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Partially Melted Kyanite Eclogite from the Roberts Victor Mine, South Africa

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ABSTRACT

Three specimens have been studied of the rare kyanite eclogite nodules in kimberlite from the Roberts Victor mine, South Africa. All are essentially the same with the primary assemblage: kyanite, omphacite, garnet, diamond (in one sample), chrome diopside, and rutile. There is also present a fine-grained secondary assemblage that appears in two forms: (1) primary omphacite altered to a mixture of plagioclase, clinopyroxene, and possibly glass; and (2) thin layers along omphacite, kyanite, and garnet grain boundaries. These layers have a clear-cut igneous texture and consist of plagioclase microlites with glass or devitrified glass, or plagioclase microlites and subhedral augite, with or without glass. Hornblende, spinel, and calcite are accessories, and analcite fills vesicles. Corundum and mullite occur at the margins of kyanite grains.

The glass in the secondary assemblage has a composition roughly equivalent to what one might expect if it was derived by incongruent melting of omphacite, followed by partial crystallization. Omphacite at one atmosphere pressure begins to melt at about 1030° C and melting is complete at about 1260° C. At 30 kilobars (O'Hara and Yoder, 1967) melting begins at about 1570° C and is complete at 1600° C. Thus, sudden pressure release of an eclogite at high temperature could cause partial melting of omphacite.

These kyanite eclogites clearly contained an interstitial melt that has been rapidly cooled. Evidence points to this melt having been generated mainly by partial melting of primary omphacite rather than by introduction of an externally derived melt. The partial melting may have occurred in response to one of the following three processes or some combination of them:

1. Increase in temperature at constant pressure.
2. Introduction of water into the eclogite at constant temperature and constant total pressure.
3. Release of pressure at constant temperature.

The third process seems to offer the most reasonable explanation for the partial melting.

Introduction

Of the several rock types found as nodules in kimberlite in South Africa, one of the most interesting and the least abundant is the kyanite eclogite from the Roberts Victor mine.

The first description of this rock seems to have been in a letter from Professor Beck of Freiburg, Germany, to E. H. V. Melville, who read the letter at the 16 July 1906 meeting of the Geological Society of South Africa (Melville, 1907). Further descriptions have been published by Johnson (1907) and Williams (1932). In these studies one of the most intriguing features of the rock, namely evidence of partial melting, was overlooked.

The purpose of this paper is to describe the evidence of partial melting and to discuss possible causes. The primary mineral assemblage of these kyanite eclogites is also of special interest and will be dealt with in another paper.

Three specimens of kyanite eclogite were available for study, USNM 87375, 110752, and 111060. The latter two were recently donated by the Geological Department of De Beers Consolidated Mines, Ltd., through Mr. D. Du Toit.

Evidence of partial melting is so pronounced in the Roberts Victor mine kyanite ecolgite that it was in these it was first recognized. Once having been rec-

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ognized, other eclogites (without kyanite) examined from the Roberts Victor mine revealed that some of these too have interstitial glass, possibly derived by partial melting. A study of the secondary assemblage of normal (non-kyanite bearing) eclogite from the Roberts Victor mine is underway and will be reported on separately.

Mineralogy

The Roberts Victor mine kyanite eclogite is made up of distinctly different primary and secondary mineral assemblages. The primary assemblage is a course aggregate of garnet, omphacite (largely altered), and kyanite, with diamond (in one specimen), chrome diopside, and rutile as accessories. Microprobe analyses made possible the elucidation of a complex, fine-grained secondary assemblage that appears to be largely the result of partial melting of primary omphacite. Table 1 lists the primary and secondary mineral assemblages.

OMPHACITE.—This primary mineral played a key role in the generation of the secondary assemblage. Data on relicts of unaltered omphacite (Figure 1) are given in Table 2.

ALTERED OMPHACITE.—The omphacite in these rocks is altered almost completely to a peculiar yet characteristic gray to greenish-gray, nearly opaque product. The grain size of the alteration product ranges from submicroscopic to a birefringent aggregate in which at least two phases can be seen but not positively identified by optical properties or microprobe analysis (Figures 1, 2). Some areas that exhibit a blotchy appearance in ordinary light, under crossed nicols show curved, stellate plagioclase crystals, giving a texture very similar to that frequently seen in quenched silicate melts (Figure 2).

Peaks on an x-ray diffraction pattern can be accounted for by plagioclase and clinopyroxene but the composition of these phases cannot be determined by this method. The presence of glass as a third phase is suspected but has not been proven.

Electron microprobe analyses of the alteration product are given in Table 2. Areas selected for analysis were those that in thin section were extremely fine grained, and the electron beam was widened to 20μ. Comparison with the analyses of fresh omphacite shows that the reaction was essentially isochemical.

SECONDARY IGNEOUS ASSEMBLAGE.—Most of the minerals in the secondary assemblage occur as thin layers along omphacite, kyanite, and garnet grain boundaries (Figure 3) and, in part, replace the pri-

TABLE 1.—*Mineralogy of Roberts Victor mine kyanite eclogite*

Primary assemblage	*Secondary assemblage*
Garnet (grossular-almandine-pyrope)	Altered omphacite (plagioclase+clinopyroxene+glass?)
Omphacite	Plagioclase (An_{39})
Diamond (noted only in 111060)	Augite (only in 87375 and 111060)
Chrome diopside (noted only in 110752)	Fassaite (only in 110752)
Rutile (noted only in 87375)	Spinel
	Hornblende
	Glass
	Analcite
	Calcite
	Corundum
	Mullite

TABLE 2.—*Omphacite and altered omphacite from Roberts Victor mine kyanite eclogite*

	Fresh omphacite [1, 2]		*Altered omphacite* [1]	
	111060	*110752*	*110752* [3]	*87375* [4]
SiO_2	52.1	53.3	56.0	56.4
TiO_2	0.3	0.3	0.3	0.4
Al_2O_3	17.5	17.9	18.6	20.2
Fe_2O_3	0.3	0.4		
FeO	1.2	1.4	1.9	2.3
MgO	7.2	6.4	6.6	4.2
CaO	11.9	12.1	11.3	9.2
Na_2O	6.8	6.4	5.0	5.2
K_2O	0.3	0.2	0.3	0.0
α	1.664 Na ±0.002			
β	1.672 Na ±0.002			
γ	1.688 Na ±0.002			
$Z \wedge c$	36°			
2V (+)	70°			
Ac	2	3		
Jd	46	42		
Ts	14	14		
Hd	3	4		
Di	35	36		

[1] Analyses by electron microprobe.

[2] Based on other analyses of similar omphacites Fe assigned on basis that 0.8 of the total Fe is Fe^{2+}. Only specimen 111060 contains enough fresh omphacite for determination of optical properties.

[3] Average of five analyses. Range: SiO_2 55.4–56.6; TiO_2 0.3–0.3; Al_2O_3 18.1–19.0; Fe 1.5–1.5; MgO 6.2–7.0; CaO 10.8–12.3; Na_2O 4.5–5.5; K_2O 0.3–0.3. All Fe taken as FeO.

[4] Average of four analyses: Range: SiO_2 55.8–56.8; TiO_2 0.3–0.4; Al_2O_3 20.1–20.5; Fe 1.6–1.9; MgO 3.8–4.6; CaO 8.6–9.7; Na_2O 4.7–5.5. All Fe taken as FeO.

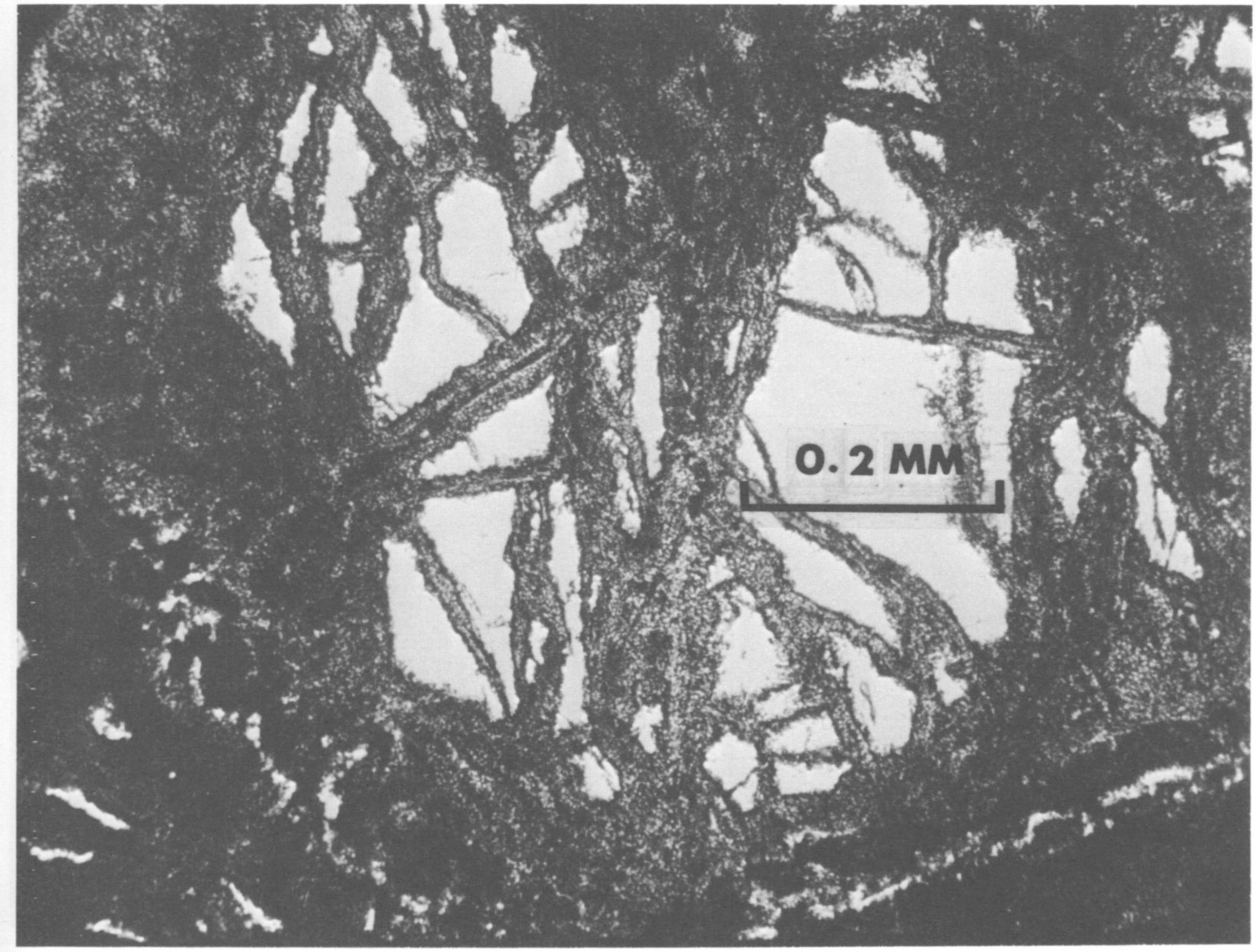

FIGURE 1.—Relicts of omphacite (white) in altered omphacite (gray). USNM 111060.

mary omphacite. Under high magnification the layers have a clear-cut igneous texture (Figure 4) showing plagioclase microlites with glass or devitrified glass, or plagioclase microlites and subhedral augite, with or without glass. Hornblende, spinel, and calcite are accessories, and analcite fills vesicles. Where the secondary igneous assemblage cuts garnet it is frequently composed entirely of augite, plagioclase, and spinel, without glass, and has ophitic texture.

Data on the minerals of the secondary igneous assemblage follow.

Plagioclase: This mineral has typical microlite habit and twinning, little or no zoning, and composition An_{29}.

Augite, fassaite, and hornblende: Augite, a major mineral of the secondary assemblage, in thin section is subhedral and colorless. The augite in specimen 87375 is Al-rich and Ti-poor as compared with normal augite. In specimen 110752 the "augite" contains 18.3 percent Al_2O_3, placing it much closer to fassaite than augite in composition, although the CaO content is a little low for this mineral. (Tabulation of fassaite analyses in Deer, Howie and Zussman, 1963, shows $CaO \approx 25$ percent). To our knowledge such a fassaite-like pyroxene has not been reported in a similar paragenesis.

In specimen 110752 the fassaite is more coarsely crystalline than the augite in the other two specimens. It occurs either as monomineralic rims around garnet, intergrown with plagioclase, or ophitically enclosing plagioclase. In thin section it is colorless.

Hornblende, a minor constituent in all three specimens, is subhedral to euhedral, brown and pleochroic brown to light brown in thin section.

FIGURE 2.—Quench texture in altered omphacite. Crystals are plagioclase. Crossed nicols. USNM 87375.

Microprobe analyses of these three minerals are given in Table 3.

Spinel: Minute, dark green octahedrons of spinel are common in the secondary igneous assemblage, particularly where the igneous assemblage is in contact with garnet. Its composition by microprobe analysis is approximately Sp_{40} He_{60}.

Glass: Local areas of residual glass are a prominent feature of the secondary igneous assemblage. The glass fills interstices in plagioclase-augite, is pale brown in color, and isotropic. Some areas are completely clear, others contain from a few to abundant microlites, and some have the typical appearance of devitrified glass.

TABLE 3.—*Augite, fassaite, and hornblende from Roberts Victor mine kyanite eclogites* [1]

	Augite in 87375	*Fassaite in 110752*	*Hornblende in 87375*	*Hornblende in 110752*
SiO_2	51.3	41.7	38.6	37.4
TiO_2	0.6	0.7	2.2	0.6
Al_2O_3	7.4	18.3	17.4	19.3
Fe	8.9	7.1	8.2	7.4
MgO	11.8	7.5	13.3	11.3
CaO	18.6	19.9	10.4	12.1
Na_2O	0.6	1.4	4.0	3.0
K_2O	0.0	0.0	0.6	1.5

[1] Analyses by electron microprobe.

The best examples of fresh glass are in specimen 87375. A microprobe analysis is given in Table 4.

TABLE 4.—*Glass in kyanite eclogite from the Roberts Victor mine* [1]

	Weight percent	Norm [2]	
SiO_2	47.7	or	11.1
TiO_2	0.6	ab	39.8
Al_2O_3	23.1	an	4.7
MgO	1.6	ne	22.7
CaO	1.0	ol	8.6
Na_2O	9.7	mg	4.9
K_2O	1.9	il	1.2
Fe	4.8	c	3.4

[1] Specimen 87375.

[2] In calculation of norm, iron was assigned one-half to Fe^{2+} and one-half to Fe^{3+} (3.1 FeO and 3.4 Fe_2O_3). With this assignment of iron the sum is 92.1. The difference is probably water.

Analcite: White, massive analcite fills vesicles in secondary igneous texture layers. Identification was by microprobe analysis and x-ray diffraction.

Calcite: Calcite is a rare accessory in the secondary igneous assemblage.

Corundum: Corundum crystals occur commonly at the margins of kyanite grains. Identification was by microprobe analysis and optical properties.

Mullite: A frequently seen phase in thin sections is a fibrous mineral in kyanite that microprobe analysis demonstrated to be compositionally identical to mullite (Table 5).

TABLE 5.—*Mullite in Roberts Victor mine kyanite eclogite*

	Mullite in 110752	Mullite theoretical	Kyanite theoretical
SiO_2	25. 9	28. 2	36. 8
Al_2O_3	73. 6	71. 8	63. 2
Total	99. 5	100. 0	100. 0

In thin section the mullite has the following optical properties: parallel extinction, length slow, index of refraction less than that of kyanite.

Incongruent Melting of Omphacite

The garnet and kyanite in these eclogites are not altered, except locally in small volumes along their boundaries. The igneous mineral assemblage and the composition of the interstitial glass suggests that they were involved in only a minor way in the generation of the melt. On the other hand, the pervasive alteration of omphacite and the features of the igneous assemblage indicate that omphacite played a major role in the formation of the melt and its melting behavior thus is of special interest here.

The system nepheline-diopside-silica has been investigated by Schairer and Yoder (1960) at one atmosphere, and the results can be used to qualitatively interpret partial melting of natural omphacite at low pressure. Mixtures along the diopside-jadeite join begin to melt at about 1120° C when these mixtures contain more than 15 percent diopside. The first liquids (equivalent to residual liquids) are highly undersaturated. The norm of such a liquid would contain mainly albite and nepheline, a feature that characterizes the composition of the glass in one of the kyanite eclogites (Table 6).

TABLE 6.—*Norms of primary omphacite and secondary glass in Roberts Victor mine kyanite eclogite*

	Omphacite in 111060	Omphacite in 110752	Glass in 87375
or	1. 7	1. 1	11. 1
ab	24. 6	30. 4	39. 8
an	16. 4	19. 7	4. 7
ne	17. 9	12. 8	22. 7
di	33. 0	31. 3	
ol	5. 2	3. 6	4. 2
il	0. 6	0. 6	1. 2
mg	0. 5	0. 7	4. 9
c			3. 4
ab + ne + di	75. 5	74. 5	62. 5

Melting experiments [1] by the authors on omphacite from a Roberts Victor mine eclogite show that melting begins at about 1030° C and is complete at about 1260° C. This lowering of the liquidus and solidus temperatures compared to the synthetic system (Schairer and Yoder, 1960) is probably due to the FeO content of the natural omphacite, the only important con-

[1] Charges placed in 60 Pd 40 Ag crucibles, or Pt crucibles above 1200° C, and crucibles sealed in evacuated silica glass tubes; vertical quench furnace, Pt 10 Rd thermocouple calibrated against Au and synthetic diopside standards; furnace temperature readings ±2° C; liquidus and solidus temperatures ±10° C.

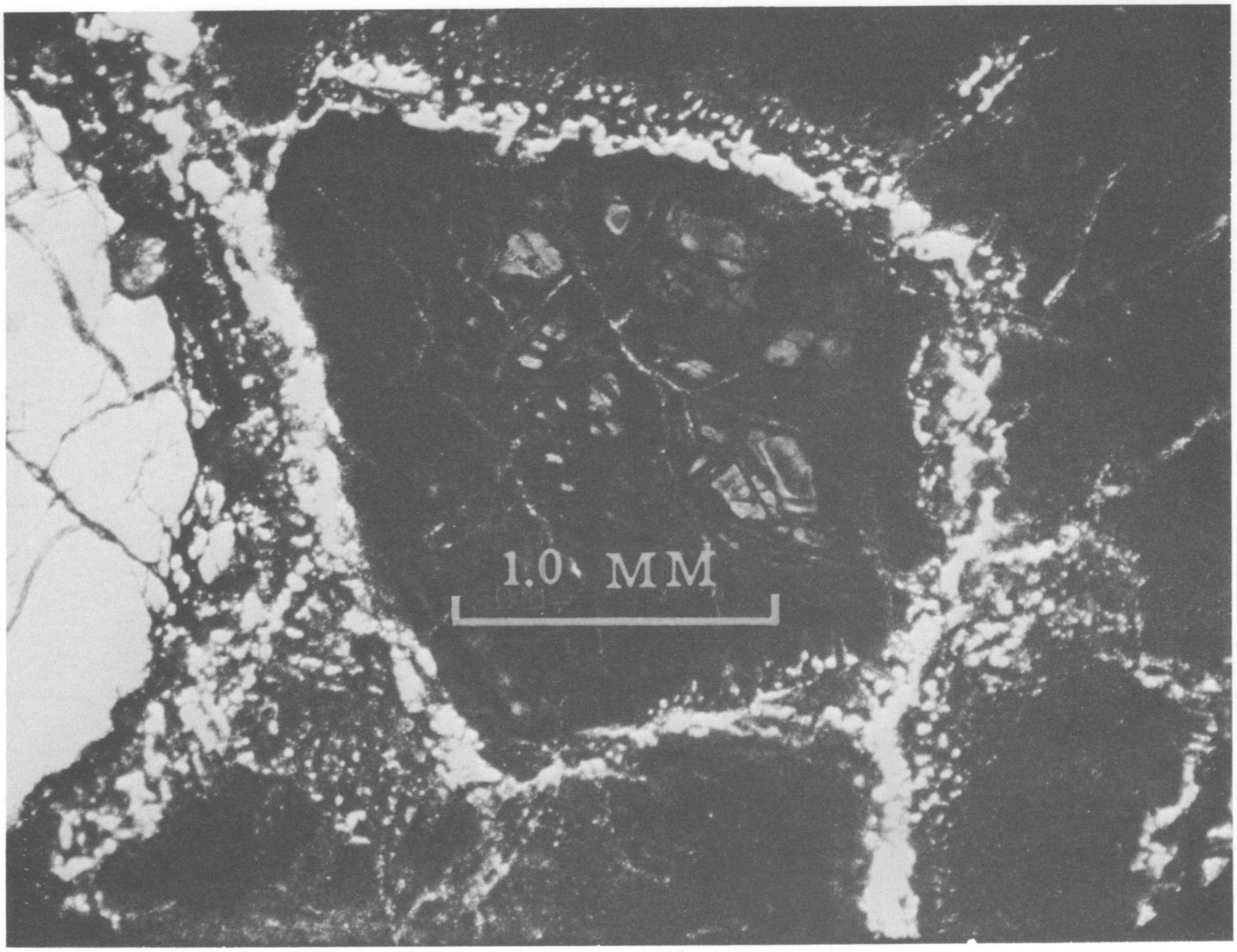

FIGURE 3.—Layers of the secondary igneous assemblage along grain boundaries of altered omphacite (black) and garnet (white). USNM 87375.

stituent not included in the synthetic system. Omphacite also melts incongruently at high pressure, but detailed phase diagrams have not been worked out. O'Hara and Yoder (1967, fig. 8) have shown that at 30 kilobars omphacite begins to melt at about 1570° C and is completely melted at 1600° C. The composition of first liquids from the melting of omphacite at high pressure has not been determined, but it is reasonable to assume that they will contain considerable normative nepheline and albite.

Cause of Partial Melting

These kyanite eclogites clearly contained interstitial magma that has been rapidly cooled. Two hypotheses may be offered to account for the presence of this magma:

1. Introduction of an externally derived melt from the kimberlitic magma.
2. Partial melting of the primary assemblage.

We believe that the latter hypothesis is much more likely, based on the following evidence: (1) the pervasive occurrence of the secondary igneous assemblage in very thin layers along all grain boundaries, combined with no more nor less of the assemblage toward the margin of the nodules; and (2) the composition of secondary assemblage can be accounted for by partial incongruent melting of the primary omphacite.

The partial melting may have occurred in response

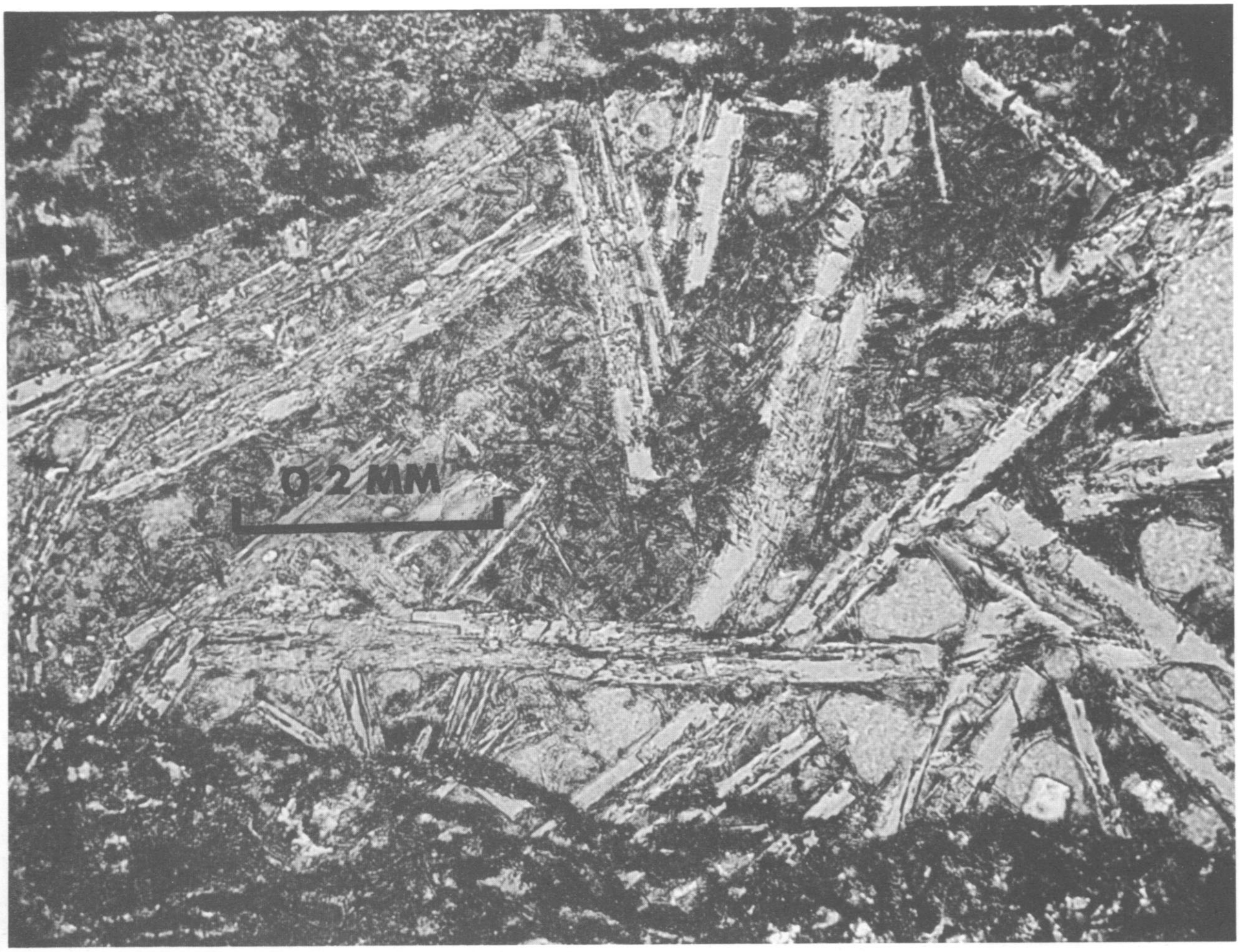

FIGURE 4.—Closeup view of a secondary igneous assemblage layer showing plagioclase microlites with interstitial glass. The bordering material is altered omphacite. USNM 87375.

to one of the following three processes, or to some combination of them:

1. Increase in temperature at constant pressure.
2. Introduction of water into the eclogite at constant temperature and constant total pressure.
3. Release of pressure at constant temperature.

The merits of each of these hypotheses are discussed in the following sections.

INCREASE IN TEMPERATURE AT CONSTANT PRESSURE.—This mechanism might be invoked, for example, by considering immersion of an eclogite nodule in kimberlitic magma. Based on the present state of knowledge of the melting of omphacite at high and low pressure as reviewed earlier, one cannot categorically choose between partial melting at high or low pressure to explain the decomposition of the omphacite in these kyanite eclogites, if indeed partial melting did occur at constant pressure. Actually, the nature of the nodules argues against this interpretation, which assumes slow heating (and slow cooling) under constant pressure. If the specimens had undergone such a history, it seems likely that the partial melting along grain boundaries would have caused disaggregation of the nodule. Such disaggregation obviously did not occur.

INTRODUCTION OF WATER AT CONSTANT TEMPERATURE AND CONSTANT TOTAL PRESSURE.—The presence of hornblende and analcite in the secondary igneous

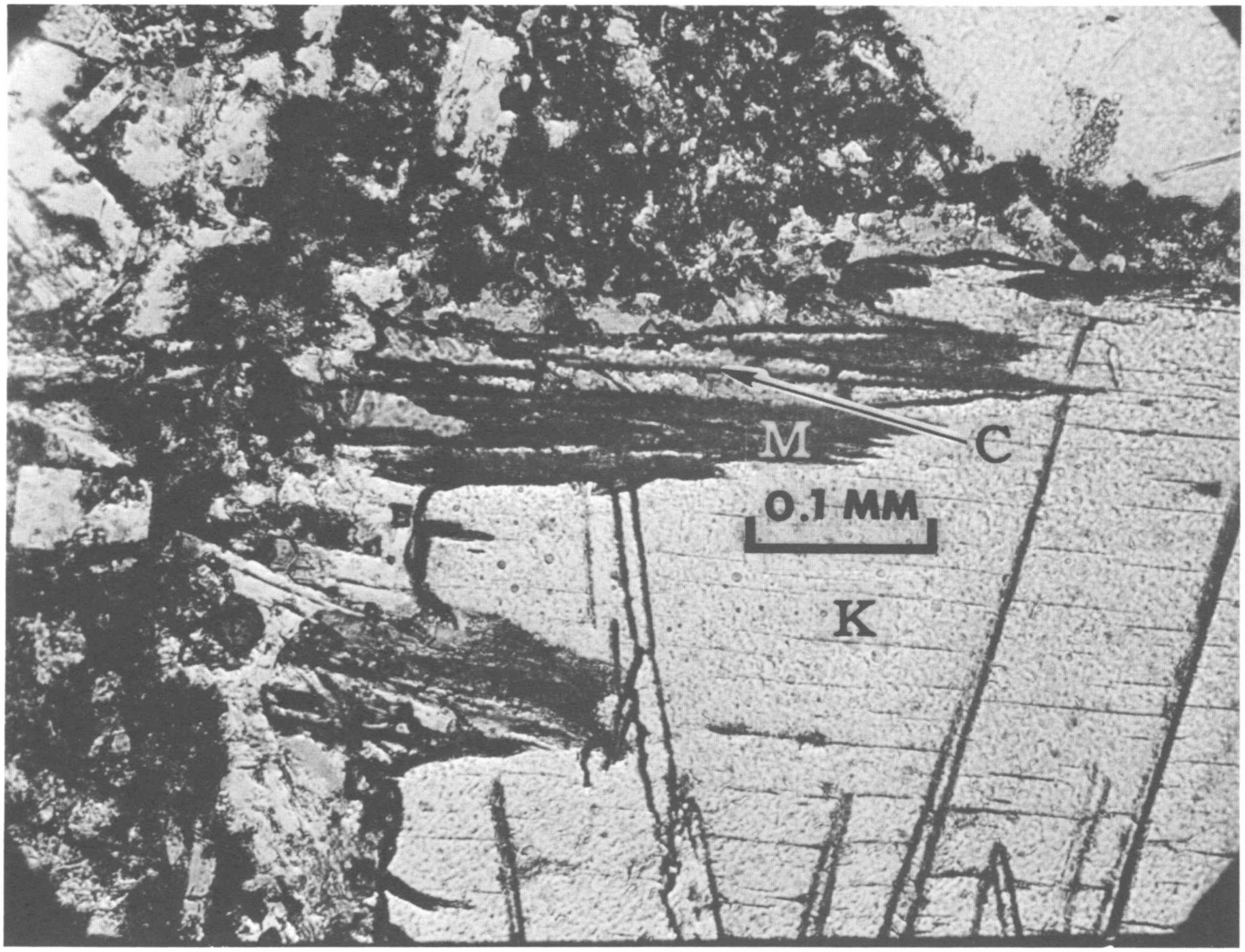

FIGURE 5.—Mullite (M) and corundum (C) on the margin of a kyanite grain (K). The lines in kyanite are twin lamellae. USNM 87375.

assemblage shows conclusively that the interstitial magma did contain dissolved water. Indeed, the vesicles observed in specimen 87375 show that, at some stage in the crystallization of this magma, the water content became high enough for the water vapor pressure of the magma (combined with the vapor pressure of other dissolved volatiles) to equal the total pressure.

Introduction of small amounts of water along grain boundaries into an anhydrous eclogite at high temperature and high total pressure would either generate a small amount of hydrous magma, or lead to the formation of a new hydrous phase, or both. If the temperature was sufficiently high, a melt rather than a hydrous phase would most likely form.

Kimberlitic magmas are known to contain considerable H_2O and CO_2. Thus water could have been introduced into the nodule from its environs. The low K_2O and high Na_2O content of the residual glass and the pervasive occurrence of the secondary igneous assemblage along grain boundaries indicate that, if anything was introduced from the surrounding kimberlitic magma, it was only water plus possibly other volatiles. It is also possible that the small amount of water that must be accounted for was derived internally, for recent work [2] has shown that practically all "anhydrous" silicates, including pyroxene, garnet, and kyanite, contain some water.

[2] C. Frondel, personal communication.

Water, either externally or internally derived, or both, certainly played a role in the formation of the interstitial magma, but at the present time there seems to be no way to evaluate its importance.

RELEASE OF PRESSURE AT CONSTANT TEMPERATURE.—As discussed earlier, at 30 kilobars omphacite begins to melt at about 1570° C, whereas at one atmosphere melting begins at about 1030° C. Thus, sudden pressure release of an eclogite at high temperature would clearly cause partial melting of omphacite. Even if the initial temperature was as low as 1150° C and the pressure release large, some melting would take place.

A rapid pressure release implies that there would also be adiabatic cooling because of insufficient time for the nodules to exchange heat conductively with their environs; however, for solids the amount of such cooling is small because of their small Δ V. Thus, initially melting would occur, the amount being determined by the temperature at the time of pressure release, the magnitude of the pressure drop, and the composition of the omphacite.

It is difficult to conceive how these eclogites could have remained intact when each grain boundary was "coated" with interstitial magma unless the time interval between melting and quenching was short. Melting on release of pressure would be almost immediate. The heat required for melting would come from the eclogite itself; that is, no conductive transfer of external heat into the nodule would be required. Quenching then took place almost immediately after the partial melting, by cooling in the rapidly ascending kimberlite magma. Kimberlite magmas are generally considered to be gas-rich and may undergo rapid cooling during ascent because of (1) expansion of an initially present gas phase, and (2) emission of gas from the magma due to rapid drop in pressure. The actual importance of this cooling, however, is difficult to evaluate.

Summary

The presence of diamond in one of the specimens studied indicates a deep-seated origin for the kyanite eclogite nodules. The mineralogical, textural, and spatial relationships of the secondary igneous assemblage are consistent with the view that the unusual features observed in these nodules resulted from emplacement into the crust in a rapidly ascending kimberlite magma, which caused first melting due to sudden release of pressure followed by quenching due to rapid cooling in rising, expanding gas-rich kimberlite magma.

These nodules are, to our knowledge, the first described examples of partial melting of very deep-seated rocks. We do not mean to imply, however, that the partial melting of these samples is necessarily pertinent to the generation of magma by the partial melting of eclogite in the upper mantle. On the contrary, the partial melting described herein is of a very specialized nature and may be a result of the specific but as yet quantitatively unspecified conditions existing during the generation, ascent, and cooling of kimberlitic magma.

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