considerably lower temperatures[6,7]. Kimberlites or carbonatites rising from the low velocity zone must evolve CO_2 as they reach the reaction boundary at depths between about 100 and 80 km. This would certainly contribute to the explosive emplacement of kimberlites.

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67

Palaeogeothermal gradients derived from xenoliths in kimberlite

GREAT problems exist in the determination of an ancient geothermal gradient. An attempt has been made by Boyd[1], based primarily upon the equilibration conditions of coexisting pyroxenes in garnet lherzolite xenoliths from the Thaba Putsoa, Letseng and Mothae kimberlite intrusions in northern Lesotho. He derived the equilibration temperature of the xenoliths from the amount of enstatite in solid solution in the diopside[2], and estimated the pressure from the amount of Al_2O_3 in the orthopyroxene[3]. He argued that, for a group of lherzolite xenoliths, a line joining a series of pyroxene-derived pressure/temperature points should define the geothermal gradient in the mantle below northern Lesotho during the Cretaceous when the xenoliths were entrained by the kimberlite during its ascent. He found a Cretaceous gradient similar to that in present-day shield areas between depths of 100 and 150 km, though from 150 to 200 km depth it was considerably steeper. Moreover, whereas the lherzolites outlining the shallower 'normal' part of the gradient are of granular texture, those outlining the high-temperature, steeper and deeper segment exhibit a range of deformation and recrystallisation textures (the porphyroclastic and mosaic textures in the classification scheme of Bouiller and Nicolas[4]).

Accordingly, it has been proposed[1,5] that the perturbation of the normal subcratonic gradient was caused by stress heating at the base of the African Plate during the breakup of Gondwanaland in the Cretaceous, with the 150 km inflection point on the gradient being the top of the sheared, low-velocity zone at that time. Inflected geothermal gradients have been proposed within the upper mantle beneath other parts of the South African Shield, the North American Craton and the Siberian Shield, based on granular and deformed peridotite suites from Jagersfontein[6]; Louwrencia[7], SW Africa; Black Butte diatreme, Montana[8]; Ming Bar diatreme, Wyoming[9]; and the Udachnaya diatreme, Yakutia[10]. These data cannot, however, be accepted unreservedly as typical of events within the upper mantle at the time of the generation and ascent of the kimberlite magma. There is evidence to the contrary in xenolith suites from at least three different kimberlite intrusions.

The peridotites and pyroxenites from the Matsoku kimberlite diatreme, Lesotho, have been more thoroughly investigated than any other xenolith suite[11-13]. They show a wide variety of textures, including those falling into the 'sheared' class of Nixon and Boyd[5]. But no matter what degree of deformation the Matsoku xenoliths have undergone, they all apparently equilibrated under the same pressure/temperature (PT) conditions and there is thus no correlation between deformation and increased temperature of equilibration in this particular xenolith suite. The restricted PT conditions indicated are those of Boyd's[1] coarse granular suite. As the Matsoku kimberlite is closely contemporaneous with the Thaba Putsoa kimberlite, and is only 20 km from it, it is difficult to accept a hypothesis involving large-scale horizontal movements in the upper mantle that did not have similar effects at both localities.

In the case of the xenolith suite from the Frank Smith Mine, north of Kimberley, a variety of deformation textures can be found in rocks apparently derived from a restricted mantle zone[14], although the range does not include granular textures as it does at Matsoku, and the equilibration temperatures are close to 1,250 °C.

We have been investigating a suite of xenoliths from the Bultfontein kimberlite diatreme, Kimberley. The garnet lherzolites show a greater textural range than those from Thaba Putsoa and we have recognised a new textural type that indicates a greater degree of deformation than recognised previously in kimberlite xenoliths. This new texture, which may be regarded as a more deformed extension of Bouiller and Nicolas' fluidal mosaic texture[15], comprises recrystallised orthopyroxene neoblasts strung out into bands that alternate with bands of fine-grained olivine neoblasts; furthermore, garnet unaffected by lower degrees of deformation has been disrupted and strung out into chains of small crystals. We call this texture 'banded and disrupted' (BAD).

We have analysed the phases in 26 selected garnet lherzolites from Bultfontein, covering the range of textural types from granular to BAD. The data will be published elsewhere but Table 1 shows analyses of phases in typical

Fig. 1 Plot of Al_2O_3 (in orthopyroxene) against Ca/Ca+Mg (in clinopyroxene) for xenolith suites from Thaba Putsoa[5] (open symbols) and Bultfontein (solid symbols). Triangles, minerals in rock of granular texture; circles, minerals in rocks of flaser (Bultfontein) and sheared (Thaba Putsoa) texture. The Bultfontein flaser peridotites exhibit porphyroclastic, mosaic and BAD textures.

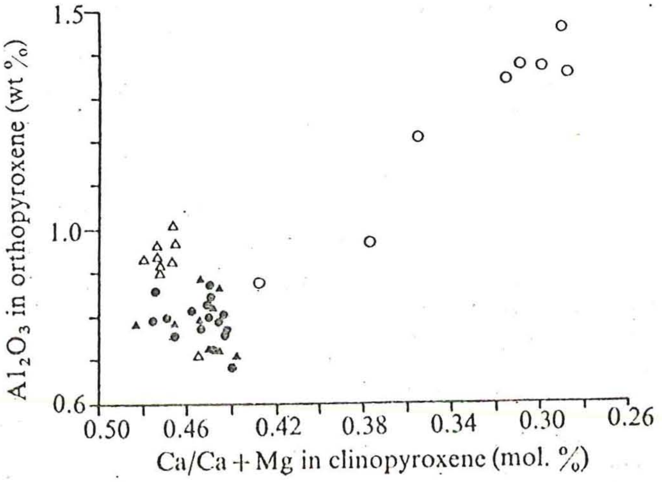

Table 1 Analyses (*a*) and structural formulae (*b*) of minerals in typical Bultfontein peridotites at opposite ends of the deformation spectrum

a	BD2382: granular garnet lherzolite				BD2446: banded and disrupted garnet lherzolite			
	Olivine	Orthopyroxene	Clinopyroxene	Garnet	Olivine	Orthopyroxene	Clinopyroxene	Garnet
SiO_2	40.00	57.38	54.79	41.69	41.51	57.05	54.83	41.93
TiO_2	0.02	0.04	0.11	0.08	0.00	0.05	0.07	0.05
Al_2O_3	0.01	0.78	2.39	22.62	0.02	0.82	2.51	20.67
Cr_2O_3	0.00	0.06	1.42	2.19	0.02	0.36	2.53	5.01
FeO*	8.87	5.58	2.51	8.19	6.88	4.22	1.88	6.92
MnO	0.04	0.03	0.00	0.36	0.00	0.09	0.07	0.36
MgO	50.96	36.14	16.27	22.62	51.41	36.48	16.54	20.34
CaO	0.02	0.27	21.26	4.78	0.01	0.31	18.94	5.05
Na_2O	0.00	0.10	2.00	0.02	0.06	0.09	2.27	0.05
K_2O	0.00	0.00	0.00	0.00	0.02	0.01	0.02	0.00
Total (wt %)	99.9	100.4	100.7	98.5	99.9	99.5	99.6	100.3
b								
Si	0.979	1.965	1.972	3.022	1.003	1.961	1.982	2.992
Ti	0.000	0.001	0.003	0.004	0.000	0.001	0.002	0.003
Al	0.000	0.031	0.100	1.933	0.001	0.033	0.107	1.732
Cr	0.000	0.002	0.040	0.126	0.000	0.010	0.072	0.282
Fe	0.181	0.160	0.076	0.540	0.139	0.121	0.057	0.413
Mn	0.001	0.001	0.000	0.022	0.000	0.006	0.002	0.022
Mg	1.859	1.845	0.873	1.925	1.852	1.872	0.892	2.164
Ca	0.001	0.010	0.820	0.371	0.000	0.011	0.732	0.386
Na	0.000	0.007	0.140	0.003	0.003	0.006	0.159	0.007
K	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.000
O	4	6	6	12	4	6	6	12
Mg/Mg+Fe	0.911	0.920	0.920	0.781	0.930	0.939	0.939	0.831
Ca/Ca+Mg			0.484				0.451	

*All iron as total FeO.

rocks from the two ends of the deformation spectrum. For the suite as a whole there are three pertinent features. First, no matter what the texture, the Ca/Ca+Mg ratio of the clinopyroxene is in the range 0.422–0.484 (wt %), indicating equilibration temperatures of 950–1,050 °C (ref. 2). Second, the Al_2O_3 content of all the orthopyroxenes is very similar to that in lherzolite orthopyroxenes in the Matsoku kimberlite (0.73–0.89 wt%), again indicating equilibration over a restricted pressure (depth) interval (Fig. 1). In view of the absence of experimental data on orthopyroxenes containing less than 2 wt% Al_2O_3, we are not prepared to draw any pressure (depth) implications from our results, other than to submit that they are of mantle origin, within the garnet lherzolite stability field. Third, the composition of the garnets is broadly similar in most lherzolites, with the exception that in a very few of the more deformed lherzolites, there are small increases in the TiO_2 content.

These data provide evidence that increased deformation cannot always be correlated with significant increases in temperature of equilibration or with increased depth or origin, as is the case for Thaba Putsoa xenoliths. Further, we have observed deformation gradients from granular to BAD textures within the same hand specimens over a distance of 2–3 cm and must assume that the deformation may be both very localised and very variable. This is not consistent with a major tectonic boundary, and may be caused by variable hydrolitic weakening.

It is clear that within the xenolith suite from each locality there is evidence of major deformation, consistent with differential movements in the upper mantle. One feature that is not clear is the sense of these movements. Strong lateral movements, accompanying the breakup of Gondwanaland, are proposed in the Thaba Putsoa model of Nixon and Boyd[5], whereas the model for the origin of kimberlites by diapiric upwelling in the upper mantle[16], invokes strong vertical movements. The evidence of individuality in the range of textures and equilibration conditions of xenolith suites from different diatremes is possibly more consistent with the latter hypothesis in that it links the characteristics of a xenolith suite with the particular upper mantle movements that culminate in the emplacement of the kimberlite intrusions. Nonetheless, we do not exclude the possibility that some of the textures developed during the kimberlite event may be additional to textures developed during earlier upper mantle creep. A model involving vertical movement finds support in the geological evidence in that, during the Cretaceous, when most South African kimberlites were emplaced, the South African continent was subjected to strong vertical movements, resulting in peripheral faults downthrowing 18,000 m towards the contiguous ocean basins[17].

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