High-Mg Tholeiitic Rocks and their Significance in the Karroo Central Province

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Averages for the composition of dolerites from the Southern and Eastern Cape, and the correlative basaltic lavas of the Stormberg, are presented for major elements and 8 of the more significant trace elements. The remarkable correspondence between these averages is indicative of the uniformity in composition of the magma emplaced over a very large area. The lavas show limited compositional variation, with 96% of samples falling within the range 5–8% MgO. The dolerites constitute a much more varied suite, because of differentiation effects. Attention is focused on a class of high-Mg rocks with 9–20% MgO which occur as chilled margins to, or schlieren within, some intrusions. It is recalled that the bulk composition of some intrusions is within this range, and that these features have been used as evidence to suggest the existence of high-Mg magmatic liquids within the Karroo Central Province. Geochemical investigation of these rocks, supported by microprobe analysis of the olivine phase, shows that they are derived simply by olivine enrichment within 'normal' Karroo magma, with the Ni/Mg and Mg/Fe ratios of the olivines being incompatible with their equilibration with high-Mg melts.

Introduction

The common dolerite of the Karroo ('ysterklip', 'burnt klip' or 'reef') might appear to be too prosaic a subject to be worthy of serious study. There are, however, sound reasons for detailed geochemical research into this common rock and its effusive equivalent, the basaltic lavas capping the high regions of the Stormberg and the Drakensberg. Current geological thought can offer no plausible alternative to regarding basaltic rocks as derivatives from the Upper Mantle underlying the thin outer crust of both continental and oceanic regions. The true nature of this mantle can, however, be deduced only by indirect means. Such means include geophysical observations (particularly in the fields of seismology, earth magnetism, heat flow and gravity), the study of exotic rock fragments carried to the surface within the conduits feeding kimberlite pipes and alkaline lava fields, and the study of ophiolite complexes. By many, these complexes are regarded as sections of oceanic crust and underlying mantle faulted to surface, but current evidence[1] suggests that the mantle-type rocks exposed here are already depleted by loss of a low-melting-point fraction. An alternative approach to the study of mantle chemistry is offered by the study of its derivative fractions generated by partial melting—the dolerite-basalt suite. In this approach it becomes critically important to establish whether the rocks now available for sampling represent true liquids evolved from mantle-derived melts, or liquids modified by either addition or subtraction of solid phases. In particular, the implications surrounding the generation of high-Mg liquids from a mantle source would render high-Mg rocks of particular significance. The present paper deals with some aspects of this problem and focuses attention on certain high-Mg rocks within the Karroo Central Province.

A milestone was reached in the study of Karroo magmatism with the publication by Walker and Poldervaart[2] of their classic paper on Karroo dolerites in 1949. Not the least valuable contribution of their study was the comprehensive compilation of analytical data available at that date. Subsequent research has been sporadic, but there has been a resurgence of interest within the period 1974–79, under the incentive provided by the National Geodynamics Project sponsored by the CSIR. This has led to the amassing of a vast amount of precise analytical data which permits, amongst other things, meaningful comparisons to be drawn for the first time between the intrusive and extrusive suites of the central Karroo region.

All whole-rock analytical data reported here have been determined by X-ray fluorescence spectrometry, while mineral data have been established by electron microprobe analysis.

The composition of Karroo dolerites and Stormberg lavas

The average composition of the dolerites within the region bounded by East London, Barkly East and Bethulie has been established by Robey,[3] who analysed selected samples of the chilled margins of a number of intrusions. The adopted averages are given in Table 1. A similar study by one of us (J.S.M.) of the dolerites between Fort Beaufort and Sutherland has yielded very similar results (Table 1, No. 2). A further study of a 600-metre column of lavas in the Barkly East-Rhodes area (Lesotho Formation of Lock *et al.*[4]) has been completed by Pemberton[5] and the averages arrived at are also reported here (Table 1, No. 3). The correspondence between the three independent sets of data is remarkable and it is therefore adopted as a fundamental premise that there is no significant difference between the intrusive and extrusive suites. The data are also significant in that they imply very limited variations in magma composition over a large area. Furthermore, the dolerite suite includes samples from the coastal regions where it is intrusive into Beaufort Group sediments, which may lie stratigraphically as much as 6 km below the lava pile.[6] There appears, therefore, to be no support for any proposition that these magmas might have systematically changed composition as they rose within the uppermost part of the crustal section.

Figure 1 compares the range of MgO values indicated by 217 analyses of Karroo dolerites of the southern, central and north-eastern Cape and Transkei, and 118 analyses of Stormberg basalts. The dolerite data include here both chilled and coarse-grained rocks. A pronounced modal class exists between 5% and 8% MgO in both the intrusive and extrusive suites, but while 96% of the volcanic rock samples fall within this range, only 55% of the intrusive rock population does so. The distribution

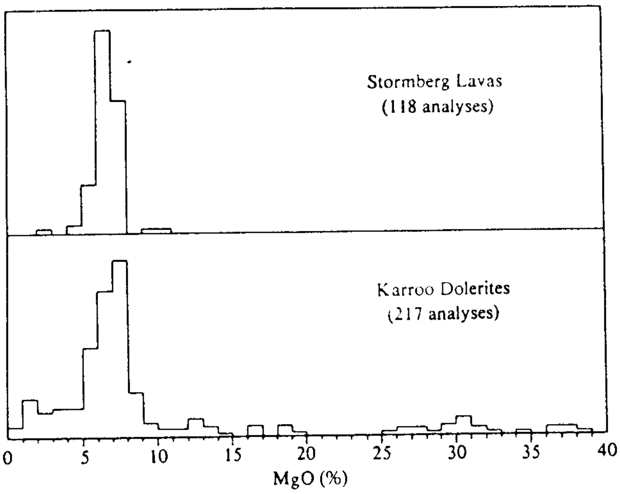

Fig. 1. Histograms showing range and frequency of MgO values in Stormberg lavas and Central Province Karroo dolerites. Data for lavas from Robey,[3] Pemberton,[5] Eales *et al.*,[7] Rumble,[14] and Mitchell.[21] Dolerite data from Walker *et al.*,[2] Robey,[3] Eales *et al.*,[7] Maske,[13] Kenyon,[22] Le Roex *et al.*[23] and unpublished analyses by the authors.

exhibited by the intrusive suite is not to be regarded as statistically representative, biased as it is by emphasis on the less common derivatives, but it is nevertheless clear that the intrusive suite encompasses certain ranges of compositions that are simply not represented amongst the extrusives.

The data of Fig. 1 exclude rocks believed to have originated by significant interaction between magma and sediment, so that those within the range 0.5–5% MgO can be interpreted as late-stage liquid residua of low-pressure fractional crystallization. Amongst the best documented examples of this type are the ferrogabbros and silicic derivatives of the Birds River intrusion near Dordrecht. Major- and trace-element data[3,7,8] together with rare earth element studies recently completed by A. R. Duncan (pers. comm.) have established a quantitative, self-consistent model of the evolution of SiO_2-enriched, MgO-depleted rocks by prolonged fractional crystallization of melts. The most highly evolved residua here represent only 12–15% of the mass of the original magma.

The range of MgO values between 25% and 40% in Fig. 1 represents cumulus rocks. These are largely composed of high-density, early crystallized silicates such as olivine, clinopyroxene and orthopyroxene, together with low-density feldspars. These minerals have settled under gravity within the basal portions of some larger intrusions while crystallization was proceeding. Well-documented examples of these rocks occur within the Elephant's Head intrusion[2,9,10] and the Insizwa[11,12] and Ingeli[13] masses.

The rocks spanning the ranges 0.5–5% and 25–40% MgO are therefore clearly identifiable in Fig. 1. Similarly, the modal class extending from 5–8% MgO, typical of both intrusive and extrusive suites, must be representative of the magma delivered to the sites of final intrusion or extrusion. A division of these lavas of the Stormberg into at least 4 sub-types is possible[5,14] on the basis of abundances of and ratios between trace elements, as well as rather subtle major-element differences, but these differences are not presently under discussion. It is the origin of rocks within the range 9–20% MgO that calls for comment. Some of these are dolerites or gabbros weakly enriched in cumulus phases and the understanding of their composition presents no problem. Some, however, are fine-grained rocks that have been found along the quenched upper contacts of intrusions, or as schlieren and, as such, they are clearly not cumulates in the normal sense. A possible inference that high-Mg basaltic melts existed within the Karroo central igneous province therefore merits examination, particularly as the bulk

Table 1. Average compositions for Karroo Central Province dolerites and Stormberg lavas.

	1		2		3	
SiO_2	51.71%	(1.1)	51.62%	(1.6)	51.60%	(2.5)
TiO_2	0.98	(6.3)	1.00	(15)	0.95	(6.2)
Al_2O_3	15.31	(2.0)	15.10	(2.3)	15.71	(3.1)
Fe_2O_3*	11.20	(3.8)	11.37	(7.1)	11.03	(4.3)
MnO	0.18		0.23		0.16	
MgO	6.83	(7.5)	6.89	(9.0)	7.11	(7.6)
CaO	10.84	(3.3)	10.58	(3.8)	10.60	(6.0)
Na_2O	2.28	(7.8)	2.39	(7.7)	2.16	(14)
K_2O	0.51	(38)	0.58	(23)	0.73	(39)
P_2O_5	0.17		0.16		0.16	
Sr	212 ppm	(8.5)	204 ppm	(9.4)	183 ppm	(16)
Rb	12	(45)	11.7	(21)	13	(72)
Y	25	(4.1)	27	(9.8)	24	(9.3)
Zr	97	(9.4)	94	(14)	91	(12)
Nb	6.9	(29)	5.0	(12)	4.4	(22)
Ni	88	(24)	79	(23)	89	(16)
V	235	(6.1)	nd		234	(7.7)
Cr	264	(22)	nd		271	(18)

1, Eastern Cape dolerites. Average of 17 duplicate analyses by Robey.[3] 2, Southern Cape dolerites. Average of 10 duplicate analyses by J. S. Marsh. 3, Lesotho Formation basalts, Naude's Nek, N.E. Cape. Average of 32 duplicate analyses by Pemberton.[5] *All Fe expressed as Fe_2O_3 All analyses calculated to 100%, on L.O.I. (loss on ignition) – and H_2O-free basis. Trace elements given in ppm. Bracketed figures are standard deviations expressed as a percentage of the mean.

composition of some large intrusions has been claimed to be within this range. Maske[13] has, for example, calculated that the bulk composition of the entire Ingeli mass averages 13.3% MgO. Bruynzeel[12] assigns a mean value of 15.2% MgO to the lower 420-metre section of the Insizwa mass, which she regards as a single intrusion, and Poldervaart[9] a value of 12.5% to the initial magma at Elephant's Head.

Table 2. Compositions of quenched margin and Mg-enriched rocks.

	1	2	3	4	5
SiO_2	45.41%	46.23%	42.46%	47.81%	49.18%
TiO_2	0.78	1.17	0.41	0.55	0.64
Al_2O_3	11.51	15.69	5.97	11.44	13.23
Fe_2O_3	12.49	12.06	13.63	11.08	11.07
MnO	0.17	0.17	0.17	0.25	0.21
MgO	18.03	7.80	31.49	16.95	12.88
CaO	8.72	11.36	4.36	8.43	9.76
Na_2O	1.32	2.28	1.13	1.58	1.56
K_2O	0.17	tr.	tr.	0.43	0.41
P_2O_5	0.06	0.25	0.03	0.08	0.09
H_2O-	0.10	0.26	0.07	nd	nd
L.O.I.	1.03	2.63	0.66	0.50	0.64
Total	99.80	99.91	100.38	99.10	99.67
Sr	127 ppm	302 ppm	75 ppm	100 ppm	117 ppm
Rb	11	3	3	12	6
Y	17	24	8	17	21
Zr	53	97	28	62	65
Nb	<1	3.4	<1	<1	2.8
Ni	890	167	1885	607	391
V	236	269	130	nd	nd
Cr	2200	183	3130	nd	nd

1, High-Mg, olivine-phyric, quenched margin *Q*. Elephant's Head. 2, 'Normal', aphyric, quenched margin *A*. Elephant's Head. 3, Picrite (*P*) Elephant's Head. 4, High-Mg, quenched rock SK12, 7 km south of Fort Beaufort. 5, High-Mg, quenched rock SK46, Munnikpass, Graaff-Reinet.

Features of high-Mg rocks in the Karroo Central Province

The strongly differentiated Elephant's Head intrusion of the Transkei[2,9,10] provides along the upper contact an exposure of chilled rock with 18% MgO (Table 2, No. 1). Poldervaart[9] has described and analysed a texturally similar variant from the lower contact at Mount Fred. This rock contains 30% MgO and is referred to as 'variolitic picrite'. Bruynzeel[12] has published an analysis showing 10% MgO in the chill phase of the Insizwa mass at Waterfall Gorge, and refers also to an earlier analysis by Goodchild where the value is given as 13.4% MgO. The high-Mg rocks near Aliwal North described by Frankel[15] are probably of similar type, while further similar examples have now been identified by us in the chilled margins of sills in the southern Cape between Fort Beaufort and Sutherland (Table 2, Nos 4–5). It is significant that these Mg-rich margins may be thin (e.g. 1 m thick in a 60 m sill) and grade rapidly to more normal dolerite.

All available evidence refutes the identification of these rocks with primary liquids of the same composition. The textures are porphyritic, with small euhedral olivine and chromiferous spinel phenocrysts[10] set in a groundmass of acicular plagioclase and pyroxene forming radial, sheaf-like masses nucleated on the phenocrysts. The textures are typical of quenched liquids bearing older-generation crystals in suspension. Strong support for this contention is found in geochemical data, which show quite unequivocally that these quenched high-Mg rocks must have been emplaced as normal basaltic melts bearing an equilibrium assemblage of suspended olivine crystals. Two approaches are adopted here—the first examines Ni/Mg ratios, and the second Mg/Fe data.

Ni-Mg-Fe geochemistry of the Elephant's Head rocks

The Ni/Mg relationships in the Elephant's Head picrites, olivine gabbros and quenched margins are illustrated in Fig. 2 by plotting Ni against MgO. Here it is seen that the lowermost (oldest) picrite, *P* (Table 2, No. 3), has the highest Ni/Mg ratio and that this ratio declines steadily with increasing height within the pile of cumulates (*P1-G*). The curve produced is a function of the high distribution coefficient for Ni in olivine, which leads to rapid depletion of Ni in the magmatic residua during olivine crystallization from a finite volume of liquid. Points *A* and *D* represent, respectively, an aphyric margin to the Elephant's Head intrusion, and the Karroo dolerite averages of Table 1. It is significant that the quenched, high-Mg sample *Q* does not fall on the curve but only slightly off the straight line *DAP* which, when extrapolated to high MgO values, intersects a cluster of data points representing the analysed compositions of both cores and outer rims to olivine phenocrysts in the quenched rock, and passes, within experimental error, through their average composition *M*. This implies that *Q* lies on a mixing line linking an initial magma close in composition to average Karroo dolerite and highly magnesian, early crystallized olivine.

It is possible to show that these olivine phenocrysts are theoretically in equilibrium with a liquid having a composition close to the adopted average for Karroo dolerite. Following Roeder and Emslie[16] and Roeder,[17] we use the equilibrium constant $K = 0.30 \pm 0.03$ for the exchange reaction:

$$\text{Mg (olivine)} + \text{Fe}^{2+} \text{(liquid)} \rightleftharpoons \text{Mg (liquid)} + \text{Fe}^{2+} \text{(olivine)}$$

from which

$$\frac{X^{ol}_{FeO}}{X^{ol}_{MgO}} = K \times \frac{X^{liq}_{FeO}}{X^{liq}_{MgO}}$$

to derive the FeO/MgO ratio of the melt with which the olivine phenocrysts were in equilibrium (X^{ol}_{FeO} etc. are mole fractions). A problem in applying this relationship to natural rocks is that the FeO content of a basaltic *liquid* is not easily determined. Most modern studies[24] suggest that the ratio Fe_2O_3/FeO in tholeiitic basalt magmas lies in the range 0.1–0.2. In the calculations that follow we have selected a value of 0.2 for the ratio but have found that our results and conclusions are not affected significantly if lower values are used or if Fe_2O_3 is calculated using the method of Irvine and Baragar.[18] Where the total Fe content, expressed as Fe_2O_3, for the Karroo magma is taken as 11.2% (Table 1) and the Fe as FeO is derived using a Fe_2O_3/FeO ratio of 0.2, the composition of the parent magma in equilibrium with the analysed olivine phenocrysts is found to be FeO = 8.54, Fe_2O_3 = 1.71, MgO = 7.35–8.98 (for the range of the equilibrium constant 0.27–0.33). This range of MgO values overlaps substantially with the modal class of Fig. 1.

Following Hart and Davis,[19] the distribution coefficient $D^{olivine}_{Ni}$ for a liquid of this composition may be computed as follows:

$$D^{olivine}_{Ni} = \frac{124.13}{\text{MgO}} - 0.897 = 13.82 \text{ (at 8.98\% MgO) to 16.8 (at 7.35\% MgO).}$$

The value of this coefficient, together with the determined average Ni content of the olivine phenocrysts (3045 ppm), indicates that the liquid from which the phenocrysts separated initially contained 181–220 ppm Ni.

This calculation is valid only if the concentrated olivine phenocrysts represent a small crystal fraction of the magma. Observations in sills elsewhere in the Karroo province, where similar rocks are found, indicate that this is so and that the olivine phenocrysts probably represent less than 0.5% of the original magma (see below).

Allowing for experimental errors and the effects of several simplifying assumptions that have been made, this value is in reasonable agreement with the determined Ni content of the aphyric margin *A* of the intrusion (167 ppm Ni, Table 2, No. 2). It is also close to the value that may be computed for the matrix of the quenched, olivine-phyric margin *Q*. Using the olivine content of this rock established by modal analysis (24.8%) and the Ni content of the phenocrysts (3045 ppm) and of the whole rock (890 ppm), the Ni content of its matrix is shown to be 179 ppm.

In summary, then, the geochemical data show that the high-Mg quenched rock *Q* is closely approximated by normal Karroo magma enriched in the olivine phase. There is no evidence that

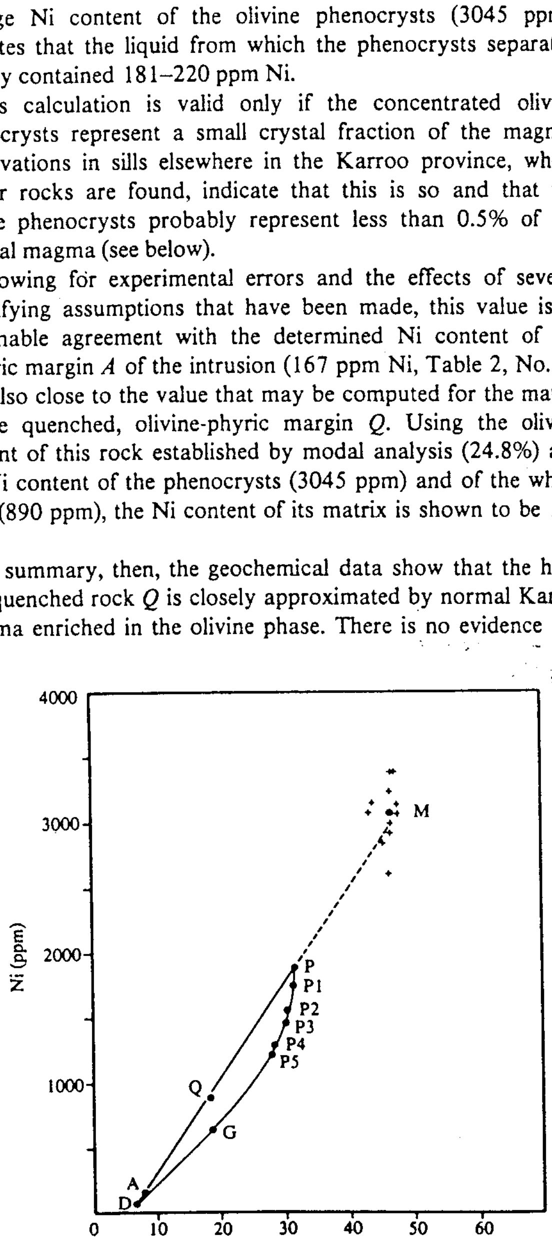

Fig. 2. Ni/MgO relationships within Elephant's Head intrusion. *P-P5* and *G* are cumulus picrites and olivine gabbro, *D* is Karroo dolerite average of Table 1, *A* is the aphyric margin and *Q* the quenched, high-Mg, olivine-phyric margin of the intrusion. Phenocrystal olivine is shown by crosses, the average composition being *M*.

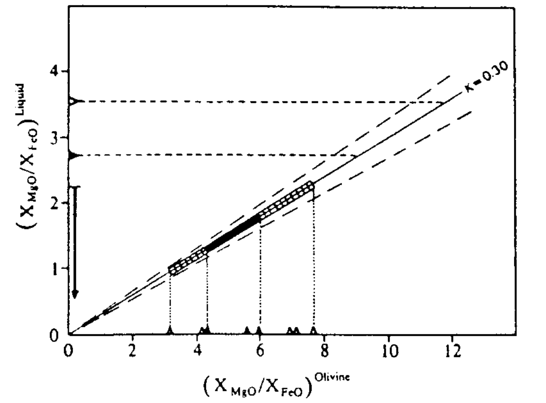

Fig. 3. Mole fraction ratios of MgO/FeO for whole-rock samples and constituent olivine phenocrysts of SK12 (open triangles) and SK46 (filled triangles). The data show that phenocrysts are not in equilibrium with high-Mg melts, but are in equilibrium with 'normal' dolerite magmas (range indicated by vertical arrow) where equilibrium constant is $K = 0.30 \pm 0.03$ (Roeder and Emslie[15]).

indicates it was derived from a high-Mg melt. The calculated Ni content of this melt (181 ppm at 7.3% MgO to 220 ppm at 9.0% MgO) is distinctly higher than the Karroo average, but the agreement between this value, the determined value of the aphyric margin *A* (167 ppm Ni) and the calculated value for the matrix of quenched rock *Q* (179 ppm) suggests that the data are valid.

Other high-Mg dolerites in the Karroo Central Province

Reference has been made to the occurrence of high-Mg rocks at several other localities within the Karroo Central Province. These rocks exhibit petrographic and chemical characteristics which make them indistinguishable from the quenched rock, *Q*, discussed above. Furthermore, their field relationships are strongly suggestive of an origin by enrichment in cumulus olivine. They occur in narrow zones or schlieren, with gradational contacts with normal olivine-free dolerite within or along the upper and lower contacts of thick sills. The obvious inference to be drawn from the field observations is that the olivine crystals have been concentrated from a large volume of magma into the narrow zones by flowage differentiation. Simple mass balance calculations indicate that if this view is correct, the olivine crystals represent fractions less than 0.5% of the original magma.

To support the inferences drawn from field relations, the bulk compositions of these rocks may be tested for compatibility with liquid compositions using the same approach adopted above. The analyses and sample locations of rocks SK12 and SK46, used here as test cases, are given in Table 2 (Nos 4–5). In Fig. 3 the whole-rock MgO/FeO mole fraction ratios are compared with the corresponding ratios for the olivine phenocrysts. For the whole-rock samples, the ratio has been determined assuming a uniform oxidation ratio (by weight) $Fe_2O_3/FeO = 0.2$. At equilibrium, the plotting of these MgO/FeO mole fraction ratios against each other should yield a line with a slope of 0.3 ± 0.03[16,17] but it is clear that even the cores of the phenocrysts have MgO contents too low for them to have crystallized from liquids having the bulk compositions of rocks SK12 or SK46. The range in the mole ratio MgO/FeO for 'normal' Karroo dolerites with MgO<8.0% is also shown in Fig. 3; the olivine phenocrysts are seen to be compatible with liquids within this range. Thus rocks like SK12 and SK46 are interpreted as being portions of 'normal', low-Mg dolerite enriched in olivine.

Figure 4 represents a computer-generated model which illustrates the theoretically derived compositional range of liquids from which crystallized olivine may accumulate to produce Mg-rich rocks. The value of the equilibrium constant for calculating olivine compositions, and the method for computing the distribution coefficient of Ni in olivine, have been presented above. The shaded field of Fig. 4 encompasses the compositions of various high-Mg Karroo rocks from the Central Province (plotted as separate points) and delineates all possible compositions formed by accumulation of olivine crystallizing from liquids within the stippled prism area. The limits of the prism area in terms of MgO have been arbitrarily set at 6.5 and 10% MgO and, in terms of Ni, are fixed by the Ni contents of the various occurrences of high-Mg rocks.

Significantly, the prism area is small and there is a small overlap at low Ni values with the field illustrating the actual compositional range of normal Karroo dolerites. If the normal Karroo dolerites are regarded as derivative complementary liquid fractions of the olivine fractionation process giving rise to high-Mg rocks, it is possible to constrain further the Ni and Mg contents of possible parent magmas within the prism. This can be done by computing fractionation curves for a variety of theoretical parents within the prism. If a fractionation curve does not pass through the field of normal dolerite, then the relevant parent composition is atypical of the majority of data points for the Karroo. The parent-liquid field constrained by the fractionation curves is shown in the inset in Fig. 4. It encompasses a narrower (lower) range of Ni values, especially at low MgO values.

The field of Karroo high-Mg rocks (Fig. 4) can be extrapolated to MgO values typical of olivines crystallizing from the theoretical parent liquids. Because the shaded field is defined by a family of mixing lines between low-MgO liquid and olivine, its intersection with MgO contents appropriate to olivine compositions allows theoretical concentrations of Ni in the olivines to be estimated. These values range from 1700 ppm to 3200 ppm and compare well with Ni concentrations of 1730–2900 ppm actually measured in olivines of SK12 and SK46 by microprobe analysis. It should be stressed that Fig. 4 is not in itself proof of mixing, but taken with other evidence presented here and in our files it supports our thesis regarding the origin of these high-Mg rocks.

Discussion and conclusions

The new data now available permit accurate comparisons to be drawn between the compositions of the uppermost Stormberg

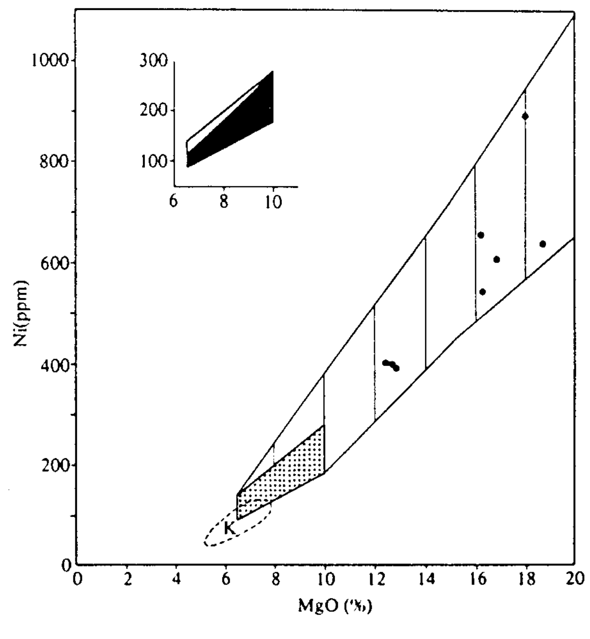

Fig. 4. Computer-generated model of possible parent-melt compositions (stippled prism) from which olivine-enriched rocks (shaded area) may be derived. Filled circles depict actual high-Mg samples, area *K* is field of common Karroo dolerites, and inset shows (black area) theoretically possible parent melts of common Karroo dolerites in area *K*.

lavas and their equivalent Karroo dolerites. The compositional differences between the two averages are seen to be very nearly negligible. No systematic trends are discernible over a very large area (in contrast with the model proposed by Rhodes and Krohn[20]) or through a crustal section that may be as much as 6 km thick.[6] The basalt suite exhibits limited compositional variation, but the intrusive sub-volcanic suite shows wider fluctuations about the modal class of 5–8% MgO. While much of the variability can clearly be linked with gravitational settling of high-density phases from their parent melts, and the evolution of complementary liquid residua, a class of intrusive, fine-grained, basaltic rocks with 9–20% MgO exists for which the origin has been less clear in the past. Many investigators[2,9,12,13] have favoured the existence of high-Mg magmas in the Karroo Central Province, but the evidence provided by Ni/Mg and Mg/Fe ratios of olivine crystals and whole-rock samples cannot be reconciled with the existence of such liquids. Furthermore, the whole-rock Ni/Mg ratios of $6–9 \times 10^{-3}$ which are encountered in these rocks are even higher than the range $4.3 - 5.2 \times 10^{-3}$ which Hart and Davis[19] calculate to be typical of the most primitive liquids in equilibrium with a mantle composed of 70% olivine, 20% orthopyroxene and 10% clinopyroxene.

It has been shown that, in all cases investigated, the features of these high-Mg rocks can be accounted for by an increment in the amount of the olivine phase within basaltic liquids of normal (5–8%) MgO contents. The Elephant's Head intrusion provides a fine example of the change of Ni/Mg ratios when crystallization of cumulus rocks takes place from a finite volume of parent melt. These ratios define a curve which diverges from the straight mixing line along which parent magma, olivine-enriched quench rock and phenocrystal olivine lie. The latter case corresponds to crystallization from an infinite volume of melt and concentration of the solid phase within a portion of the melt.

It is important to account for the striking absence of the high-Mg rocks from the volcanic suite within the region under review. The mechanism of flow differentiation offers a partial solution, at least in the case of some sills, for the occurrence of Mg-enriched schlieren but there is then no explanation for its ineffectiveness in producing high-Mg lavas. It is possible that the answer lies within a fundamental difference between the movement of magma within conduits open to surface and those feeding intrusions within the uppermost crust. The uniformity of compositions exhibited by the extrusive basalt suite is suggestive of a uniform velocity of magma transport to surface, whereby a balance between crystal settling and vertical flow rate was maintained. By contrast, lateral injection of magma into sediments implies forcible separation of strata and the exploitation of available fractures or zones of weakness. Intrusion is almost certainly a spasmodic process during which lateral flow, sometimes over large distances in the case of large sheets or sills, is periodically impeded. At other times, the brittle yielding of rocks by cauldron subsidence, faulting or the type of tensional opening proposed by Maske[13] in the case of the Ingeli range, will cause rapid emplacement of large volumes of melt. During such periods of high-velocity flow, scour of unconsolidated cumulates will be possible, while within vertical conduits upward-flow rates may temporarily greatly exceed crustal-settling velocities. The load of high-density cumulus phases picked up in this way will adequately account for the geochemical features of the rocks under discussion. Their dominant characteristic will be their clustering around a mixing line linking the composition of phenocrystal olivine with parent liquid.

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