

Nature and origin of an exceptional Cr-rich kyanite-bearing clinopyroxenite xenolith from Mbuji-Mayi kimberlite (DRC)

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Abstract: A xenolith made of exceptionally Cr-rich minerals (mostly omphacite, kyanite and minor rutile) has been found in the diamondiferous Mbuji-Mayi kimberlite province, Democratic Republic of Congo (DRC). Chromium contents (Cr_2O_3) are heterogeneously distributed in the bulk sample, as well as in a single crystal: 3.34–5.70 wt% in omphacite, 4.45–11.81 wt% in kyanite and 2.68–4.65 wt% in rutile. Such Cr-rich kyanite is extremely rare; only grosspydite xenoliths from the Zagadochnaya kimberlite (Yakutia) have been reported with kyanite containing up to 12.86 wt% Cr_2O_3 . However, unlike typical grosspydites, no garnet is observed in the Mbuji-Mayi Cr-rich kyanite-bearing clinopyroxenite.

The textural features of this rock and the tentative thermobarometric equilibration conditions (25–35 kbar, 700–800 °C) argue for an origin related to that of eclogites, which are the predominant xenoliths in the Mbuji-Mayi kimberlites. The calculated whole-rock composition suggests an Al-, Ca- and Cr-rich protolith that resembles Cr-rich leucogabbros or anorthosites commonly found in Archean anorthosite massifs. The peak *P-T* conditions registered by this unusual rock can be reached either by Archean subduction or by mafic magma underplating at the crust-to-mantle boundary with subsequent delamination into the upper mantle.

Key-words: kyanite clinopyroxenite, chromium-rich, Mbuji-Mayi, kimberlite, xenolith, Kasai-Lomami Complex, eclogite.

1. Introduction

Kimberlites are important carriers of xenoliths sampled from the upper mantle and deep crust in cratonic areas and at their borders. They actually allow petrologists to study inaccessible parts of the Earth, helping to understand the composition and structure of the upper mantle.

The xenolith populations of kimberlites worldwide are mostly composed of mantle peridotites. However, in some localities, like Roberts Victor, Bellsbank and Newlands in South Africa, Koidu in Sierra Leone, Zagadochnaya in Siberia, and Mbuji-Mayi in Democratic Republic of Congo (DRC), eclogites are dominant. The relative abundance of eclogites could reflect the local presence of fertile material in the upper mantle but could also result from the preferential alteration/disaggregation of peridotitic xenoliths during the entrainment by the kimberlite magma, as orthopyroxene and olivine are easily alterable. Indeed, no peridotite was found at Mbuji-Mayi but garnet and clinopyroxene xenocrysts from a metasomatised mantle source are abundant (Pivin *et al.*, 2009).

Amongst the eclogite suite of xenoliths, bimineralic eclogites (omphacite and garnet) are the most abundant but other varieties are also described: *e.g.* corundum-bearing, diamond-bearing, coesite-bearing and kyanite-bearing eclogites (*e.g.* Spetsius, 2004). The models proposed for the origin of eclogite suites are variable: (1) high-pressure crystallisation

of mafic cumulates in the upper mantle or at the lithosphere-asthenosphere boundary (Griffin & O'Reilly, 2007); (2) transformation of seawater-altered subducted oceanic crust (with or without removal of tonalitic melts); (3) transformation of upper mantle phlogopite-pyroxenite veins (Jacob, 2004 and references therein); and 4) underplating and subsequent isobaric cooling of mafic magma at the crust/mantle boundary or in the upper mantle (*e.g.* Pearson & O'Reilly, 1991; Pearson *et al.*, 1991; El Fadili & Demaiffe, 1999). Protolith mineralogy is variable, depending on mineralogical and chemical composition of the eclogite nodule: *e.g.* basalts, gabbros, spinel-gabbros or anorthosites.

Unusual kyanite-bearing eclogites that have been termed “grosspydites” (Sobolev *et al.*, 1968) are made of garnet rich in the grossular component (>50 mol% grs). There is actually a compositional continuum between the grossular content of garnet in eclogites and grosspydites (30–81 mol% grs). The origin of these rare xenoliths is closely related to that of eclogites (*e.g.* Sobolev *et al.*, 1968; Lappin, 1978). The first grosspydite xenoliths have been found in the non-diamondiferous Zagadochnaya pipe, located in the diamondiferous Daldyn-Alakit kimberlite province, in Yakutia, Siberia (Sobolev *et al.*, 1968). These xenoliths are associated to abundant kyanite eclogites. Grosspydite xenoliths have later been found in Roberts Victor Mine (South Africa) (*e.g.* Chinner & Cornell, 1974; Lappin, 1978), where eclogite

compositions compare well to those of Zagadochnaya (Sobolev *et al.*, 1968), and in Udachnaya and Zarnitsa pipes of Yakutia (Spetsius, 2004).

In the diamond-rich Mbuji-Mayi kimberlites from DRC, eclogites form 90 % of the whole xenolith population (160 nodules studied; El Fadili & Demaiffe, 1999). Some granulites and few garnet clinopyroxenites are also found. Three petrographic groups of eclogites have been distinguished: bimineralic, kyanite-bearing and diamond-bearing (1 sample). The estimated *P-T* conditions (815–946 °C – 20–25 kbar) for kyanite-bearing eclogites, which are characterised by kyanite-omphacite intergrowths, are similar to those of granulites (920 °C at 20 kbar) that often contain chemically similar intergrowths. A progressive transition from granulites to eclogites, by isobaric cooling, has thus been suggested. The proposed magmatic precursors of these rocks are deep crustal/upper mantle equivalents to gabbro-norites and anorthosites forming the Archean basement at Mbuji-Mayi (El Fadili & Demaiffe, 1999).

Besides typical garnet, clinopyroxene, zircon and ilmenite megacrysts, Mbuji-Mayi kimberlites notably include centimetre-sized kyanite and corundum crystals, which have not been studied yet.

This paper is focused on the petrographical and mineralogical investigation of a unique xenolith made of clinopyroxene, kyanite and rutile. The exceptional character of this rock holds from the high chromium concentration of the constituent minerals, particularly kyanite, for which such concentrations have rarely been reported in the literature. The origin of this unusual Cr-rich xenolith is tentatively discussed on the basis of mineral compositions, thermobarometric estimations and geological context.

2. Geological setting

Mbuji-Mayi kimberlites have been dated at 69.8 ± 0.5 Ma by ID-TIMS U–Pb dating on zircon and baddeleyite megacrysts (average of 45 analyses; Schärer *et al.*, 1997). This diamondiferous kimberlite province (Demaiffe *et al.*, 1991), made of 15 pipes, is located in the Archean Congo-Kasai Craton (Fig. 1), extending from southern DRC to its borders with northern Angola and Zambia. This craton, which is part of the Angola-Kasai Block, crops out 100 km to the S-SE of Mbuji-Mayi and in southern and central Angola. However, Phanerozoic covers between Angola and DRC cratonic areas make the direct correlation between both areas impossible.

The Congo-Kasai Craton is composed of two distinct metamorphic units that make up the Kasai-Lomami Complex: 1) to the south, a felsic complex made of >2.9 Ga enderbitic to charnockitic gneisses with sillimanite- and garnet-bearing granulite lenses, intruded by randomly oriented younger metadolerite dykes and 2) to the north, a 2.4 Ga old plutonic gabbro-noritic complex with subordinate olivine-bearing anorthosite layers, in which granulite-facies metamorphic recrystallisation textures overprint magmatic textures (Delhal *et al.*, 1976, 1986; Delhal & Liégeois, 1982; Bingen *et al.*, 1984). The felsic unit of the complex underwent a first metamorphic event at *ca.* 2.8–2.9 Ga (Delhal

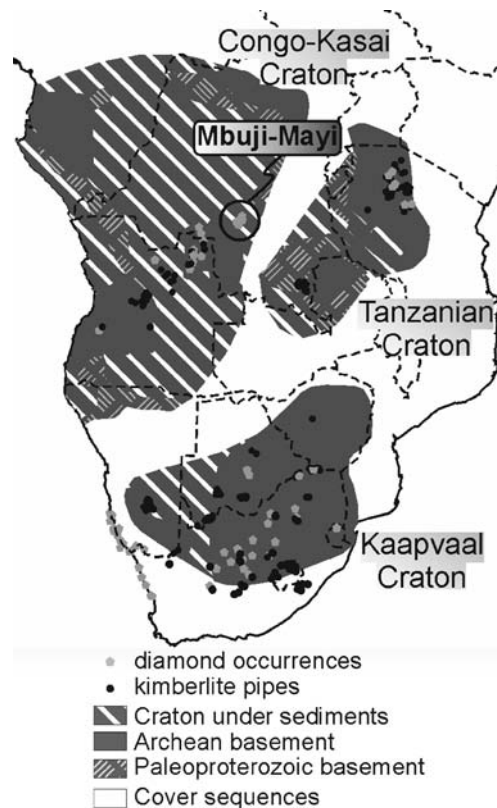


Fig. 1. Location of the Mbuji-Mayi kimberlite province (Democratic Republic of Congo) in the general context of kimberlites of Central and South Africa.

et al., 1976) whereas the mafic complex and metadolerite dykes were metamorphosed at 2.4 ± 0.1 Ga (Delhal *et al.*, 1986). Besides the Archean basement, Mbuji-Mayi kimberlites also cut across (Demaiffe & Fieremans, 1981): 1) the Proterozoic sandstones and stromatolitic dolomitic limestones of the Mbuji-Mayi Supergroup whose age is comprised between 1.3 Ga (the main tectonic phase of the Kibarian orogeny) and 0.95 Ga (the extrusion age of doleritic lavas at the top of the limestone sequence), and 2) Mesozoic (120 Ma) sandstones of the Lualaba series.

3. Sample petrography and mineralogy

Like many other xenoliths from kimberlites, the studied kyanite-bearing clinopyroxenite is oval-shaped (peanut-like); it measures about 1.4 cm long and 0.7 cm width (Fig. 2). Clinopyroxene forms 79 vol% of the bulk-sample and is slightly pleochroic from green to yellow-green. Kyanite, the second most abundant mineral (20 vol%), is strongly pleochroic, from colourless to deep blue. Brown rutile is the only accessory phase observed (<1 vol%) and chlorite (<1 vol%) forms secondary intergranular veins partly surrounding clinopyroxene crystals.

Clinopyroxene is present as rather large (<1–2 mm) anhedral grains. It often encloses lath-shaped or rounded kyanite inclusion aggregates, giving the rock its poikiloblastic character. Kyanite occurs as subhedral, partly

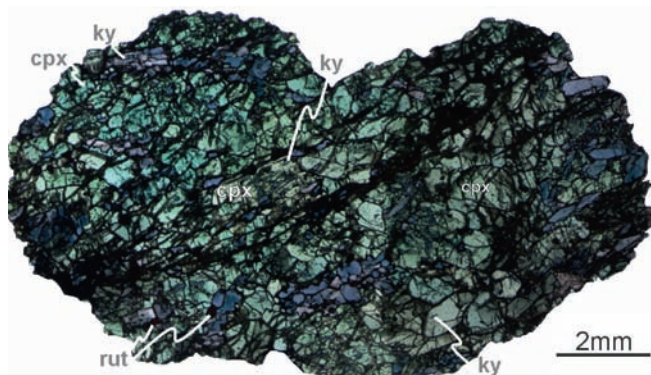


Fig. 2. Transmitted-light microphotograph of a 150 μm thick section of the Cr-rich kyanite-bearing clinopyroxenite. The local concentration of blue kyanite forms either aggregates or bands within the xenolith. cpx = clinopyroxene, ky = kyanite and rut = rutile.

polygonal crystals (<1–1 mm) locally concentrated to varying degrees, forming randomly distributed elongated aggregates. Kyanite is also found as inclusions into clinopyroxene and into coarser kyanite. Small (<1 mm) rutile grains occur as interstitial euhedral crystals or are included in clinopyroxene and kyanite. Clinopyroxene and kyanite crystals sometimes contain both kyanite and rutile inclusions together.

The textural features of this rock remind those of typical grosspydite xenoliths described in Siberia and South Africa. Indeed, grosspydites are poikiloblastic or porphyroblastic rocks that are often banded (alternation of garnet-clinopyroxene or garnet-kyanite bands) (*e.g.* Sobolev *et al.*, 1968; Lappin, 1978). Moreover, in Siberian grosspydites, bands made of Cr-rich minerals are observed in some xenoliths (Sobolev *et al.*, 1968). Few Mbuji-Mayi kyanite-bearing eclogites also have a banded texture, marked by the alternation of garnet-rich and clinopyroxene-rich layers, with sometimes also kyanite-rich layers (El Fadili & Demaiffe, 1999). In Mbuji-Mayi eclogites, the accessory phases are dominated by rutile and quartz, with subsidiary phlogopite and zoisite. In the kyanite-bearing variety, kyanite occurs in three different habits: as intergrowths with omphacitic clinopyroxene, as small laths cutting across garnet and omphacite and as poikilitic grains enclosing garnet, clinopyroxene and quartz. Granulites (plagioclase-diopside-garnet assemblages) also often contain similar kyanite-omphacite intergrowths (El Fadili & Demaiffe, 1999). Despite careful investigations by optical microscopy and SEM, no garnet was found in the Cr-rich kyanite-bearing clinopyroxenite from Mbuji-Mayi; this is at contrast with grosspydite and eclogite xenoliths from worldwide kimberlite pipes.

4. Mineral chemistry

Major element analyses on minerals have been undertaken on a 150 μm thick section with electron microprobes equipped with four wavelength dispersive spectrometers at the

CAMPARIS section (Cameca SX 100) of the University of Paris 6 (France) and at the CAMST (Cameca SX 50) of the University of Louvain-la-Neuve (Belgium). The operating conditions were the same in both laboratories, *i.e.* an accelerating voltage of 15 kV and a beam current of 10 nA. Counting times were fixed at 10 s for both peak and background intensity measurement. External calibration was made with a set of natural and synthetic silicates and oxides and reduction of raw data were processed following the PAP method (Pouchou & Pichoir, 1984).

Mineral compositions were determined in different areas of the rock in order to compare the composition of phases that occur under different habits (see above). Representative mineral compositions (clinopyroxene-kyanite-rutile) are given in Table 1.

4.1. Clinopyroxene

Clinopyroxenes from the Cr-rich clinopyroxenite of Mbuji-Mayi have quite low $\text{Mg}^\#$ ($100 \cdot \text{Mg}/(\text{Mg} + \text{Fe}) = 82.0\text{--}83.2$) and high $\text{Ca}^\#$ ($100 \cdot \text{Ca}/(\text{Ca} + \text{Mg}) = 52.6\text{--}54.7$) compared to mantle clinopyroxene megacrysts from the same locality (89.3–93.5 and 39.5–49.4, respectively; Pivin *et al.*, 2009). They are rich in Al_2O_3 (~ 10 wt%) and Na_2O (~ 7 wt%) and hence are omphacitic (Morimoto *et al.*, 1988) with the jadeite content varying between 40 and 45 mol%. Clinopyroxene is characterised by extremely high Cr_2O_3 content (3.34–5.70 wt%) that varies widely within and between the grains. Crystals are zoned with the core of grains being richer in Cr than the rim (*e.g.* from 5.70 to 3.89 wt% Cr_2O_3 , respectively). Moreover, the Cr content measured close to a kyanite inclusion is higher than elsewhere in the crystal (*e.g.* 5.70 vs. 4.27 wt%); the lowest chromium content was found in a grain devoid of inclusion. Cr^{3+} ions enter in the M1 site of the clinopyroxene, in substitution of Al^{3+} (the tetrahedral site is almost completely filled with Si). The charge excess created by the substitution of trivalent cations for divalent cations in the M1 site is compensated by Na^+ substituting for Ca^{2+} into the M2 site. The other constituent oxides do not vary a lot between the different crystals and $\text{Mg}^\#$ is not correlated with any other oxide.

Clinopyroxenes from Mbuji-Mayi eclogites and granulites are chemically homogeneous and Cr-poor, the highest Cr_2O_3 content (0.23 wt%) is measured in an omphacite from a bimineralic eclogite (El Fadili, 1998). The jadeite content of omphacites in the Cr-clinopyroxenite is higher than that of Mbuji-Mayi granulites and bimineralic eclogites, and less variable than that of the kyanite-bearing variety (Fig. 3a). $\text{Mg}^\#$ of omphacites in the studied sample are uniform (82.0–83.2) and close to those of granulites (81.7–83.0) but lower than those of kyanite eclogites (83.7–93.6) and bimineralic eclogites (87.5–93.7).

Similar compositional relationships are observed between omphacite in the clinopyroxenite and eclogites from Mbuji-Mayi and between omphacite in grosspydites and eclogites from Zagadochnaya. In Siberian grosspydites, emerald-green clinopyroxenes have up to 0.92 wt% Cr_2O_3 (Sobolev *et al.*, 1968). Omphacites from Siberian eclogites and grosspydites

Table 1. Representative major-element analyses of omphacite, kyanite and rutile of the Mbuji-Mayi Cr-rich kyanite-bearing clinopyroxenite.

	Omphacite					Kyanite					Rutile				
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
SiO ₂	55.81	55.38	55.41	55.87	55.65	36.65	36.49	36.32	36.45	35.77	35.87	35.69	0.07	0.10	0.11
TiO ₂	0.07	0.12	0.08	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	94.77	96.66	93.64
Al ₂ O ₃	10.80	10.15	9.78	10.07	9.87	58.94	55.49	55.84	55.82	53.49	52.25	52.12	0.38	0.09	1.30
Cr ₂ O ₃	3.34	4.27	5.70	4.55	4.94	4.45	7.80	6.76	7.57	9.82	11.21	11.79	4.48	2.68	4.37
FeO	2.92	2.83	2.57	2.69	2.91	0.33	0.20	0.31	0.38	0.36	0.37	0.49	0.00	0.18	0.18
MgO	7.47	7.68	7.13	7.37	7.24	—	—	—	—	—	—	—	—	—	—
CaO	12.31	12.65	11.97	12.09	11.72	—	—	—	—	—	—	0.09	—	0.45	0.05
Na ₂ O	7.23	7.11	7.35	7.26	7.50	—	—	—	—	—	—	—	—	—	—
Total	99.94	100.19	99.98	99.89	99.95	100.36	99.98	99.23	100.21	99.44	99.70	100.18	99.70	100.16	99.65

	Number of cations (apfu) calculated on the basis of														
	6 oxygen atoms and 4 cations					5 oxygen atoms and 3 cations					2 oxygen atoms and 1 cation				
Si	1.993	1.979	1.991	2.003	1.995	1.000	1.012	1.011	1.007	1.004	1.009	1.001	0.001	0.001	0.001
Al	0.455	0.427	0.414	0.425	0.416	1.896	1.813	1.833	1.818	1.770	1.733	1.723	0.006	0.001	0.020
Ti	0.002	0.003	0.002	0.000	0.003	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.946	0.961	0.930
Cr	0.094	0.120	0.162	0.129	0.140	0.096	0.171	0.149	0.165	0.218	0.249	0.262	0.047	0.028	0.046
Fe	0.087	0.084	0.077	0.080	0.087	0.007	0.005	0.007	0.009	0.008	0.009	0.011	0.000	0.002	0.002
Mg	0.397	0.409	0.382	0.394	0.387	—	—	—	—	—	—	—	—	—	—
Ca	0.471	0.484	0.461	0.464	0.450	—	—	—	—	—	—	0.003	—	0.006	0.001
Na	0.499	0.492	0.510	0.502	0.520	—	—	—	—	—	—	—	—	—	—
Mg [#]	82.0	82.9	83.2	83.0	81.6	—	—	—	—	—	—	—	—	—	—
Cr ₂ SiO ₅	—	—	—	—	—	4.8	8.6	7.5	8.3	11.0	12.6	13.2	—	—	—
Al ₂ SiO ₅	—	—	—	—	—	95.2	91.4	92.5	91.7	89.0	87.4	86.8	—	—	—

1. cpx devoid of inclusion; 2. cpx containing ky inclusions (far from inclusion); 3. (same as 2.) cpx containing ky inclusions (close to inclusion); 4. cpx containing ky and rut inclusions; 5. cpx containing ky inclusions; 6. ky included in ky also containing rut; 7. subhedral ky containing ky (6.) and rut; 8. ky included in cpx; 9. subhedral ky; 10. and 12. ky included in the same cpx; 11. ky included in a cpx also containing rut; 13. subhedral rut; 14. rut included in cpx also containing ky; 15. rut included in ky also containing ky. (1–5; FeO content calculated as Fe²⁺ cation; Mg[#] = Mg/(Mg + Fe); 6–12, the FeO content has been recalculated as Fe³⁺ cation).

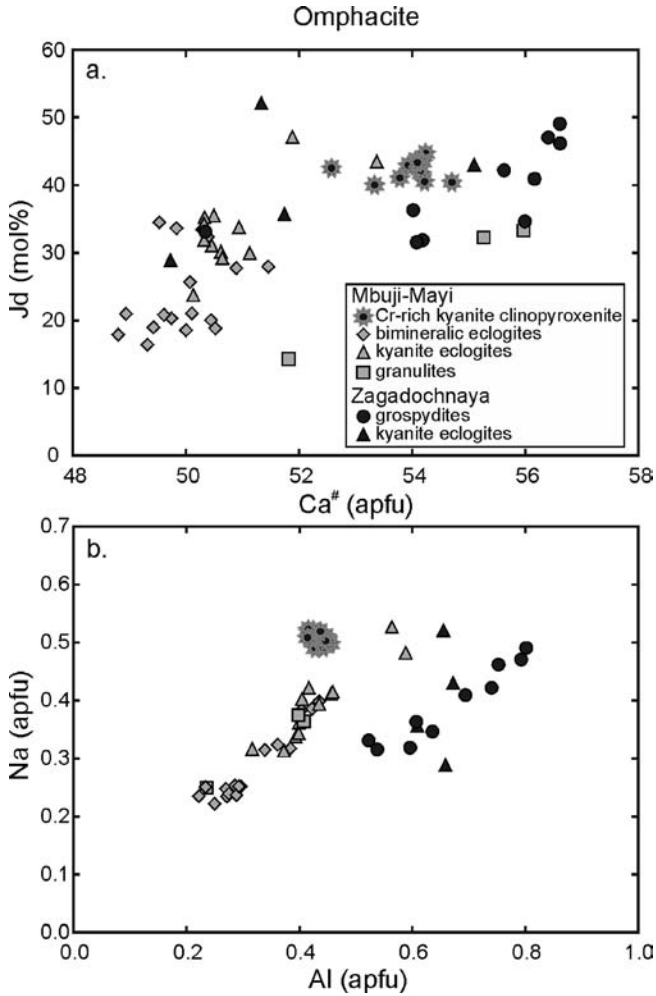


Fig. 3. Binary plots illustrating the omphacite compositions of the Mbuji-Mayi clinopyroxenite. Comparison with the Mbuji-Mayi bimineralec and kyanite eclogites and granulites (omphacite from kyanite-omphacite intergrowths) (data from El Fadili, 1998) and Siberian kyanite eclogites and grosphydites (data from Sobolev *et al.*, 1968). (a) Jd (mol%) vs. Ca# (apfu) ($Ca/(Ca + Mg)$) and (b) Na (apfu) vs. Al (apfu).

are richer in Al (and usually Na) than those of Mbuji-Mayi clinopyroxenite and eclogites (Fig. 3b). In Siberian grosphydites, clinopyroxenes are characterised by quite higher Ca# and usually also Na and Al contents than in Siberian eclogites (Fig. 3a, b), which is also the case for omphacites from the Mbuji-Mayi clinopyroxenite by comparison to those in the two types of eclogite from the same locality (Fig. 3a, b).

4.2. Kyanite

Kyanite crystals are particularly rich in Cr₂O₃ (4.45–11.81 wt%). They are strongly zoned, with Cr₂O₃ content varying from 11.81 wt% in the core to 6.25 wt% in the rim, for example. There is a good negative correlation between Cr and Al contents, showing that Cr substitutes for Al in the kyanite lattice. The lowest Cr concentration has been measured in a kyanite included in another, Cr-rich, kyanite whereas inclusions in omphacites are usually richer in Cr than aggregates of subhedral grains. Measured FeO

concentrations are low (0.20–0.49 wt%); assuming that all iron is ferric, Fe³⁺ is slightly positively correlated to Cr³⁺.

There is no compositional variation between the three different textural habits of kyanite in Mbuji-Mayi eclogites (intergrowths with omphacites, laths cutting across garnet and clinopyroxene or poikilitic grains), nor with the granulites (El Fadili & Demaiffe, 1999). Kyanite in the Cr-rich clinopyroxenite is significantly richer in Cr and also in Si compared to those of eclogite and granulite xenoliths (<0.25 wt% Cr₂O₃). The negative correlation between the sum of the trivalent cations (Al + Fe³⁺ + Cr) and Si evidences a compositional continuum between the kyanites in the clinopyroxenite and those from eclogites and granulites (Fig. 4a).

Such Cr-rich kyanite has only been described in grosphydites from Zagadochnaya. Sobolev *et al.* (1968) reported a Cr₂O₃ content of 12.86 wt% from kyanite included in violet garnet. Strong variations of chromium content, from 3.5 to 9 wt% Cr₂O₃, have also been estimated on the basis of differences in refractive indices in a single kyanite grain from another grosphydite. Delor & Leyreloup (1986) also reported

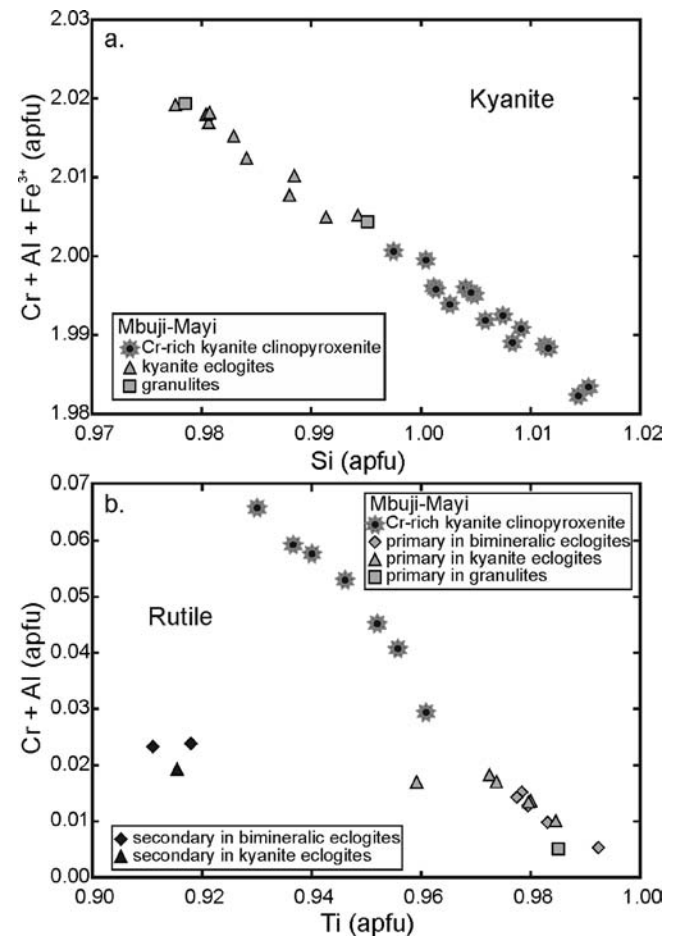


Fig. 4. (a) $(Cr + Al + Fe^{3+})$ (apfu) vs. Si (apfu) binary diagram comparing the kyanite compositions of the Mbuji-Mayi Cr-rich clinopyroxenite to those of Mbuji-Mayi kyanite eclogites and granulites (kyanite from kyanite-omphacite intergrowths). (b) $(Cr + Al)$ (apfu) vs. Ti (apfu) binary diagram comparing the rutile compositions of the Mbuji-Mayi Cr-rich clinopyroxenite to primary and metasomatic (secondary) rutile in Mbuji-Mayi bimineralec and kyanite eclogites and granulites (data from El Fadili, 1998).

high Cr₂O₃ content (up to 7 wt%) in zoned kyanite in eclogites (7.0 wt% to 1.1 wt% from core to rim) that occur as lenses in the Leptyno-amphibolitic Unit representing an old suture zone in Rouergue area, French Massif Central. Relatively Cr-rich kyanite (up to 4.35 wt% Cr₂O₃) has been reported in Al-rich, staurolite- and kyanite-bearing metamorphic ultramafic rocks that are associated to eclogites in Cabo Ortegal, NW Spain (Ibarguchi *et al.*, 1991). However, there is no omphacite in these rocks; the associated minerals are Ca-amphibole, zoisite and garnet.

4.3. Rutile

Rutile is also particularly rich in Cr₂O₃ (2.68–4.65 wt%). Rutile inclusions in clinopyroxene or kyanite are poorer in chromium than isolated idiomorphic grains. Abundances of other elements are low, except for Al₂O₃ (0.09–1.30 wt%); the highest concentration has been obtained from a rutile inclusion in kyanite. Similar Cr-rich rutile (up to 3.16 wt% Cr₂O₃) is also observed in MARID mantle xenoliths associated to kimberlites (Dawson & Smith, 1977) and in some Mbuji-Mayi rutile megacrysts (up to 4.85 wt% Cr₂O₃, Pivin *et al.*, unpublished data).

Rutile is also a characteristic accessory phase in Mbuji-Mayi eclogites (El Fadili, 1998): it can be of primary or metasomatic (= secondary) origin. These two types of rutile are distinguished by their Ti content (Fig. 4b), the metasomatic rutile is enriched in Nb₂O₅ (7–8 wt%). Nb has not been measured in the rutiles of the Cr-rich clinopyroxenite but the compositions of the analysed rutiles are close to 100% and the structural formulae are correct, suggesting that Nb₂O₅ is not abundant (<1 wt%). Primary rutile in the eclogites is almost a pure phase; it is characterised by low Cr₂O₃ (<0.6 wt%), MnO (<1 wt%) and Al₂O₃ (<1 wt%) contents. Al₂O₃ is slightly more abundant in the metasomatic rutile (1–1.3 wt%). Primary rutile from Mbuji-Mayi eclogites and rutile from the clinopyroxenite display a negative correlation between Ti and the sum of trivalent cations that is higher in the latter (Fig. 4b).

It is interesting to note that kyanite and rutile analysed in this single Cr-rich clinopyroxenite represent a compositional domain as large as those measured in many eclogites and granulites from Mbuji-Mayi (Fig. 4a, b).

5. Whole-rock chemistry

It was not possible to analyse the whole-rock composition of the Cr-rich clinopyroxenite because the xenolith was too small. The bulk composition has been estimated on the basis of the modal proportions of the different phases and their average compositions measured by electron microprobe. Because minerals are zoned with respect to Cr contents, the whole range of possible bulk composition has been evaluated by using the composition of the lowest and highest Cr content, respectively. This clinopyroxenite has a calculated SiO₂ content of 51.4 wt%, with high Al, Ca and Na but low Mg and Fe contents (Table 2). It does not match any mineral composition; consequently, the nodule cannot be interpreted as the breakdown product of a single

Table 2. Calculated whole rock major element composition of the Mbuji-Mayi Cr-rich kyanite-bearing clinopyroxenite.

	Calculated whole rock	
	Wt%	
		Mean
SiO ₂	51.16–51.62	51.44
TiO ₂	0.72–0.74	0.75
Al ₂ O ₃	18.02–20.19	18.95
Cr ₂ O ₃	3.55–6.88	5.26
FeO	2.12–2.4	2.30
MgO	5.71–5.98	5.93
CaO	9.51–9.77	9.58
Na ₂ O	5.74–5.83	5.83
Total	99.97–99.99	100.05

The compositional range has been determined using mineral compositions with the lowest and highest Cr contents respectively and the mean composition with all the available analyses.

crystal. Chromium content is obviously high (5.26 wt% Cr₂O₃), which is quite unusual for magmatic rocks in general, except for chromite-rich cumulates.

The clinopyroxenite is richer in Si and poorer in Mg than the Mbuji-Mayi eclogites (El Fadili, 1998) (Fig. 5). Its Ca content is however close to that of bimineraleclogites and its Al content in the range of values of the kyanite-bearing variety (Fig. 5). The kyanite eclogites, kyanite pyroxenite and grospsydites from Siberia (Sobolev *et al.*, 1968) are depleted in Si and Mg, and enriched in Al compared to Mbuji-Mayi eclogites; their Ca content is similar. The Siberian pyroxenite is chemically comparable to grospsydites. Siberian grospsydites are richer in Al and Si and lower in Mg than eclogites from the same locality (Fig. 5). Interestingly, the same chemical relationships are observed between the Mbuji-Mayi clinopyroxenite and eclogites.

Sobolev *et al.* (1968) linked the composition of grospsydites to Mg-rich, Si-undersaturated spinel-bearing anorthosites. Besides, on the basis of the relatively high Cr content of grospsydites (0.01–0.05 wt% Cr₂O₃), which is much lower than in the Mbuji-Mayi clinopyroxenite, they also suggested a link to ultramafic rocks. The Mbuji-Mayi Cr-rich kyanite clinopyroxenite is richer in Si and Cr and slightly poorer in Al than the Siberian grospsydites but the Ca and Mg contents are similar (Fig. 5). This whole-rock composition can tentatively be compared to a Cr-spinel-bearing anorthosite.

6. Geothermobarometric investigations

Because garnet is absent and because only two silicate mineral phases (clinopyroxene and kyanite) are present, none of the known cation-exchange thermometers or barometers is applicable to the Mbuji-Mayi Cr-rich kyanite clinopyroxenite. The stability field of the omphacite-kyanite assemblage has been determined over a *P-T* range of 10–50 kbar and 500–1500 °C, using the THERMOCALC software in the Na₂O-CaO-MgO-Al₂O₃-SiO₂ (NCMAS) system and considering jadeite-diopside-kyanite-pyrope-enstatite-anorthite-albite-spinel

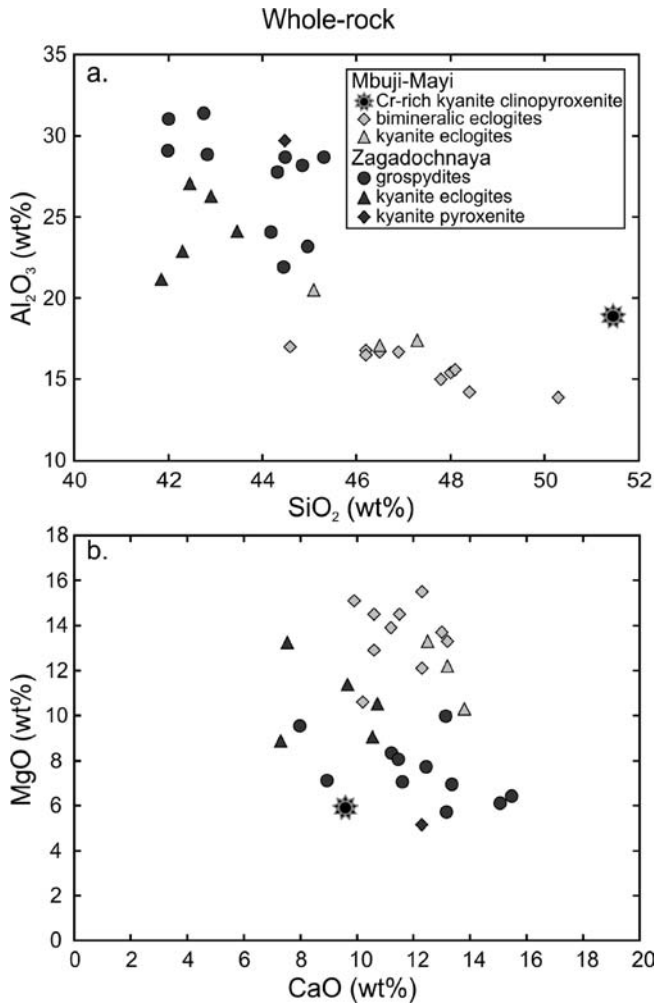


Fig. 5. Binary plots showing the whole-rock compositions of the Mbuji-Mayi clinopyroxenite and bimineralic and kyanite-bearing eclogites (data from El Fadili, 1998). Comparison with the Zagadochnaya kyanite eclogites, clinopyroxenite and grosspydites (data from Sobolev *et al.*, 1968): (a) Al₂O₃ vs. SiO₂ (wt%) and (b). MgO vs. CaO (wt%).

and quartz as the possible reacting minerals in high-pressure mafic rocks. The petrogenetic grid was constructed using the thermodynamic dataset 5.5 (Holland & Powell, 1998; November 2003 upgrade). The lower stability limit of the jadeite + kyanite assemblage increases from 10 kbar at 500 °C to 19 kbar at 895 °C (Fig. 6a); the temperature limit decreases then from 895 °C down to 795 °C for a pressure increase from 19 to 30 kbar. The thermodynamic dataset used in this study does not take into account Cr-bearing phases. However, Seifert & Langer (1970) have experimentally shown that the solubility of Cr₂SiO₅ in Al₂SiO₅ increases with pressure. The *P-T* conditions of their experiment are between 1000 and 1600 °C at 20–30 kbar, which is out of the temperature range of the stability field found for the omphacite + kyanite assemblage. Yet, Seifert & Langer (1970) have shown (under their experimental conditions) that the temperature has not a strong influence on the Cr solubility in kyanite.

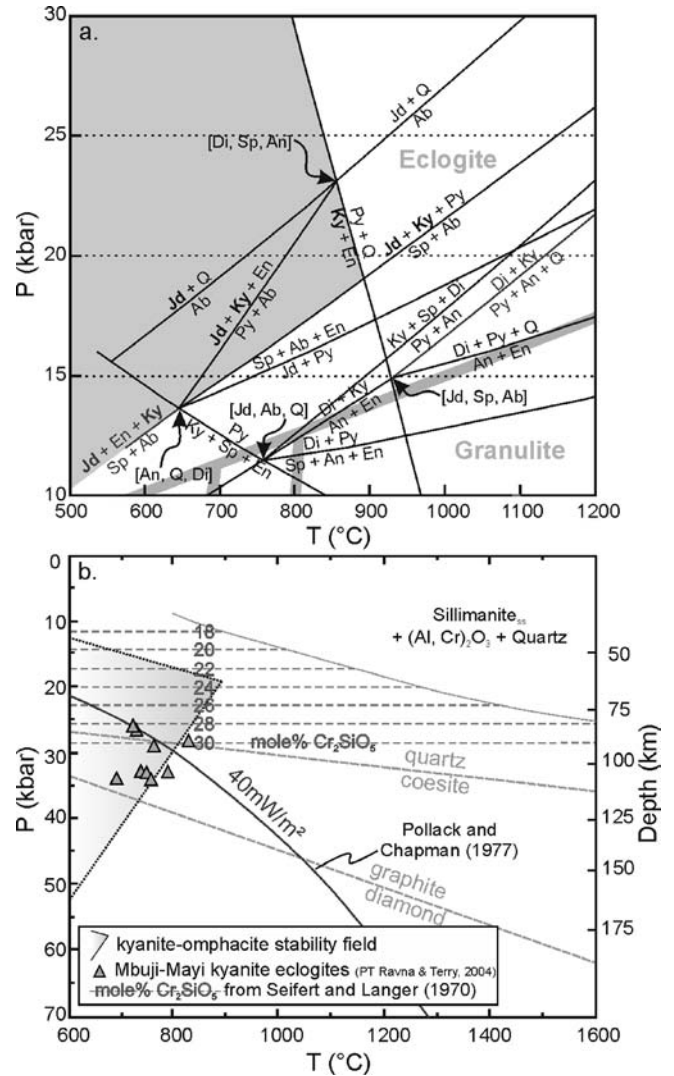


Fig. 6. (a) *P-T* grid showing the stability field of the assemblage Jd + Ky. Calculation with the THERMOCALC software in the Na₂O-CaO-MgO-Al₂O₃-SiO₂ (NCMAS) system, over a *P-T* range of 10–50 kbar and 500–1500 °C. Ab = albite, An = anorthite, Di = diopside, En = enstatite, Jd = jadeite, Ky = kyanite, Py = pyrope, Q = quartz, Sp = spinel. Eclogite and granulite facies metamorphic fields are also represented. (b). Pressure-Temperature diagram with recalculated (this work) equilibrium conditions (using Ravná & Terry, 2004) for the Mbuji-Mayi kyanite-bearing eclogites (data from El Fadili, 1998), the kyanite-omphacite stability field found in (a) and horizontal lines that indicate the minimum pressure required for the formation of kyanite_{ss} with a given Cr₂SiO₅ (mol%) content (Seifert & Langer, 1970). Graphite-diamond and quartz-coesite boundaries are from Kennedy & Kennedy (1976) and Bohlen & Boettcher (1982) respectively and the 40 mW/m² geotherm from Pollack & Chapman (1977).

All the available information to constrain the *P-T* equilibration conditions of the Cr-rich kyanite clinopyroxenite of Mbuji-Mayi is plotted on Fig. 6b:

- the kyanite-omphacite stability field (from Fig. 6a);
- the isobaric lines representing the maximum Cr₂SiO₅ content (mol%) of chromium kyanite for a given pressure (Seifert & Langer, 1970).

- the equilibration P - T conditions of the Mbuji-Mayi kyanite-bearing eclogites that have been recalculated from the data of El Fadili (1998) using the more recent GCPKS EXCEL spreadsheet of Ravna & Terry (2004). They are in the ranges 25–35 kbar and 700–850 °C.

The mole percentage of Cr_2SiO_5 in kyanite of the Mbuji-Mayi clinopyroxenite is comprised between 4.8 and 13.2. Considering 14 mol% Cr_2SiO_5 as the maximum content in this sample, Seifert & Langer's results would imply a minimum pressure of about 7 kbar (Fig. 6b) that is unrealistically low and completely outside their experimentation range (20–30 kbar). As already underlined by Ibaruchi *et al.* (1991), the chromium content of kyanites is not only dependent on pressure, but also simply on the Cr availability in the environment and on the coexisting phases. This last point is in fact of minor importance because kyanite is the mineral that has the greatest affinity for Cr in the Mbuji-Mayi clinopyroxenite. The variations in Cr content could then result from local Cr availability in the rock.

Though precise thermobarometric equilibration conditions cannot be determined on the basis of Cr miscibility experiments in kyanite, the available constraints support a high pressure origin for this xenolith. Moreover, the kyanite clinopyroxenite shares textural, mineralogical and chemical (Jd content and $\text{Mg}^\#$ of omphacites) characteristics with the Mbuji-Mayi eclogite nodules. It can be suggested that the kyanite clinopyroxenite equilibrated in the same P - T range as the kyanite eclogites; that is 25–35 kbar and 700–800 °C. This is compatible with the pressure estimations (20–30 kbar) made for Siberian grosspydite xenoliths (Sobolev *et al.*, 1968).

7. Discussion

The high chromium content (5.26 wt% Cr_2O_3) of the kyanite-bearing clinopyroxenite suggests that the protolith was Cr-rich, so that an ultramafic precursor could be foreseen. However, the relatively high silica (~51 wt% SiO_2) and low magnesium (5.93 wt% MgO) contents make it unlikely but suggest an Al- and Cr-rich mafic precursor. The textural and mineralogical features of the kyanite clinopyroxenite, though lacking garnet, remind those of eclogite and grosspydite xenoliths. Moreover, mineralogical (presence of omphacite) and geochemical (high Al_2O_3 and CaO contents) evidence suggests a probable linkage between the clinopyroxenite and Mbuji-Mayi eclogites, especially the kyanite-bearing variety.

7.1. Protolith mineralogy modelling

Estimate of the protolith primary mineral composition is problematic because it is not possible to know whether elements have been added or removed during the metamorphic transformation. However, we have tried to match the estimated whole-rock composition from Table 2 by using a mixture of pure compositions of different mineral phases (see supplementary data, freely available online as Supplementary Material linked to this article on the GSW website of the journal, [\[eurjmin.geoscienceworld.org/\]\(http://eurjmin.geoscienceworld.org/\)\). The phases used are those typically found in leucogabbros or anorthosites: plagioclase \(albite – anorthite\), clinopyroxene \(diopside – hedenbergite – aegirine – Ca-tschermak\), orthopyroxene \(ferrosilite – enstatite\), olivine \(fayalite – forsterite\), a Cr-bearing spinel \(spinel-hercynite-chromite-magnesiocromite\) and ilmenite as the Ti-bearing oxide. Cr-, Fe- and Ti-oxides could effectively be segregated in bands and/or layers in differentiated anorthosite complexes, more particularly in Archean anorthosites \(Ashwal, 1993\). Amphibole is not considered as a primary phase because of the complexity of its composition and the bias it could induce in the calculation.](http://</p>
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A realistic modal composition has been obtained for the protolith: plagioclase An_{27} + diopside + magnesiocromite + ilmenite, in volume proportions 61: 27: 10: 1.5. Forsterite composes the minor ~0.5 vol% left and no orthopyroxene is present. This composition corresponds to a Cr-spinel- and ilmenite-bearing leucogabbro. In an ACFM ternary plot (Fig. 7), it falls in the Archean Fiskenaesset Cr-bearing anorthosite field, close to leucogabbros.

Nevertheless few points deserve discussion:

- (1) The calculated clinopyroxene is Fe-poor ($\text{Mg}^\# = 86.4$) by comparison to those found in anorthosites (64.6–80.3; Owens & Dymek, 1997). Its Na content is also elevated (0.12 vs. 0.04–0.05 apfu). Overall, this composition is quite comparable to those of clinopyroxenes of the Kasai-Lomami leuconorites ($\text{Mg}^\#$: 81.5 and 0.06 apfu Na; Bingen *et al.*, 1984).
- (2) The magnesiocromite is Cr- and Mg-rich and relatively Fe- and Al-poor compared to Archean chromites associated to anorthosites (*e.g.* Rollinson *et al.*, 2002) that have lower $\text{Cr}^\#$ ($100 \cdot \text{Cr}/(\text{Cr} + \text{Al}) = 18\text{--}35$ vs. 62) and higher $\text{Fe}^\#$ ($100 \cdot \text{Fe}^{2+}/(\text{Fe}^{2+} + \text{Mg}) = 48\text{--}73$ vs. 14).

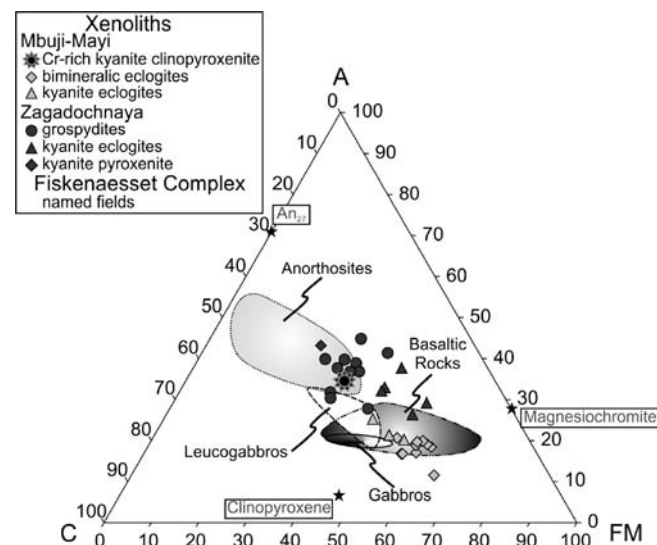


Fig. 7. Eskola-type ACFM projection comparing the whole-rock composition of the Mbuji-Mayi clinopyroxenite to the Mbuji-Mayi and Zagadochnaya eclogite and grosspydite xenoliths (see caption of Fig. 5) and to the different rock types (anorthosites, gabbros, leucogabbros and basaltic rocks) of the Archean Fiskenaesset anorthosite complex, SW Greenland (data from Polat *et al.*, 2009). The mineral compositions obtained by modelling (see text) are represented by stars.

- (3) The calculated plagioclase composition (An_{27}) is too sodic when compared to typical Archean anorthosite plagioclase (An_{75-90} ; Ashwal, 1993) but it is closer to plagioclases in the Archean Kasai-Lomami gabbro-norites (An_{40-60} ; Bingen *et al.*, 1984). Its Na-rich composition could be explained by the highly mobile character of Na during eclogitic metamorphism. Na could have been added to the protolith by channelled fluids (John *et al.*, 2008), either during late- to post-magmatic transformation of the magmatic precursor or during the eclogitic metamorphism. Metamorphic recrystallisation of anorthosites might also induce changes in the Na content of the plagioclase: formation of metamorphic amphibole lowers it, while retrograde epidote recrystallisation raises it (Owens & Dymek, 1997). On the other hand, if primary Ca-amphibole (hornblende) was present in the protolith, it could also trap a significant part of the whole-rock Na_2O budget and consequently rise the An content of the calculated plagioclase and lower the Na content of the clinopyroxene.

The estimated protolith modal mineralogical composition (see Supplementary Material) is probably not perfect. Several parameters (*e.g.* transport of element before metamorphism; true primary mineral compositions, including the potential presence of magmatic amphibole; possible complex-multi-phase metamorphic history) could have modified this composition but we feel that it is reasonable to suggest a Cr-spinel- and ilmenite-bearing leucogabbroic protolith.

7.2. Relationship to grospsydite xenoliths

At Roberts Victor, grospsydites grade into kyanite eclogites that themselves grade into bimineralic eclogites over centimetres and display complex layering and cryptic mineral variations (Lappin, 1978). Besides, a close connection between the Ca content of the garnet and the Na content of the coexisting clinopyroxene has been observed. An increase of the chemical potential of Na stabilises the assemblage kyanite-clinopyroxene over associations containing garnet of intermediate composition (50 mol% grossular; Sobolev *et al.*, 1968). The high Na_2O content of omphacite in the studied sample (7.17–7.59 wt%; Fig. 4b) could probably explain the lack of garnet. Moreover, even if there is no general agreement about the grospsydite petrogenesis, the possible late origin of the garnet with respect to early omphacite and kyanite association has been envisaged by some authors (*e.g.* Sobolev *et al.*, 1968; Lappin, 1978).

The calculated whole-rock composition of the Cr-rich clinopyroxenite from Mbuji-Mayi is quite similar to those of grospsydite xenoliths and to Archean anorthosite complexes (Fig. 7), suggesting a possible relationship. The possibility that grospsydites might actually represent originally anorthositic material, similar to Archean anorthosites, has been previously considered by Sobolev *et al.* (1968) and Ashwal (1993). Furthermore, the latter also reminded the possible oceanic affinity inferred for Archean anorthosite complexes and proposed that it

could explain the Ca-rich nature of the grospsydites and the presence of Cr-rich bands in these xenoliths.

7.3. Relationship to Mbuji-Mayi eclogite and granulite xenoliths

The high Al, Ca and Na contents of the clinopyroxenite (Table 2) require a plagioclase-rich mafic protolith. At Mbuji-Mayi, El Fadili & Demaiffe (1999) proposed that the bimineralic and kyanite eclogites share the same metamorphic evolution and that both eclogite types are close to granulites in terms of geochemical composition and metamorphic evolution. They suggested that the kyanite-bearing granulite and eclogite xenoliths are deep crustal/uppermost mantle equivalents of metamorphosed gabbro-norites and anorthosites that constitute the northern part of the Archean Kasai-Lomami mafic complex. The prolonged cooling, at depth, of the various mafic rocks could give rise to the range of observed eclogite nodules, from bimineralic eclogites (gabbro-noritic protoliths) to kyanite eclogites (gabbroic anorthosite or anorthosite protoliths).

In the Kasai-Lomami Complex, coarse-grained anorthosites are composed of 90 % of Ca-rich plagioclase (An_{70-85}), olivine or orthopyroxene and amphibole and spinel accessory phases (Bingen *et al.*, 1984). The coarse-grained nature and Ca-rich character of anorthosites is a common feature for Archean anorthosite complexes (An_{75-90} ; Ashwal, 1993). Though gabbros, gabbro-norites, anorthosites and leuconorites of the Kasai complex have been subject to few geochronological studies (*e.g.* Delhal *et al.*, 1976, 1986) and a mineralogical study (Bingen *et al.*, 1984), their origin and possible linkage to other worldwide Archean anorthosite complexes have not been discussed.

7.4. Possible linkage to Archean anorthosite complexes

Whole-rock compositions of the various Mbuji-Mayi xenoliths (bimineralic and kyanite-bearing eclogites from El Fadili & Demaiffe (1999); Cr-rich kyanite clinopyroxenite, this study) have been plotted on an AFM ternary plot (Fig. 8) and compared, on the one hand, to the Zagadochnaya xenoliths (Sobolev *et al.*, 1968) and, on the other hand, to various mafic lithologies from the Kasai-Lomami Complex (data from Bingen *et al.*, 1984) and from the Archean Fiskenaasset anorthosite complex (fields from data of Polat *et al.*, 2009). While Mbuji-Mayi eclogites are compositionally more comparable to mafic rocks (basaltic rocks, gabbros and leucogabbros from Fiskenaasset and gabbro-norites from Mbuji-Mayi), the Cr-rich kyanite clinopyroxenite of Mbuji-Mayi is closer to the wide anorthosite field from Fiskenaasset that also encloses the Kasai-Lomami anorthosites and leuconorites. The Cr-rich kyanite-clinopyroxenite is however significantly poorer in Fe than the plotted anorthosites. Nevertheless, when Cr_2O_3 content is added to the total FeO content in this AFM plot (as, in chromites, Cr^{3+} ions replace the Fe^{3+} ions of the magnetite), the Cr-rich kyanite clinopyroxenite shifts towards the F apex ($FeO + Cr_2O_3$) of the AFM diagram (as represented by the arrow)

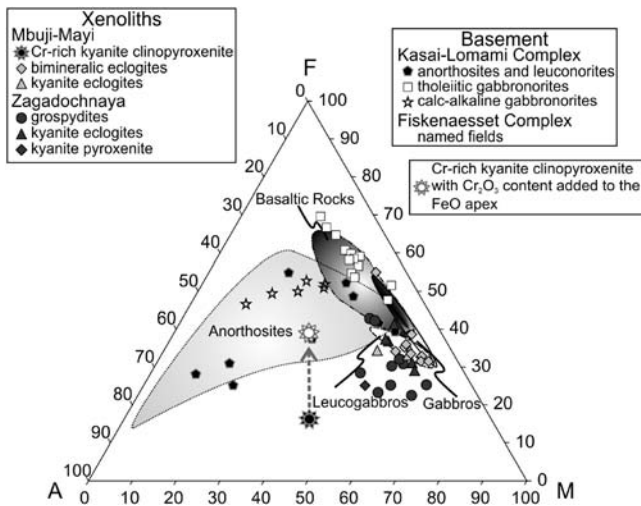


Fig. 8. AFM ($A = \text{Na}_2\text{O} + \text{K}_2\text{O}$; $F = \text{FeO}$; $M = \text{MgO}$, wt%) ternary plot comparing the whole-rock composition of the Mbuji-Mayi clinopyroxenite to the Mbuji-Mayi and Zagadochnaya eclogite and grospsydite xenoliths (see caption of Fig. 5) and to the different rock types (anorthosites, gabbros, leucogabbros and basaltic rocks) of the Archean Fiskenaeset anorthosite complex, SW Greenland (data from Polat *et al.*, 2009). Data of anorthosites, leuconorites and gabbro-norites from the Kasai-Lomami Complex are taken from Bingen *et al.* (1984; their Fig. 2). The arrow links the composition of the Cr-rich kyanite clinopyroxenite in the AFM plot to its position in the same ternary plot in which the Cr_2O_3 content is added to the FeO content.

and plots in the anorthosite field, while the other rocks do not shift (their Cr content is negligible).

In Archean anorthosite complexes, segregations of Fe-Ti-rich minerals (ilmenite, magnetite) are common but some complexes (*e.g.* Fiskenaeset, SW Greenland and Sittampundi, S India; Ashwal, 1993) are also characterised by chromitite horizons. In Fiskenaeset, chromitite-rich layers that are several tens of centimetres to several metres thick (up to 20 m) occur in anorthosites and leucogabbros (Polat *et al.*, 2009). The chromitite bands that are made of 60–80 vol% chromite and subordinate quantities of hornblende, biotite, rutile, magnetite and ilmenite (Ashwal, 1993) are thought to be of magmatic origin (Polat *et al.*, 2009). In other layered mafic complexes (*e.g.* Rum, Scotland), thin (few mm) chromitite-rich layers occur in anorthosite cumulates (Emeleus, 1997). Similar chromitite horizons might be present in the Kasai anorthosites. In this area (which has not been studied since Bingen *et al.*, 1984), anorthosites are only present in subordinate quantities, interlayered with gabbro-norites. An anorthositic protolith with localised Cr-spinel segregations can be a close magmatic equivalent to the Cr-rich kyanite clinopyroxenite of Mbuji-Mayi.

7.5. Proposed geodynamic scenarios

Geochemical investigations clearly demonstrate that the precursor of the kyanite clinopyroxenite was a plagioclase-rich mafic rock close to those found in the Archean anorthositic massifs or mafic layered intrusions. These can be emplaced either in the Archean oceanic crust or in the deep continental crust (see Ashwal, 1993).

Three mechanisms could explain the origin of the kyanite clinopyroxenite nodule and the related eclogites at Mbuji-Mayi: (1) subduction of Archean oceanic crust (altered or not); (2) magmatic underplating of precursor magma in the lowermost cratonic crust followed by delamination into the upper mantle and (3) crystallisation of the precursor magma, at depths corresponding to a pressure range of 25–35 kbar and subsequent cooling and recrystallisation of the deep mafic rocks into eclogites and related rocks.

The last mechanism can however be rejected because (1) plagioclase does not crystallise at that pressure and would be replaced by garnet (Green & Ringwood, 1967) and (2) the constituent phases of the kyanite-bearing eclogites are not in equilibrium with upper mantle peridotites (kyanite would react with olivine to form garnet and pyroxene, Jacob *et al.*, 1998) and should be of crustal origin.

The subduction hypothesis is questionable since there is no direct evidence for a subduction event during the Archean in the Congo craton even though the origin of TTG series is generally explained by melting of subducted mafic crust (see Martin *et al.*, 2005). Indeed, though not in the Mbuji-Mayi area, subduction-related 2.9 Ga TTG series have been evidenced in the Ntem Complex (Cameroon) of the NW Congo craton (Shang *et al.*, 2004).

Eclogites might form from underplating of precursor magma followed by cooling towards eclogite-facies conditions (Pearson & O'Reilly, 1991; Pearson *et al.*, 1991; El Fadili & Demaiffe, 1999). The estimated thickness of the crust below Mbuji-Mayi (30–35 km, Pasyanos & Nyblade, 2007) is however not sufficient to explain the equilibration pressure of the clinopyroxenite and eclogites (25–35 kbar). Nevertheless, mafic lithologies transformed into granulites and/or eclogites in the lowermost crust of cratons may be denser than upper mantle peridotites and delaminate into the mantle towards higher pressures (Kay & Kay, 1993; Anderson, 2005; Gao *et al.*, 2008), resulting in the thin crust observed at present.

8. Conclusions

A unique kyanite-bearing clinopyroxenite xenolith, composed of Cr-rich omphacite, kyanite and rutile, has been found in the Cretaceous Mbuji-Mayi kimberlite province (DRC) whose xenolith population is dominated by eclogite nodules. The very high Cr content of kyanite (4.45–11.81 wt% Cr_2O_3) makes this rock exceptional. Indeed such Cr-rich kyanite has only been described from grospsydite xenoliths from the Zagadochnaya kimberlite (Yakutia). Few other occurrences of relatively Cr-rich kyanites have been reported from different geological environments; they are always associated to eclogites.

Although lacking garnet, the Mbuji-Mayi Cr-rich kyanite clinopyroxenite shares many similarities with grospsydite xenoliths. The chemical variations observed between eclogites and grospsydites in Siberia (either considering whole-rock or clinopyroxene compositions) are also observed between eclogites and the Cr-rich clinopyroxenite in Mbuji-Mayi. As the origins of grospsydite and eclogite xenoliths are

closely related, the origin of the clinopyroxenite is most probably also linked to that of eclogites (and granulites) from Mbuji-Mayi. Moreover, the estimated *P-T* equilibration conditions (25–35 kbar, 700–850 °C) of this rock, although difficult to determine precisely, are probably in the same range as those of eclogites. The absence of garnet in the Cr-rich kyanite clinopyroxenite can be explained either by the high Na₂O content (7.11–7.59 wt%) of omphacite that favours the stability of the observed assemblage at the expense of garnet of intermediate composition (50 mol% grossular) or by the fact that garnet formation is sometimes considered to be late compared to the early formation of kyanite and omphacite in grosspydites.

The calculated whole-rock composition of the Cr-rich clinopyroxenite suggests an Al-, Ca- and Cr-rich protolith that could have been a Cr-spinel- (or chromite-) bearing leucogabbro or an anorthosite with interlayered chromite horizons. In the geological environment of the Mbuji-Mayi kimberlite province, the Kasai-Lomami mafic complex that is composed of various gabbro-norites and anorthosites crops out 100 km to the S-SE of Mbuji-Mayi. The An-rich character and coarse-grained texture of the plagioclase from the anorthosites suggest a possible link to Archean anorthosite complexes that sometimes contain interlayered chromite bands, which might have been overlooked during fieldwork in the 60–70's. It appears that the Cr-rich kyanite clinopyroxenite xenolith and the abundant and various eclogite xenoliths of the Mbuji-Mayi kimberlites could be related. The origin of the Cr-rich kyanite clinopyroxenite could either be related to a subduction event affecting Archean gabbro-norites and anorthosites equivalents to the mafic Kasai-Lomami Complex, or to magmatic underplating of mafic precursor magma in the lowermost crust and subsequent delamination into the mantle.

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