) method to the analysis of komatiites, which for the first time provided reliable data for a complete range of trace elements (Xie *et al.*, 1993; Xie and Kerrich, 1994). *In-situ* analysis using the ion microprobe and laser-source ICPMS provided important constraints on mineral compositions (Parman *et al.*, 2003), and application of the same techniques on melt inclusions yielded the concentrations of elements that normally were mobile during alteration (McDonough and Ireland, 1993). These developments are discussed in Chapters 4 and 5. New types of isotopic analysis were performed on komatiites, including the Lu–Hf (Gruau *et al.*, 1990a) and Re–Os (Walker *et al.*, 1988) systems and for the first time He isotopes were used (Richard *et al.*, 1996) (Chapter 6). Experimental studies, both at high pressures and under conditions of rapid cooling at low pressure provided valuable constraints on the conditions of formation and crystallization of komatiite (Chapter 7).

Another major development was presented in a remarkable series of papers published by Steve Sparks, Herbert Huppert and coworkers (Huppert and

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Sparks, 1985a, b; Turner *et al.*, 1986; Huppert and Sparks, 1989). For the first time fluid dynamic principles were applied in a rigorous manner to the study of komatiites, and this work thoroughly changed our understanding of how these ultramafic lavas erupted and crystallized. The notion that komatiite flowed turbulently and was capable of thermally eroding its substrate stemmed from this work. When combined with detailed studies of field relations of komatiites in Western Australia by R. E. T. Hill and coworkers (Hill *et al.*, 1987, 1995; Perring *et al.*, 1995; Barnes *et al.*, 1999; Hill, 2001) and with C. M. Lesher's studies of Kambalda komatiites (Lesher, 1983, 1989; Lesher *et al.*, 1984), these ideas formed the basis of our understanding of the volcanology of komatiite (Chapter 9). And when combined with work on the Kambalda deposits themselves, they lie at the core of models for the formation of komatiite-hosted ore deposits, as described in Chapter 10.

Komatiites in two particular regions were subjected to rigorous investigation because of their excellent state of preservation. The first of these regions is Gorgona Island, whose extremely fresh komatiites had been known since their initial discovery by Gansser (Gansser 1950; Gansser *et al.* 1979). Subsequent geochemical studies have thoroughly documented the petrological and geochemical characteristics of these rocks (Echeverría and Aitken, 1986; Walker *et al.*, 1991; Kerr *et al.*, 1996; Sylvester *et al.*, 2000; Kerr, 2005). The second region is Zvishavane in the Archean Belingwe belt of Zimbabwe. Euan Nisbet and coworkers mapped the rocks in outcrop and then organized the drilling of the SASKMAR hole, which recovered the core that has provided the best samples available of Archean komatiite. The characteristics of these rocks were first described in the Geology paper of Nisbet *et al.* (1987) and then in many other papers that present the results of numerous petrological and geochemical investigations of these remarkable komatiites (e.g. Bickle *et al.*, 1993; Bickle and Nisbet, 1993; McDonough and Ireland, 1993; Nisbet *et al.*, 1993; Renner *et al.*, 1994; Silva *et al.*, 1997; Danyushevsky *et al.*, 2002).

1.3 Nomenclature

The Penrose conference on komatiites was held in April 1980 in a rather seedy motel in the outskirts of Val d'Or, a gold-mining town in the Quebec portion of the Abitibi greenstone belt. There we reviewed what had been learnt in the decade that followed the initial discovery of the rock type. Examples from South Africa, Canada, Australia, Zimbabwe and Colombia were described and the models for their formation were discussed, but the most important issue of the conference was, perhaps, a new definition of the rock type. It had come to be realized that the distinctive geochemical feature of the

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Barberton komatiites – their high CaO–Al_2O_3 ratios – was not shared by the majority of ultramafic volcanic lavas that had been discovered in other areas. For a while it had been argued that these komatiites, which had lower, near-chondritic CaO–Al_2O_3 ratios, deserved another name. Nesbitt (1971) suggested 'Archean greenstone peridotite' (a name that nobody really liked) and in my long forgotten first paper on komatiites (Arndt, 1976b), I proposed 'magnesian magmatic series' (which was received equally badly). At the Penrose conference, Allen Zindler pointed out that the term komatiite deserved the status of a rock type. His suggestion was that komatiite should be defined simply as a 'volcanic rock of ultramafic composition', the petrological equivalent of basalt or andesite. It followed that the basalts associated with komatiites could be considered part of the 'komatiitic' magma series and should be named 'komatiitic basalts'. The terms 'peridotitic komatiite' and 'basaltic komatiite', coined in the original papers by Viljoen and Viljoen (1969a,c), were to be abandoned. These ideas were explained and developed by Arndt and Brooks (1980) and Arndt and Nisbet (1982b).

Komatiite can therefore be defined as a rock whose field relations or textures provide evidence of a volcanic or subvolcanic origin and whose mineral assemblages or major-element contents indicate an ultramafic composition. Features that can be used to indicate a volcanic setting include a fine-grained, chilled upper margin or, more conclusively, the presence of breccia or hyaloclastite. Fine grain size throughout the unit, spinifex textures, amygdales, complete conformity with surrounding units (lack of intrusive contacts) are consistent with, but do not prove, a volcanic origin.

The limit between komatiite and other less magnesian volcanic rocks was set, rather arbitrarily, at 18% MgO, a value that corresponds to a minimum in the relative abundances of komatiitic rocks in many, though not all, greenstone belts. 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.

Like any petrological term, the definition of komatiite is not without problems and ambiguities. Implicit to the definition of komatiite is the notion – difficult to prove – that komatiites crystallize from liquids that contained more than about 18% MgO. (Throughout the book major-element abundances are quoted as weight per cent oxide, normalized to 100% on an anhydrous basis, unless stated otherwise). The selection of 18% MgO as the limit between komatiite and komatiitic basalt has been questioned in several papers: some authors would prefer to see it set higher, at about 25% MgO for komatiites from the Barberton belt according to Smith and Erlank (1982) or lower, at 12–15% MgO for komatiites from Gorgona Island, in the view of Echeverría

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