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AN ILMENITE–GARNET–CLINOPYROXENE NODULE FROM MATSOKU: EVIDENCE FOR OXIDE-RICH LIQUID IMMISCIBILITY IN KIMBERLITES?

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ABSTRACT

An unusual nodule from the Matsoku kimberlite pipe, Lesotho, consists of 50% ilmenite, 40% garnet, 5% rutile, 3% aegirine–augite, 1% apatite, and 1% biotite. The polygonal granular to sideronitic texture of the nodule suggests that ilmenite was the last phase to crystallize, and that it may have been an interstitial liquid. Geothermobarometry calculations yield equilibration temperatures of 700–800°C and pressures within the crust. The mineralogy, texture, and composition suggest that it may represent the product of an Fe–Ti oxide-rich immiscibility (ORLI) in a kimberlitic magma during its ascent toward the surface. If ORLI occurs as a process in kimberlites, then the kimberlite compositional paradox of high *mg*-numbers and high concentrations of *LIL* elements can be partly resolved.

Keywords: Matsoku, kimberlite, liquid immiscibility, ilmenite, garnet, clinopyroxene, rutile, geothermometry, geobarometry, nodule, xenolith, Lesotho.

SOMMAIRE

Un nodule étrange découvert dans la pipe kimberlitique de Matsoku, au Lesotho, contient ilménite (50%), grenat (40%), rutile (5%), augite aegyrinique (3%), apatite (1%) et biotite (1%). Sa texture polygonale granulaire à sidéronitique fait penser que l'ilménite a cristallisé en dernier, et possiblement d'un liquide interstitiel de composition semblable. Les calculs géothermobarométriques donnent une température d'équilibrage de 700–800°C et une pression crustale. La minéralogie, la texture et la composition chimique concordent avec l'hypothèse qu'il s'agit d'une manifestation d'immiscibilité d'un liquide à base d'oxydes de Fe et Ti dans un magma kimberlitique pendant sa montée vers la surface. Si un tel processus s'avère important dans les kimberlites, il pourrait expliquer, en partie du moins, le paradoxe d'un rapport Mg/(Mg + Fe) élevé et d'un enrichissement dans les ions lithophiles dans les kimberlites.

(Traduite par la Rédaction)

Mots-clés: Matsoku, kimberlite, immiscibilité liquide, ilménite, grenat, clinopyroxène, rutile, géothermométrie, géobarométrie, nodule, xénolithe, Lesotho.

INTRODUCTION

Nodules in kimberlites

Kimberlites are renowned for their abundant nodules, most of which have mineral assemblages, compositions, and textures characteristic of either the upper mantle or the continental crust. These inclusions, acquired by kimberlite magmas during explosive ascent, are true xenoliths genetically unrelated to their kimberlite host. Most nodules in kimberlite are probably of accidental origin; however, some eclogites and members of the discrete nodule suite (individual crystals or essentially monomineralic aggregates of chrome diopside, pyrope-rich garnet, or ilmenite) may be genetically related to the kimberlite magma as products of fractional crystallization (Moore 1987). Dawson (1980, p. 213) stated that "fractionation of garnet and pyroxene (together with olivine, ilmenite and ?phlogopite) is believed to be instrumental in the formation of kimberlite", but proof of a cognate origin for any nodule in kimberlite is always problematic.

Ilmenite in kimberlite

Ilmenite is a common constituent of kimberlite, but what is the connection between them? Pasteris *et al.* (1979, p. 265) stated that the "relationship between kimberlite and the abundant ilmenite nodules . . . needs clarification in order to better understand the origin of kimberlite magma." Ilmenite in kimberlite has a very wide range of chemical composition (especially in terms of Mg/Fe and Cr), and it occurs in many modes: as large discrete grains or polycrystalline aggregates, as apparent groundmass grains mantled by other oxide phases or perovskite (or both), as lamellar intergrowths with silicates, as inclusions in diamonds, as veins in xenoliths, and as lamellae in magnetite and rutile. Such wide variation, even within a single kimberlite pipe, demands several types of origin, including fractional crystallization to produce cumulates that are disrupted during ascent of the kimberlite (Mitchell 1973), mantle metasomatism for some of the veins (Dawson & Smith 1977), exsolution or oxidation (or both) for the intergrowths with other oxides (Haggerty 1975), thermal breakdown of armalcolite (Haggerty 1975), and even liquid immiscibility for some ilmenite–phlogopite and ilmenite–sulfide intergrowths (Pasteris 1980, Haggerty & Tomkins 1983). In short, the association of ilmenite in kimberlite is too common to be accidental, and many genetic relationships have been proposed.

In this paper we show that an unusual ilmenite-rich nodule from Matsoku, in Lesotho, is different from most other known nodules, that its mineralogy and texture suggest an immiscible relationship to a silicate magma, and that the consequences of such an immiscible relationship may be important in kimberlite petrogenesis. Our purpose is to generate a discussion upon which others may be able to test the case for liquid immiscibility in other kimberlites.

The Matsoku kimberlite pipe

The Matsoku kimberlite pipe is a small, elliptical (90 × 35 m) diatreme located in the northern part of Lesotho (29°05′S, 24°44′E). The pipe intrudes the Stormberg sediments belonging to the Karoo System (Dempster & Richard 1973) and the overlying Drakensberg tholeiitic volcanic suite of Jurassic age. Abundant peridotite xenoliths characterize this diatreme (Cox *et al.* 1973); however, among the nodules, one sample (Nodule 2612), measuring roughly 5 cm on each side and weighing 208 g, consists of grey-brown-weathering material, red garnet, and vitreous black ilmenite. This nodule was found loose within the outcrop area of the diatreme. Evidence of its association with the kimberlite is the occurrence of small veinlets of chlorite, serpentine, and carbonate that traverse all mineral phases of the nodule.

DESCRIPTION OF NODULE 2612

Mineralogy and texture

The average modal composition of Nodule 2612 is 50% ilmenite, 40% garnet, 5% rutile, 3% aegirine–augite, 1% apatite, and 1% biotite, but the

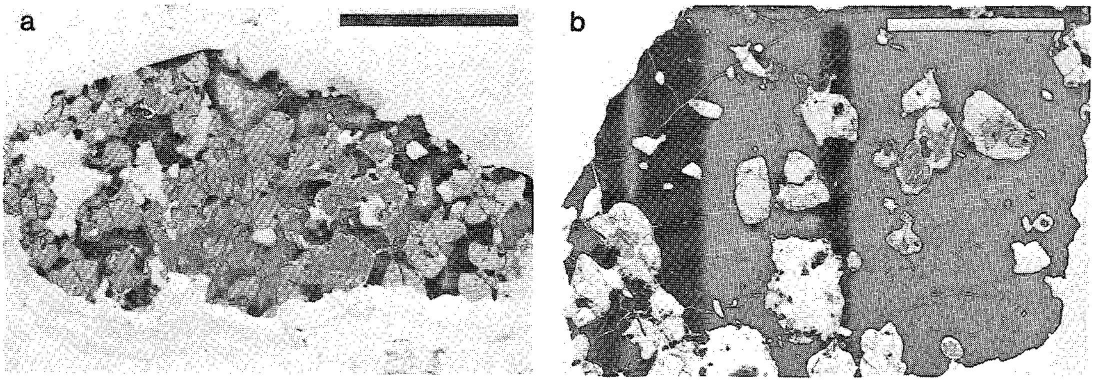

FIG. 1. Macrophotographs of Nodule 2612 showing the variation in modal mineralogy and texture in the sample. (a) Garnet-rich part of the nodule, in which ilmenite is interstitial. (b) Ilmenite-rich part of the nodule in which the roughly spherical garnet crystals with cores of darker clinopyroxene 'float' in a matrix of ilmenite. Scale bars are 1 cm.

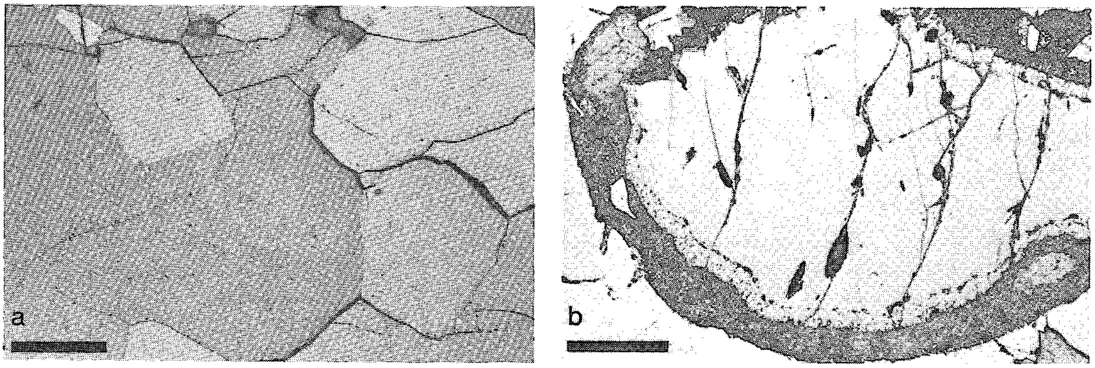

FIG. 2. Reflected-light photomicrographs. (a) Ilmenite-rich part of the nodule showing the textural relationships between the oxide minerals. Ilmenite appears as shades of grey; rutile grains are white. (b) An inclusion of kelyphitic garnet (dark rim) and clinopyroxene (light center) with a symplectitic outer zone. Scale bars are 0.2 mm.

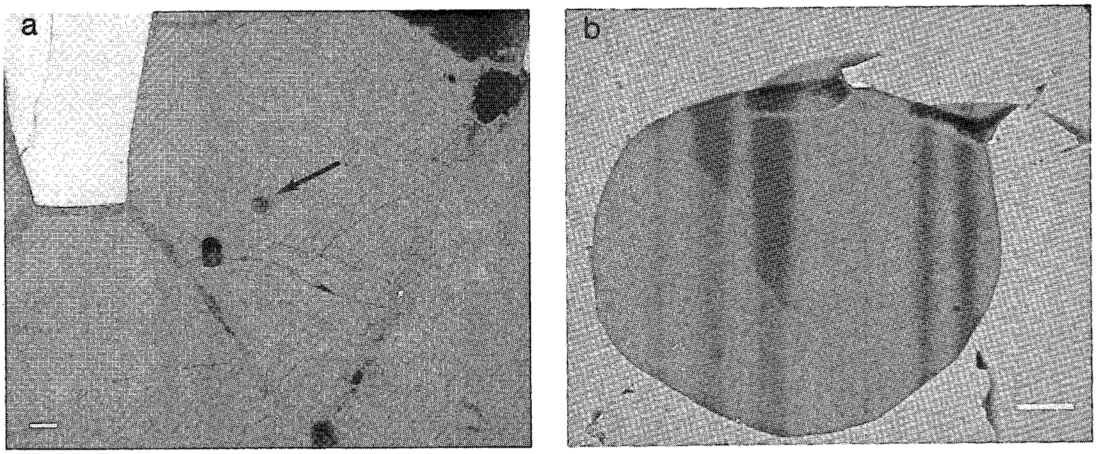

FIG. 3. The single feldspar inclusion in garnet. (a) Back-scattered electron image showing the feldspar inclusion (arrow) and three garnet grains in 120° contact with rutile. (b) Enlarged back-scattered electron image of the feldspar inclusion showing potassic feldspar (left) and sodic feldspar (right). Scale bars correspond to 100 (a) and 10 μm (b).

modal proportions of ilmenite and garnet within the nodule are highly variable (Fig. 1). In addition, traces of a talc-like mineral are associated with the biotite, and one small inclusion of feldspar occurs in garnet.

The texture of Nodule 2612 is medium grained, xenomorphic granular to sideronitic (Moorhouse 1959), in which the silicate phases are partly to entirely enclosed in a matrix of coarse granular ilmenite and minor rutile (Fig. 1). Most silicate phases have a thin reaction rim and pervasive cracks filled with very fine-grained secondary minerals.

Features of the individual minerals are as follows:

Ilmenite: The ilmenite grains are large (1–10 mm), polygonal, with prominent 120° triple junctions and reaction (alteration?) rims between them and the silicate minerals. Ilmenite encloses round grains of garnet, apatite, rare clinopyroxene, and angular grains of rutile (Fig. 2a).

Rutile: Discrete grains of rutile up to 2 mm in length are subhedral in shape, are reddish brown in plane polarized light, and contain regularly arranged inclusions of ilmenite parallel to (110). Minor amounts of rutile also occur as fine needles in garnet and clinopyroxene.

Garnet: Garnet grains average 4 mm in diameter, are subhedral in shape, and are pink in plane-polarized light. They commonly occur as clusters, but also occur as individual grains included in the ilmenite. Round apatite, ilmenite, clinopyroxene, and acicular rutile in a regular pattern are found as inclusions in the garnet.

Clinopyroxene: The clinopyroxene grains are up to 5 mm in diameter, anhedral to round in shape, and light green and nonpleochroic in plane-polarized light. Most grains occur as inclusions in garnet, and each grain is surrounded by a narrow symplectitic reaction rim (Fig. 2b). Many clinopyroxene grains contain small acicular or bladed inclusions of ilmenite and rutile.

Apatite: All the apatite grains are small (<0.1 mm), almost invariably anhedral, round grains occurring mainly as inclusions in ilmenite and garnet. Some discrete grains of apatite occur along the boundaries between ilmenite and garnet.

Biotite: Biotite grains are normally small (<1 mm) and show normal pleochroism. They occupy small cavities in contact with ilmenite, are associated with

TABLE 1. AVERAGE COMPOSITIONS OF MINERALS IN NODULE 2612

	Ilm	Rt	Grt	Cpx	Bt	Pl	Kfs
SiO_2			38.37	51.42	37.78	65.48	64.57
TiO_2	41.48	99.64	0.06	0.47	5.49		
Al_2O_3	0.32	0.22	20.54	5.36	12.85	21.25	19.33
Cr_2O_3	0.14	0.05	0.04	0.08			
Fe_2O_3	22.40					0.53	0.59
FeO	34.69	0.70	27.20	10.13	14.32		
MnO	0.07	0.03	0.34	0.06			
MgO	1.60	0.01	7.21	10.26	14.92		
CaO			6.33	17.89		1.87	0.10
Na_2O				3.49	0.31	9.81	3.76
K_2O				0.05	9.49	1.29	10.97
BaO							1.08
Total	100.70	100.64	100.09	99.21	95.16	100.23	100.40
Formulae							
Si			2.974	1.905	5.650	2.887	2.947
^{iv}Al			0.026	0.095	2.265	1.104	1.042
^{vi}Al	0.009	0.003	1.850	0.139			
Cr	0.003	0.001	0.002	0.002			
Fe^{3+}	0.422		0.166	0.181		0.018	0.022
Fe^{2+}	0.726	0.008	1.597	0.132	1.791		
Ti	0.781	0.993	0.003	0.013	0.617		
Mn	0.001		0.022	0.002			
Mg	0.060		0.833	0.566	3.325		
Ca			0.526	0.710		0.088	0.005
Na				0.251	0.090	0.838	0.334
K				0.002	1.812	0.073	0.636
Ba							0.019
O	3.000	2.000	12.000	6.000	22.000	8.000	8.000
Σcations	2.002	1.005	7.999	3.998	15.550	5.008	5.005

Analyses of minerals by Cambridge Microscan V and JEOL 733 electron microprobes operating at 15 kV and 5 nA using natural minerals as standards. Calculated ferric iron contents satisfy a stoichiometric balance between cations and oxygen. Mineral abbreviations after Kretz (1983).

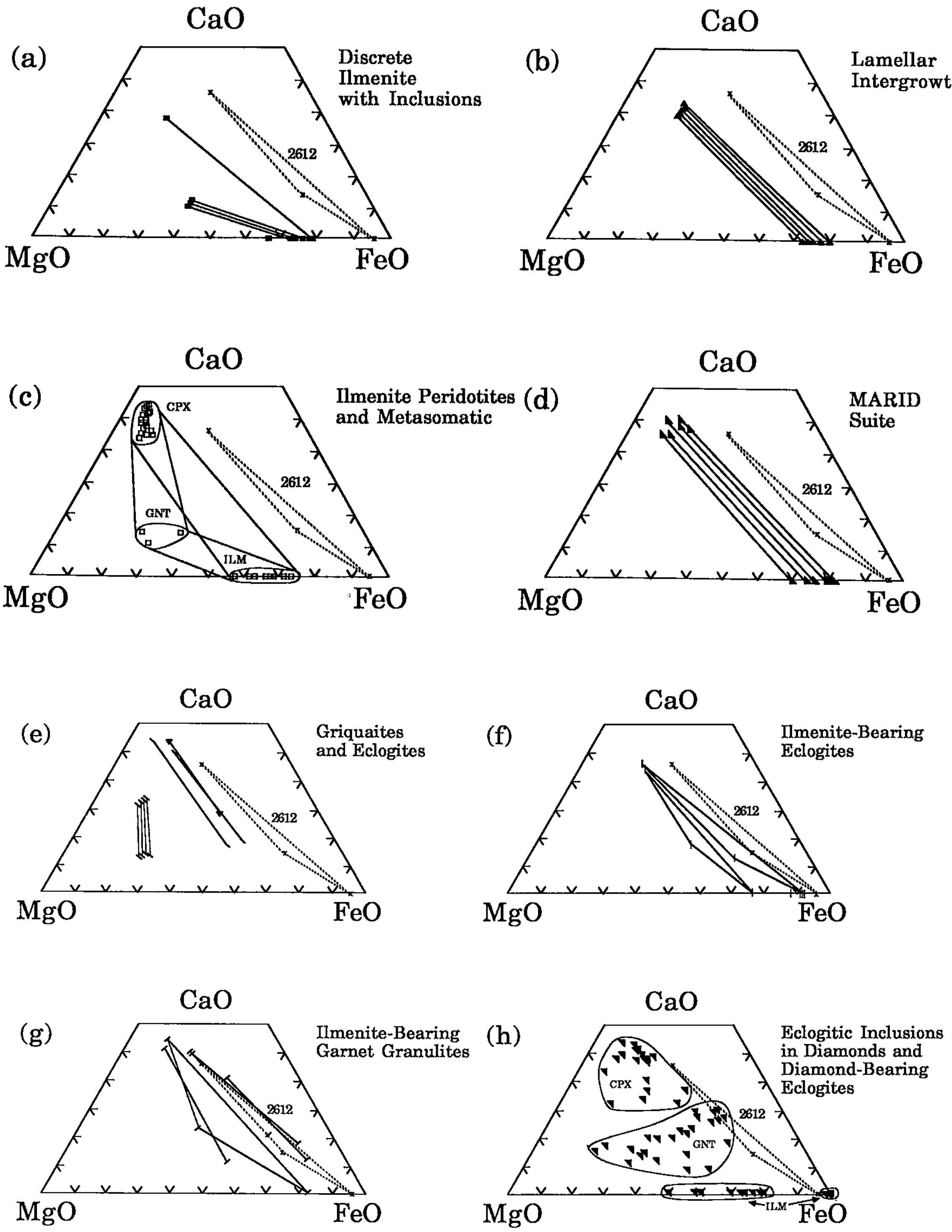

FIG. 4. Ilmenite, garnet and clinopyroxene mineral compositions of Nodule 2612 compared with those from other associations in kimberlite diatremes. All phases of Nodule 2612 are enriched in iron over those from most other parageneses found in kimberlites. Sources of data are: (a) lamellar intergrowths: Boyd & Nixon (1975), Gurney *et al.* (1973),

small veinlets of alteration products, and probably are secondary in origin.

Feldspar: Feldspar occurs in only one spherical, and apparently primary, inclusion (75 μm diameter) in garnet, consisting of two hemispheres, one side potassic and the other sodic (Fig. 3, Table 1).

The primary mineral assemblage of Nodule 2612 appears to be ilmenite + rutile + garnet + clinopyroxene + apatite ± feldspar.

Mineral chemistry

All phases, except for the feldspars, are homogeneous, and Table 1 shows their average compositions. Of note are the high Fe/Mg and calculated Fe^{3+}/Fe^{2+} values in the clinopyroxene, garnet, and ilmenite, the low Ti in the clinopyroxene and garnet for a system saturated in titanium, the high Ti in the biotite, the high Ba content of the potassic feldspar, and the high K content of the sodic feldspar. The clinopyroxene is aegirine–augite (Morimoto 1989), and garnet has the composition $Grs_9And_8Prp_{29}Alm_{53}Sps_1$. Chemical variation diagrams for the three principal mineral phases (Fig. 4) show that Nodule 2612 is distinct in its chemistry from the same phases in most other ilmenite-bearing assemblages found in kimberlites. Possible interpretations of the origin of Nodule 2612 are presented in the next section.

DISCUSSION

Mineral assemblage and mineral compositions of Nodule 2612

The mineral assemblage, mineral compositions, and texture of Nodule 2612 are the only clues to its origin. In this section, the mineral compositions of Nodule 2612 are compared with various types of ilmenite-bearing assemblages from kimberlites.

Ilmenite in kimberlites occurs as discrete megacrysts with compositions that range from 30 to 70 mol.% giekielite ($MgTiO_3$) (Haggerty 1976). Some of these ilmenite megacrysts contain silicate inclusions (Fig. 4a). Ilmenite also is an essential constituent of lamellar intergrowths of clinopyroxene with ilmenite (Fig. 4b) from the Monastery mine in South Africa, and elsewhere. In addition, ilmenite is a common constituent of metasomatically altered peridotite xenoliths (Figs. 4c,d). However, none of these assemblages has the mineral compositions of Nodule 2612.

The silicate mineral assemblage in Nodule 2612 is essentially garnet – clinopyroxene, similar to griquaites, eclogites, and garnet-bearing mafic granulites. Figure 4e shows the compositions of some ilmenite-free griquaites and eclogites, and Figure 4f shows the compositions of some ilmenite-bearing eclogites. One of these, from the Mir kimberlite pipe in Siberia (Garanin *et al.* 1982), approaches the composition of Nodule 2612. Figure 4g shows several ilmenite- and garnet-bearing mafic granulites (many have no reported compositional data for the ilmenite). Their clinopyroxene and garnet compositions are similar to those of Nodule 2612. Finally, there is a wide range of composition of silicate inclusions in diamonds that belong generally to either a peridotitic suite (not shown) or an eclogitic suite (Fig. 4h). It is noteworthy that whereas most ilmenite-bearing eclogites are different from Nodule 2612, the eclogitic suite in diamonds is the only assemblage to contain ilmenite that is as rich in iron as Nodule 2612. In fact, the Mg-free, primary ilmenite inclusions in diamonds demonstrate that iron-rich ilmenite can form under mantle conditions; therefore, Nodule 2612 is not precluded from being mantle-derived, or kimberlite-associated, solely on the basis of its *composition*. In summary, Nodule 2612 has compositional affinities closer to ilmenite-bearing eclogites, ilmenite-bearing mafic granulites, and some inclusions in diamond, than any of the other ilmenite-bearing assemblages known in kimberlites.

The mineral compositions may also be used for *P–T* estimates; however, the limited mineral assemblage of Nodule 2612 makes application of some of the more common geothermometers and geobarometers impossible (Table 2). Those involving clinopyroxene may not be particularly well constrained owing to its high Na and Fe^{3+} contents.

Temperature: Simple two-phase geothermometers give temperatures in the 700–800°C range (Table 2). This is also the temperature suggested by a theoretical thermodynamic treatment of the entire mineral assemblage (Perkins *et al.* 1986).

Pressure: In the absence of coexisting orthopyroxene, the constraints on pressure conditions are poor. Much uncertainty in the pressure estimate involves the small inclusion of coexisting feldspars. If

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Mitchell *et al.* (1973), Nixon (1973), Nixon & Boyd (1973a,d); (b) discrete ilmenite with silicate inclusions: Boyd & Nixon (1973), Nixon (1973), and Nixon & Boyd (1973c,d); (c) ilmenite-bearing peridotites and metasomatized peridotites: Boyd & Nixon (1973), Dawson (1987), Harte & Gurney (1975), Harte *et al.* (1987), Jones *et al.* (1982), and Nixon & Boyd (1973b); (d) MARID suite: Dawson & Smith (1977); (e) eclogites and griquaites: Lappin & Dawson (1975), and Nixon & Boyd (1973c,d). (f) ilmenite-bearing eclogites: Garanin *et al.* (1982), Meyer & Brookins (1971), and Meyer & Boctor (1975); (g) mafic granulites: Griffin *et al.* (1979); Nixon & Boyd (1973d); (h) eclogitic and ilmenite inclusions in diamond: Gurney *et al.* (1979), Meyer & McCallum (1986), Meyer & Svisero (1975), Moore (1987), Mvuemba Ntanda *et al.* (1982), Pokhilenko *et al.* (1976), Ponomarenko (1977), Tsai & Meyer (1979).

TABLE 2. EQUILIBRATION CONDITIONS FOR NODULE 2612

Method	Temp (°C)	Press (kbar)	Reference
Temperature			
clinopyroxene-garnet	808	[10]	Råheim & Green (1974)
clinopyroxene-garnet	832	[10]	Mori & Green (1978)
clinopyroxene-garnet	854	[10]	Ellis & Green (1979)
clinopyroxene-garnet	810	[10]	Pattison & Newton (1989)
biotite-garnet	710	-	Ferry & Spear (1978)
ilmenite-rutile	<1140	-	Haggerty & Lindsley (1970)
ilmenite-clinopyroxene	760	[2]	Bishop (1980)
	785	[10]	
two feldspar	670	[5]	Stormer (1975)
	725	[10]	
two feldspar	645	[5]	Fuhrman & Lindsley (1988)
	730	[10]	
Temperature and Pressure			
ilm-rt-grt-cpx-bt-kfs-pl	700	6	Perkins et al. (1986)

primary, it constrains the nodule to low pressures; however, it might represent unmixing of an originally homogeneous ternary K–Na–Ca feldspar stable at higher temperature (and pressure?). Primary sanidine does occur in eclogites of various origins in kimberlite (Smyth & Hatton 1977, Schulze & Helmstaedt 1988). If secondary, the feldspars indicate a history for the nodule in the P–T stability field of two feldspars. Marakushev *et al.* (1982) reported a high-pressure, diamond-bearing eclogite from the Udachnaya kimberlite that contains secondary plagioclase. The P–T conditions derived from an assumption that the entire mineral assemblage was in equilibrium (Perkins *et al.* 1986) are definitely crustal.

The geothermometry–geobarometry results of Table 2 suggest that Nodule 2612 *last* equilibrated at conditions of relatively low temperature (for magmas), and at pressures appropriate to the lower crust. The exsolution textures [ilmenite in rutile, rutile in clinopyroxene and garnet, unmixing of ternary feldspars(?)] indicate that the calculated temperatures and pressures may represent subsolidus re-equilibration.

Texture of Nodule 2612

In terms of mineral compositions (above), Nodule 2612 appears to have close affinities with ilmenite- and garnet-bearing mafic granulites, but their modal mineralogy (>95% clinopyroxene – garnet – orthopyroxene – plagioclase) and polygonal granoblastic textures for all minerals (Griffin *et al.* 1979) differ considerably from the textures of the silicates in Nodule 2612. Nodule 2612 also is different in modal mineralogy and texture from a suite of ilmenite-bearing nodules from Matsoku (Harte & Matthews 1989). In fact, the texture of Nodule 2612 more closely resembles a group of garnet – ilmenite – clinopyroxene nodules from the Koidu kimberlite complex (see Fig. 5 in Tomkins & Haggerty 1984). Like Nodule 2612, the Koidu nodules are characterized by substantial variation in the proportions of ilmenite and garnet, with minor inclusions of clinopyroxene. Tomkins & Haggerty considered this suite to represent the products of crystallization from a high-pressure (*ca.* 47 kbar) kimberlite precursor magma, at a stage of evolution intermediate between formation of early pyroxene megacrysts and later eclogites.

The sideronitic texture of Nodule 2612 (silicate crystals suspended in oxides), and round inclusions of ilmenite in garnet, suggest either a cumulus silicate–intercumulus oxide, or a liquid immiscibility relationship. The spherical clinopyroxene grains enclosed in spherical garnet clearly represent a disequilibrium texture, but the triple junctions between the ilmenite grains suggests the possibility of textural equilibration of the oxide minerals under static high-pressure conditions. The association of high concentrations of oxide with included and interstitial apatite, characteristic of many immiscible oxide-rich liquids, strengthens the suggestion that the oxide-rich material may have formerly represented a liquid. Finally, the symplectitic (decompression?) texture of the clinopyroxene may be attributable to rapid ascent from high-pressure conditions. Taken together, some of the textural features suggest that Nodule 2612 could represent a high-pressure immiscible oxide-rich liquid.

Possible origins for Nodule 2612

Mineral *compositions* in Nodule 2612 closely resemble those in accidental garnet-bearing mafic granulites, but both its *texture* (like those of the cognate Koidu nodules) and its *association* with apatite (suggesting an immiscible liquid) point to a cognate igneous, and perhaps immiscible, relationship to the host kimberlite or a precursor magma (Table 3). The mineral compositions, which are shifted to higher Fe/Mg values than the Koidu nodules, suggest that Nodule 2612 could be the product (fractional crystallization? immiscibility?) of a magma more evolved than the Koidu magma. In very general terms, the high modal proportion of ilmenite in Nodule 2612 suggests a genetic relationship with kimberlite. If true, then the high Fe/Mg value of the minerals indicates either a highly evolved magma, or possibly a metastable immiscible relationship, or even an equilibrium immiscible relationship from an evolved magma.

Types of immiscibility in silicate systems

Levin (1970) and Roedder (1979) have reviewed the general principles of liquid immiscibility. The most widely studied synthetic system that has a possible bearing on kimberlites is K_2O–FeO–Al_2O_3–SiO_2 (Roedder 1951), to which have been added TiO_2 and P_2O_5 (Watson 1976, Freestone 1978, Visser & Koster van Groos 1979). The Ti^{4+} and P^{5+} cations have high field strengths and are not readily held in a polymerized silicate melt, and thus their high concentrations promote liquid immiscibility. Indeed, experimental systems doped with these elements all show enlarged stable fields of liquid immiscibility, although there is some question as to their persistence in MgO-rich systems (Cygan & Koster van Groos 1978). In addition, Irvine (1976) reported extensive metastable liquid immiscibility relationships in the system Fo–Fa–An–Or–Qz. From this experimental work, it is clear that both the occurrence of liquid immiscibility in any system and the differences in composition between the conjugate liquids are complex functions of temperature, pressure, bulk composition, $f(O_2)$ (Naslund 1976) and, in the case of metastable immiscibility, cooling rate.

In naturally occurring silicate magmatic systems, there is convincing textural and chemical evidence for silicate–silicate liquid immiscibility (*e.g.*, the lunar glasses; Roedder & Weiblen 1970), silicate–sulfide liquid immiscibility (*e.g.*, Stillwater Complex; Page 1979), silicate–carbonate liquid immiscibility (*e.g.*, some lamprophyres; Strong & Harris 1974), and silicate – Fe–Ti oxide-rich liquid immiscibility (*e.g.*, in some anorthosites; Philpotts 1967, Powell *et al.* 1982, Kolker 1982; in some intermediate volcanic rocks; Park 1961, Haggerty 1970, Henriquez & Martin 1978; and in some alkaline and carbonatitic complexes, *e.g.*, Palabora; Heinrich 1966). In kimberlites, Clarke & Mitchell (1975) have shown clear silicate–sulfide and silicate–carbonate immiscibility textural relationships, Haggerty & Tompkins (1983) have suggested that oxide-rich immiscibility may explain rare ilmenite–sulfide nodules in kimberlite, and Pasteris (1980) identified possible immiscibility textures involving ilmenite in the De Beers kimberlite.

As in other known immiscible relationships, pure end-member compositions do not form. Instead, there should be some silicate material dissolved in an iron–titanium oxide-rich immiscible liquid, but subsequent gravity separation of the crystallizing phases may be very effective. If a process of Fe–Ti oxide-rich liquid immiscibility (ORLI) can occur in silicate magmas as diverse as basalts, diorites, andesites, lamprophyres and carbonatites, then it could presumably also occur in kimberlites. The combination of reasonably high levels of TiO_2, high P_2O_5, high $f(O_2)$ (especially during and after fluidization, possibly in the crust, and evidenced by the high level of Fe^{3+} in the minerals, and the coexisting ilmenite–rutile pair), and rapid cooling, with the enhanced possibility of intersecting a metastable immiscibility gap, all suggest that kimberlites are reasonable candidates for liquation. It is our view that Nodule 2612 represents evidence that such a process operated in a rapidly ascending kimberlitic magma, that the metastable immiscible liquid crystallized, and that the nodule was later brought to the surface by the Matsoku kimberlite.

TABLE 3. EVIDENCE FOR THE ORIGIN OF NODULE 2612

	accidental mafic granulite	cognate to kimberlite
mineral assemblage	ilm + grt + cpx ± sodic feldspar ± potassic feldspar assemblage is typical of many mafic granulite xenoliths in kimberlite	if feldspars are primary, then mineral assemblage is unlike most kimberlite associations, although rare sanidine and plagioclase occur in eclogites from kimberlite; if feldspars are secondary, then the assemblage ilm + grt + cpx is common in the kimberlite discrete nodule suite; the association of ilmenite and apatite suggests liquid immiscibility
modal proportions	the dominance of ilm + grt is unlike mafic granulites	unlike most kimberlite nodules, but resemble cognate nodules from Koidu kimberlites
mineral compositions	iron-rich mineral compositions similar to those in mafic granulites	high Fe/Mg ratios atypical of kimberlites, unless derived from an evolved precursor magma or the product of oxide-rich liquid immiscibility; iron-rich ilmenites have been reported as inclusions in diamonds
texture	sideronitic texture unlike any described mafic granulite	rare in kimberlite nodules, but similar to Koidu 'discrete' nodule suite
P-T conditions	low temperatures and pressure suggest middle to lower crustal conditions, i.e granulite facies	lower crustal conditions could reflect crystallization by a magma that had reached the lower crust, or by temporary re-equilibration of a deep-seated nodule at lower crustal levels

Consequences of ORLI for kimberlite compositions

Observed compositions of igneous rocks are the complex products of source-rock composition and many processes experienced *en route* to the surface. If, at some stage in the evolution of a typical kimberlite, an immiscible Fe–Ti oxide-rich liquid forms and separates, several interesting compositional consequences for the interpretation of kimberlites result:

(i) If ORLI occurs before crystallization of the kimberlite precursor magma, then the chemical effects on the conjugate silicate melt, beyond a profound decrease in the Fe/Mg ratio, are indeterminate because partitioning of the elements between an Fe-Ti oxide-rich liquid and a silicate liquid are unknown for such a system (see Watson 1976).

(ii) If, however, ORLI occurs during crystallization of the kimberlite precursor magma, and if the crystallizing phases are garnet + clinopyroxene [*i.e.*, eclogite (or griquaite) fractionation, as advocated by O'Hara & Yoder 1967] ± ilmenite, then the two conjugate compositions may be:

Fe–Ti rich melt + grt + cpx + ilm < = >
very high Fe/Mg in all phases
Nodule 2612
silicate melt + grt + cpx + ilm
very low Fe/Mg in all phases
kimberlite + discrete nodules

This *combination* of eclogite fractionation *sensu lato* and ORLI operating on a precursor magma would better account for compositional paradox of both high *mg*-numbers and high concentrations of large-ion lithophile elements (*LILE*) (Mitchell 1986) in kimberlitic magmas than eclogite fractionation alone. In fact, if this process occurs, there *should be* a positive correlation between *mg*-number and *LILE* concentrations in the silicate fraction, especially if ORLI is part of the differentiation mechanism. Subsequent gravity separation of the dense ORLI and its contained silicate phases should readily occur, accounting for both the rare evidence of its existence, and for the high Fe/Mg of its minerals that no longer have to establish equilibrium also with the Mg-rich silicate liquid.

(iii) Among igneous rocks generally, discrete nodules are rare. In kimberlites, however, the common occurrence of discrete nodules of magnesian ilmenite, chrome pyrope garnet, and chrome diopside suggests that their formation is associated with the origin and evolution of kimberlites. The reason for their 'discreteness' in most cases may be their very different specific gravities (ilm 4.7; grt 3.8; cpx 3.3), which can promote separation of these phases soon after their formation. The rule, then, may be that they occur as separate discrete nodules; the rare exception is that they occur together, as in the case of the Koidu nodules and Nodule 2612. Judging from the Fe/Mg values in the minerals, the Koidu nodules formed earlier in the magmatic evolution than Nodule 2612. Therefore, although its mineral *compositions* are different, the same three phases are present in Nodule 2612, an observation suggesting that all three members of the discrete nodule suite could form together by eclogite fractionation and ORLI.

Further testing of the ORLI hypothesis

Several problems are associated with a rigorous testing of the ORLI hypothesis. First, the specific gravity of one of the conjugate phases, the Fe–Ti oxide-rich liquid or its solid product, is considerably higher than that of eclogite nodules and, therefore, even less likely to be entrained in an ascending magma. Secondly, if further evidence is sought through the compositions of kimberlites, as the other product of liquation, then contamination and secondary alteration create problems in obtaining samples representative of the original kimberlite melt. Nevertheless, kimberlites that have undergone ORLI might also have correlated depletions of Ti, V, and P, perhaps showing as negative spikes on spider diagrams. The case for ORLI will depend on the extent to which similar variations in other elements are correlated with Ti, V, and P. Preservation of the chemical fingerprints of this process is always subject to the influence of subsequent processes such as contamination and metasomatic alteration. Fourthly, if the combination of high Mg–Cr–Ni concentrations in kimberlites is a derivative characteristic, the association of these elements with Mg-rich mantle nodules becomes somewhat less credible (*i.e.*, the high Mg of the nodules is a primary characteristic, but the high Mg of the kimberlites is secondary). Finally, the kimberlites that contain oxide-rich nodules may not be those that produced them (multiple intrusions) and, therefore, may not have the expected chemical characteristics.

CONCLUSIONS

1. The modal, textural, and compositional data on Nodule 2612 have been considered in the light of two competing hypotheses, accidental mafic granulite or cognate immiscibility. We recognize that the compositional evidence supports a lower crustal xenolithic origin but, on balance, we believe that the mineral assemblage, mineral proportions, mineral compositions, and texture point to Fe–Ti oxide-rich liquid immiscibility as the origin.
2. If a genetic relationship exists between the ilmenite-rich nodule and kimberlite, then a process of Fe–Ti oxide-rich liquid immiscibility may occur in the evolution of kimberlitic magmas. ORLI would help to explain the kimberlite compositional paradox of high *mg*-numbers and high concentrations of incompatible trace elements. We do not propose, however, that ORLI is the only mechanism of differentiation, or even the main mechanism of differentiation, in kimberlites. As in other magmatic systems, the final compositions result from the interplay of many processes, and we seek only to discover the existence and, if possible, to establish relative importance, of each one.
3. Kimberlites are emplaced as volumetrically small bodies, possibly suggesting low degrees of partial melting, or high degrees of differentiation, or both. Perhaps their immediate magmatic precursors are larger volumes of more normal, more iron-rich magma (fractionated basalt?) that have experienced a combination of eclogite fractionation and ORLI.

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