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Stressed pyroxenite nodules from the Jagersfontein kimberlite

G. D. BORLEY AND P. SUDDABY
Dept. of Geology, Imperial College of Science and Technology, London, S.W.7

SUMMARY. Examination of some pyroxenite nodules from the Jagersfontein kimberlite shows that they have suffered variable deformation followed by different degrees of recovery. Most interesting of the nodules is the 'diallage rock', which consists of highly sheared and broken lamellar crystals of diopside containing exsolved enstatite. Petrographic evidence indicates a pre-tectonic exsolution of enstatite and a syntectonic exsolution of pyrope–almandine from enstatite. Deformation occurred in the mantle, prior to incorporation of the nodule in the kimberlite. Compositions of pyroxenes from the diallage rock suggest it re-equilibrated at a temperature of 1000 °C and at a pressure of about 35 kb. Olivine and phlogopite, accompanied by serpentine, occur only in broken kink-bands in the diallage rock and they are considered to be of secondary origin, precipitated from kimberlite magma at temperatures near 700 °C.

IN 'Genesis of the Diamond' (1932), Williams described in some detail many of the discrete chrome-diopside nodules found in kimberlite. He commented particularly on the abundance, size, and microscopic textures of nodules of this type from the Kimberley and Jagersfontein pipes. Williams also had many of the chrome-diopside nodules analysed and gave an analysis (Table I), which, allowing for the fact that it is an averaged analysis of bulk-nodules that showed some degree of alteration, is interesting in that it is of a low-chrome sub-calcic diopside. The fact that sub-calcic diopside is common in many discrete diopside nodules and diopside-bearing xenoliths from kimberlites has only recently been recognized by Nixon *et al.* (1963), Sobolev (1970), and Boyd and Nixon (1972). Among the Jagersfontein group of diopside nodules is an unusual variant referred to by Williams as 'diallage rock'. His description refers to a lamellar diopside with '. . . separation planes altered to serpentine, so that the mass now consists of alternate layers of these two minerals; . . .'. It is with an investigation of fragments of this nodule, inadequately described by Williams, and of a few other diopside nodules that this paper is concerned.

Petrography and mineralogy. The size of the original diallage nodule is not known but from the size and shape of the cut fragments in the Imperial College collection it could have been about 15 cm in diameter. Examination of the hand specimens shows that the nodule consisted of slightly bent, coarse, lamellar crystals of diopside that had been kinked and broken at right angles to the length. The resulting main kink-band varies in width but is considerably less than 1 cm (fig. 1*a*). When parted along the lamellae the specimens appear slickensided. Small areas of the 'outer skin' of the nodule cut sharply across the direction of the bent lamellae, indicating that deforma-

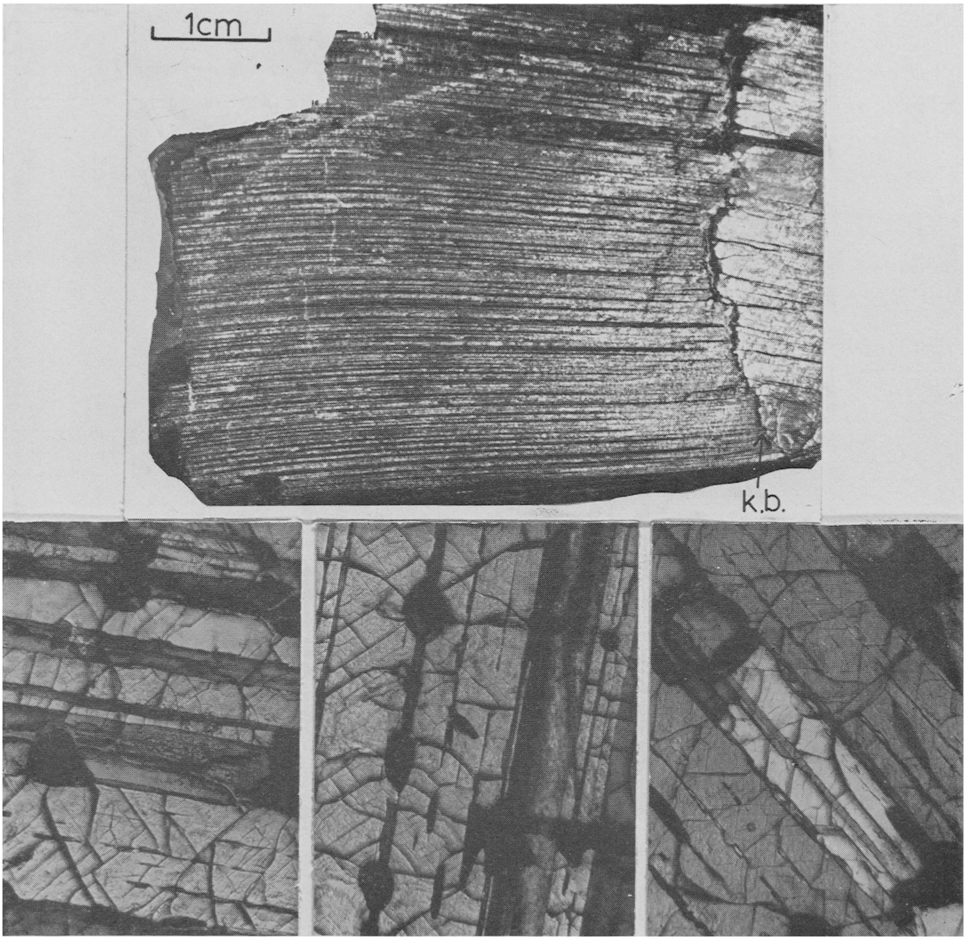

FIG. 1. *a* (top): Side view of cut hand-specimen of diallage rock showing serpentinized lamellar texture and, on right, part of the kink-band (k.b.) cutting the lamellae at right angles; *b* (bottom left): (001) section of diallage rock showing serpentinized enstatite lamellae (dark) in diopside. Grains of pyrope–almandine can be seen in the enstatite. Crossed polars, ×37; *c* (bottom, middle) and *d* (bottom, right): (001) sections of diallage rock showing different forms of garnet (black) in enstatite. Crossed polars, ×37.

tion occurred in the mantle, prior to incorporation of the nodule in the kimberlite magma.

In thin sections cut parallel to (001) the diopside is seen to contain partly or wholly serpentinized exsolution lamellae of enstatite (fig. 1*b*). Minute crystals of pyrope–almandine are aligned along the enstatite lamellae, an orientation that suggests that they also have an exsolution origin. The garnet adopts a number of forms similar in many ways to those shown by garnet exsolved from clinopyroxene described by Lappin (1973). Common forms are: elongate rods aligned along fine lamellae of enstatite; chunky ellipsoids whose long axes are in the direction of the enstatite lamellae; rhomb-shaped (the shape defined by the cleavage traces in the enstatite); blocky rectangular (a shape defined by the edges of the enstatite lamellae and a perpendicular fracture direction), (fig. 1*c* and 1*d*). In the kink-band the lamellar texture of the nodule has been destroyed and pyroxene appears to have recrystallized to variably-sized grains (fig. 2*a*). Some garnet grains are aligned in stringers along the

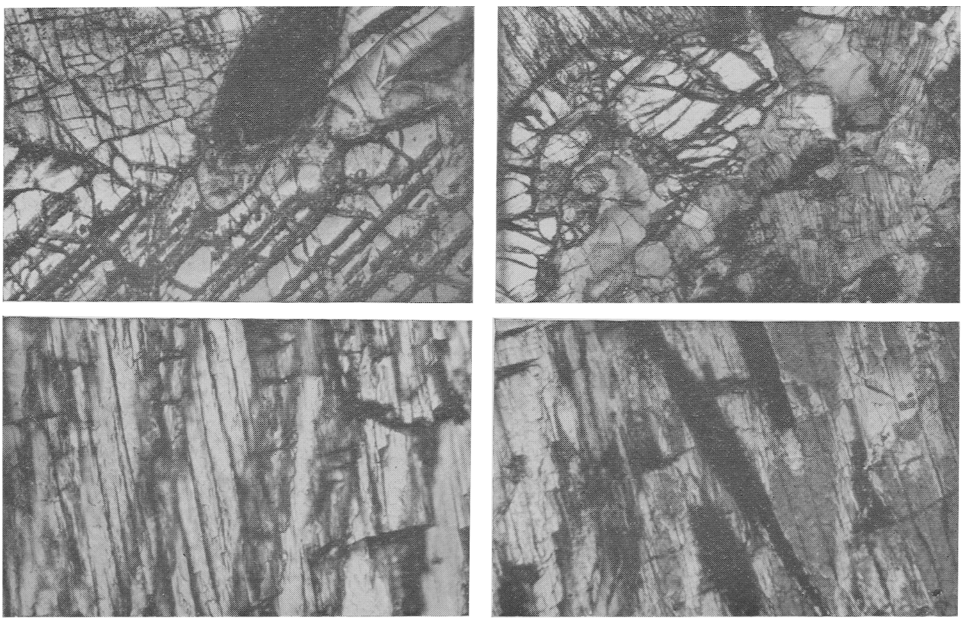

FIG. 2. *a* (top left): Recrystallized diopside in kink-band of diallage rock, with large garnet grain (black). Crossed polars, ×7; *b* (top right): Olivine (colourless, high relief), and phlogopite (well-cleaved) with serpentine in kink-band. Note the very slight indication of deformation in the mica (bent cleavage). Crossed polars, ×12; *c* (bottom left): (010) section of diallage rock showing cleavage, or parting-plane, cutting the diopside and enstatite lamellae (dark) at an acute angle. Crossed polars, ×37; *d* (bottom right): Pyrope–almandine (black) elongated in the direction of the parting-plane. Crossed polars, ×37.

boundaries between lamellar and granular pyroxene and others are scattered randomly through the kink-band. In addition to the recrystallized primary minerals two other important phases are present in the kink-band: forsterite and phlogopite, which are associated with serpentine (fig. 2*b*). The phlogopite is slightly zoned. All the minerals in the kink-band show some interfingering with the lamellar pyroxene. In thin sections cut at right angles to (001), e.g. (010), mineral textures and relationships are seen to be a little more complex. On one side of the kink-band a parting is present, which is parallel to the pyroxene lamellae. This could represent the trace of the parting-plane (100) or prism-plane (110). But on the other side of the kink-band, where the hand-specimen shows the lamellae to be definitely bent, the parting-plane cuts both host and exsolution lamellae at an acute angle (fig. 2*c*). Abundant tension cracks have developed at right angles to this parting and these have apparently acted as channels for serpentinizing solutions, especially where they cut the enstatite lamellae. Slight step-like movements of the lamellae have occurred along the direction of the parting-plane. The most important feature of the (010) sections, however, is that they demonstrate that the pyrope–almandine has a rod or spindle-like form and is oriented in the parting-plane (whatever the orientation of the latter), fig. *2d*. From the petrographic evidence it seems certain that the stress that deformed the nodule and produced the parting-plane was later than the exsolution of the enstatite but prior to, or possibly the cause of, the exsolution of the garnet.

Fragments of two other diopside nodules from the Jagersfontein suite were also examined and, again, the size of the hand specimens suggests the original nodules may have been 10 to 15 cm in diameter. Thin sections of one of them shows a part-lamellar texture though the bulk of the diopside is granulated. The lamellar texture appears to be caused by deformation twinning in the diopside, rather than exsolution. In the other nodule there is no trace of an over-all lamellar texture and the whole mass consists of a granular mosaic in which the diopside shows evidence of deformation and syntectonic recrystallization followed by some grain-growth.

Chemistry. Analyses of minerals from the diallage rock and from other pyroxenites are given in Table I.

Most notable features of the minerals from the diallage rock are that recrystallization of diopside, which took place after the exsolution of enstatite, was not accompanied by compositional changes, that the Ti, Al, and Cr contents of the pyroxenes are low, and that the orthopyroxene has an exceptionally low Ca content. The garnet contains significant amounts of the almandine, uvarovite, and grossular molecules and in this respect is similar to many other pyrope garnets reported by Carswell and Dawson (1969), Boyd and Nixon (1972), and others. Of the postulated secondary minerals the olivine (88 % Fo) has a composition within the normal spread for kimberlitic olivine, and the phlogopite is enriched in Ti and Cr. The Cr content of the phlogopite is similar to that reported by Carswell (1973) for 'secondary' phlogopite in garnet lherzolites from kimberlites, but the Ti and Fe content of the phlogopite in Table I is much higher than in Carswell's analyses. The diopsides from the part-lamellar and granular pyroxenites (Table I) are richer in Ti, Fe, Cr, Na, and Al than diopside from the diallage rock, and it is suggested that these variations are the result of minor element redistributions during deformation, exsolution, and recrystallization of diopside in the different nodules. In their major and minor element chemistry, however, the newly analysed diopsides from both the diallage and other pyroxenite nodules given in Table I differ from the diopsides from discrete nodules, whose deformation state was not mentioned, discussed by Boyd and Nixon (1972). The enrichment in Na and Al shown by diopside from the more granular nodules might indicate a greater degree of solid solution towards soda pyroxene but the absence of $FeO:Fe_2O_3$ ratios makes this speculative.

The low Al contents of the pyroxenes from the diallage rock can be interpreted in two different ways: initial crystallization and re-equilibration took place under conditions of very high pressures, as experimental work (Boyd *et al.*, 1964; Boyd, 1970)

TABLE I. *Analyses of minerals from 'diallage rock' and from other discrete pyroxenite nodules*

	1	2	3	4	5	6	7	8	9	10
SiO_2	54·7	54·2	57·7	41·5	40·4	38·6	54·0	54·1	54·2	53·38
TiO_2	0·02	0·01	0·02	—	—	3·57	0·39	0·42	n.d.	0·67
Al_2O_3	0·79	1·05	0·37	22·0	—	12·92	1·52	1·54	0·35	1·76
Cr_2O_3	0·33	0·34	0·03	0·93	0·05	1·72	1·03	1·03	1·33	0·30
Fe_2O_3	n.d.*	n.d.*	n.d.*	n.d.*	n.d.*	n.d.*	n.d.*	n.d.*	n.d.*	3·74
FeO	1·93	2·1	6·9	11·7	11·1	4·1	3·44	3·45	2·03	4·32
MnO	0·04	0·11	0·12	0·69	0·16	0·04	0·12	0·11	0·08	—
NiO	0·12	0·1	0·15	—	0·48	0·23	n.d.	n.d.	n.d.	0·26
MgO	17·1	16·8	34·8	17·8	46·6	21·6	16·1	15·8	17·0	22·03
CaO	23·4	23·2	0·31	5·0	0·03	0·06	20·6	20·6	22·8	13·55
Na_2O	0·65	0·70	—	—	—	0·4	1·9	1·9	1·1	—
K_2O	—	—	—	—	—	10·0	tr.	0·07	—	—
Sum	99·08	98·51	100·40	99·62	98·82	93·24	99·08	99·02	98·91	[100]†
Cations on a basis of n oxygens:										
n	*6*	*6*	*6*	*12*	*4*	*23*	*6*	*6*	*6*	*6*
Si	2·006	1·987	1·979	2·998	1·009	5·922	1·971	1·991	1·968	1·940
Al	0·035	0·048	0·016	1·888	—	2·321	0·065	0·066	0·013	0·078
Ti	—	—	—	—	—	0·414	0·011	0·011	—	0·017
Cr	0·009	0·009	—	0·052	—	0·202	0·031	0·031	0·040	0·009
Fe^{3+}	*	*	*	*	*	*	*	*	*	0·100
Fe^{2+}	0·057	0·064	0·198	0·712	0·231	0·525	0·102	0·104	0·064	0·131
Mn	—	0·002	0·002	0·044	0·005	—	0·002	0·002	0·002	—
Ni	0·002	—	0·004	—	0·010	0·027	—	—	—	0·006
Mg	0·942	0·924	1·792	1·945	1·748	4·973	0·882	0·889	0·943	1·201
Ca	0·922	0·915	0·012	0·389	—	—	0·808	0·814	0·927	0·529
Na	0·044	0·048	—	—	—	0·110	0·131	0·132	0·040	—
K	—	—	—	—	—	1·952	—	—	—	—
Atomic % in pyroxenes:										
Ca	48	49	—				46	46	48	
Mg	49	48	90				49	49	49	
Fe	3	3	10				5	5	3	
Mol. % Fo in olivine					88					

* Electron-probe analyses; all Fe calculated as FeO. † Recalculated to 100 %.
Anals. 1 to 6 are from 'diallage rock'. 7 and 8 from part-lamellar pyroxenite.
1. Lamellar diopside 2. Granular diopside 3. Enstatite 4. Pyrope–almandine 5. Forsterite 6. Phlogopite 7. Lamellar diopside 8. Granular diopside 9. Diopside from granular pyroxenite 10. Williams (1932), average diopside nodule

shows that high pressure favours formation of low Al enstatites; or pyroxene crystallized initially from a high αSiO_2 melt as high silica activity favours formation of low-Al pyroxenes (Kushiro, 1960; Verhoogen, 1962; Campbell, 1973). A high-pressure origin for many xenoliths in kimberlite is now accepted and it is considered that the exsolution of enstatite from diopside in the diallage rock also represents a high-pressure reaction, but the possibility of the initial formation of diopside being from a high αSiO_2 magma seems worth considering. In general, the partition of the minor elements Al, Ti, Mn, Ni, Cr among the different phases in the pyroxenites accords with that predicted from a consideration of coupled substitutions, site-size variations (octahedral), and the values of crystal-field stabilization energies of the transition metals (Burns, 1970). In the pyroxenes Al and Cr favour the clinopyroxene and Ni and Mn marginally favour the orthopyroxene sites.

Origin and deformation history of the diallage rock. Applying the experimental data of Davis and Boyd (1966) on the diopside(en) solvus gives a re-equilibration temperature of *c.* 1000 °C for the diallage rock. Using the pressure correction of Wood and Banno (1973) in the manner of Boyd (1973) for iron-bearing pyroxenes and garnets gives a re-equilibration depth of *c.* 110 km (about 35 kb pressure). Following equilibration and exsolution of enstatite, the diallage was subject to a high non-isotropic shearing stress during which pyrope–almandine was exsolved from the enstatite. This exsolution of garnet from the stressed orthopyroxene is very similar to that described by Dawson and Smith (1973) for garnet in the orthopyroxene of a garnet lherzolite. During the shearing, or later, breaking of the diallage took place along kink-bands and in these areas the pyroxene recrystallized in granular form.

Later events in the history of this rock are considered to have followed its incorporation into the kimberlite magma. Firstly, minor quantities of magma percolated the broken area of the kink-band and precipitated forsterite and phlogopite. Evidence for this view is threefold: the occurrence of these two minerals is restricted to the kink-bands and to areas close-by; neither mineral occurs in the other, probably related, pyroxenites described in earlier sections; and kimberlite magmas are rich in Cr, which is high in the phlogopite and which, partitioned between co-precipitating olivine and phlogopite, is likely, on the basis of substitution and crystal-field considerations, to favour octahedral sites in phlogopite. A final, and perhaps substantial, point in favour of a secondary origin for these minerals is that olivine shows no signs of deformation and phlogopite only minor evidence of deformation textures. If the suggestion of a secondary origin is valid then possible temperatures of formation of the minerals can be put forward. Seifert and Schreyer (1966) showed that olivine and phlogopite plus fluid could coexist at temperatures down to 700 °C/600 °C and, as olivine and phlogopite are the minerals formed in the kimberlite groundmass, Mitchell (1973) suggested the latter crystallized at about 600 °C. A temperature of 700 °C to 600 °C would not be unreasonable in view of the suggested temperature of 1000 °C for diopside re-equilibration. The final event to affect the nodule was the serpentinization of the enstatite and secondary minerals in the broken kink-bands.

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