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PETROLOGY AND Ni–Cu–PGE POTENTIAL OF THE INSIZWA LOBE, MOUNT AYLIFF INTRUSION, SOUTH AFRICA

R. GRANT CAWTHORN[§] AND F. JOHAN KRUGER

School of Geosciences, University of the Witwatersrand, PO Wits, 2050, South Africa

ABSTRACT

The Insizwa lobe of the Mount Ayliff Intrusion, South Africa, is part of an extensive intrusive body that reaches up to 1 km in thickness, and has a variably developed ultramafic basal facies, with minor Ni–Cu–PGE sulfide mineralization. An interpretation of gravity data indicated the existence of a deep graben structure in which was preserved a thick succession of ultramafic rocks. This hypothesis has been confirmed by the drilling of a borehole into the center of the Insizwa lobe that revealed an abnormally thick ultramafic section (400 m). Detailed geochemical data on whole rocks and olivine along this borehole suggest that the olivine-rich rocks formed from a magma with up to 14% MgO. The highest Fo content of olivine is 87%, and does not change systematically or markedly upward, indicating throughflow of large volumes of magma, rather than *in situ* differentiation. The initial $^{87}Sr/^{86}Sr$ (R_o) values at 183 Ma for the entire body show wide variations (0.705 to 0.711). Based on the combined isotopic, mineral and whole-rock chemical information, five periods of magma injection are identified. The first magma was a low-Mg basalt that was contaminated by crustal rocks at the base (but which did not cause sulfide separation). The second magma was a high-Mg liquid with an anomalously high initial Sr isotope ratio ($R_o > 0.710$). Subsequent magmas are harder to define chemically, but two further isotopically identifiable events are recognized in the ultramafic succession. Most of the upper half of the body is gabbronorite, derived from a low-Mg magma with an initial Sr isotope ratio of 0.705. No significant sulfide mineralization was intersected, but two intervals of Ni-depletion in the ultramafic section suggest that an immiscible sulfide liquid has formed. These intervals of Ni-depletion are not vertically extensive, suggesting that large volumes of magma have not experienced such sulfide segregation. In the gabbronorite are three olivine-rich layers, the lower two of which contain sulfides. A thin sill in the footwall contains quenched glass with over 10% MgO. Compositions of hopper and equant olivine grains range from Fo_{86} to Fo_{74}. This sill has a low Ni content, indicating prior separation of sulfide.

Keywords: Insizwa, Mount Ayliff Intrusion, Karoo magmatism, multiple intrusive events, sulfide mineralization, magnesian magma, Ni depletion, Sr isotopes, South Africa.

SOMMAIRE

Le lobe d'Insizwa de la masse intrusive de Mont Ayliff, en Afrique du Sud, pait partie d'une masse intrusive plus vaste, qui atteint jusqu'à 1 km en épaisseur, et qui possède par endroits un faciès ultramafique à sa base, avec un développement mineur de minéralisation en sulfures de Ni, Cu et éléments du groupe du platine. D'après une interprétation de données de gravité, il semble exister une structure profonde en graben dans laquelle est préservée une succession épaisse de roches ultramafiques. Cette hypothèse a pû être confirmée par le forage d'un trou au centre de la lobe d'Insizwa, qui révèle la présence d'une section anormalement épaisse de roches ultramafiques (400 m). Des données détaillées portant sur les roches globales et sur l'olivine le long de ce trou de forage font penser que les roches riches en olivine se sont formées à partir d'un magma contenant jusqu'à 14% de MgO. La teneur en Fo de l'olivine la plus élevée est 87%, et elle ne change pas systématiquement vers le haut, ce qui indique qu'il y a eu transfert de gros volumes de magma, plutôt qu'une différenciation *in situ*. Les valeurs du rapport initial $^{87}Sr/^{86}Sr$ (R_o) à 183 Ma pour la masse intrusive en entier témoigne de variations importantes (de 0.705 à 0.711). A la lumière des données chimiques portant sur les isotopes, les minéraux et les roches, cinq périodes d'injection de magma auraient été identifiées. Le premier magma était un basalte à faible teneur en Mg qui fut contaminé par la croûte à la base, ce qui n'a cependant pas mené à une saturation en sulfures. La seconde venue de magma était riche en Mg, mais avec un rapport initial des isotopes de Sr anormalement élevé ($R_o > 0.710$). Les magmas subséquents sont plus difficiles à définir chimiquement, mais deux autres événements seraient identifiables dans la séquence ultramafique. La plupart de la séquence supérieure est faite de gabbronorite, dérivée à partir d'un magma à faible teneur en Mg, avec un rapport initial des isotopes de Sr de 0.705. Aucune minéralisation en sulfures a été intersectée, mais nous avons décelé un appauvrissement en Ni sur deux intervalles dans la section ultramafique, ce qui fait penser qu'un liquide sulfuré immiscible en serait la cause. Ces intervalles d'appauvrissement en Ni n'ont pas une grande étendue verticale, et la saturation en sulfures n'aurait donc pas impliqué de gros volumes de magma. Dans la gabbronorite se trouvent trois niveaux riches en olivine, et les deux niveaux inférieurs contiennent des sulfures. Un mince filon-couche dans les

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[§] *E-mail address:* cawthorng@geosciences.wits.ac.za

roches du socle contient un verre trempé avec plus de 10% de MgO. La composition de l'olivine en trémis et de l'olivine équidimensionnelle varie de Fo_{86} à Fo_{74}. Ce filon-couche a aussi une faible teneur en Ni, indication de la séparation antérieure d'une fraction sulfurée.

(Traduit par la Rédaction)

Mots-clés: Insizwa, masse intrusive du Mont Ayliff, magmatisme d'âge Karoo, intrusion multiple, minéralisation en sulfures, magma magnésien, appauvrissement en Ni, isotopes de Sr, Afrique du Sud.

INTRODUCTION

The Insizwa lobe of the Mount Ayliff Intrusion (Fig. 1) is one of the thickest mafic bodies of the swarm of dolerite sills that was emplaced into the flat-lying sedimentary rocks of the Karoo Supergroup in Southern Africa (Winter & Venter 1970). These sills are considered to be coeval with, and genetically related to, extensive flood basalts of the Karoo Igneous Province (Cox 1983) that erupted 183 ± 1 Ma ago (Duncan *et al.* 1997, Marsh *et al.* 1997), and are preserved 100 km northwest of Mount Ayliff (Eales *et al.* 1984). The Mount Ayliff Intrusion, which covers about 3000 km^2 and in places exceeds 1 km in thickness, comprises four originally connected lobes, Insizwa, Tabankulu, Ingeli and Tonti (Fig. 1). They are considered to be preserved in undulating depressions, the intervening connections having been eroded (Scholtz 1936). The intrusive bodies have differentiated into a variably developed ultramafic (lherzolite) base, a more continuous mafic (gabbronorite) central section, and locally developed, evolved (diorite) roof facies (Scholtz 1936).

The Insizwa lobe is best known for its basal Cu–Ni sulfide mineralization at Waterfall Gorge, shown in Figure 1 (Scholtz 1936, Lightfoot *et al.* 1984), mined intermittently from 1865 to about 1915. Unsuccessful exploration programs both at Waterfall Gorge and in the surrounding area have been undertaken. Exploration has followed two themes. The adits into Waterfall Gorge have been re-drilled down dip and along strike, but only irregular patches of mineralization were intersected. Also, geological mapping, magnetometer surveys and soil geochemical sampling have been undertaken along 112 km of the basal contact of all four lobes (Dowsett & Reid 1967). Results of more recent exploration programs have not been published.

In this study, we document the geochemistry of samples from a borehole from the center of the Insizwa lobe, together with material from a thin sill discovered in the footwall at Waterfall Gorge.

TOPOGRAPHY AND STRUCTURE

Scholtz (1936) suggested that all four bodies are part of an undulating sheet, at the base of which olivine-rich rocks (called picrite by Scholtz and later authors) accumulated. It was suggested that sulfide mineralization might also be found in such depressions. An alternative view was presented by Lightfoot & Naldrett (1984a), at least for the Tabankulu body, which was shown to have a possible ultramafic feeder dyke beneath it, with an upward extension into an elongate, funnel-shaped body. Numerous dolerite dykes occur in the area, but their relationship, if any, to the main intrusive bodies is not clear.

There is considerable relief associated with this intrusion, since it lies on the southeastern edge of the Drakensberg escarpment, where there is active erosion (Partridge 1998). Mountain peaks on Insizwa reach 2000 m above mean sea-level, incised by rivers to 1000 m. Steep cliffs of gabbronorite, up to 500 m high, surround most of the lobes. The basal contact of the intrusion at Waterfall Gorge lies at an elevation of 1150–1200 m. The lowest exposed level of the basal contact of the Insizwa lobe is at 1000 m in the Mzintlava River (Fig. 1). To investigate the depth of the basal contact, a gravity survey was undertaken over the Insizwa lobe (Sander 1993, Sander & Cawthorn 1989, 1996). Results indicate that there is a thick sequence of ultramafic rocks (Fig. 2.) The steep gradients on the edges of the gravity anomalies indicate that the sheet does not gently undulate, but plunges sharply into a possible graben structure that trends northwest–southeast. Based on air-photo interpretation of lineaments, orientation of dykes, gravity data and the known altitude of the basal contact around the periphery of the intrusion, a contour map of the elevation of the basal contact of the intrusion was constructed (Fig. 3). In this re-interpretation, the Waterfall Gorge locality, with its sulfide mineralization, occurs on the southern shoulder of a north–northwest-oriented graben (Sander & Cawthorn 1996).

This geophysical model was confirmed by a borehole (INZ1) drilled by Randgold Exploration into this proposed graben in the Mzimvubu River valley (Figs. 1, 2 and 3). The borehole traversed over 400 m of ultramafic rocks and intersected the basal contact with metamorphosed shales at approximately 100 m above mean sea-level. Maier *et al.* (2002) have documented the stratigraphy and geochemistry of another borehole (INS96–02 in Figs. 1 and 3) drilled 1 km northwest of Waterfall Gorge. The elevation of its basal contact at 400 m above mean sea-level is in agreement with the existence of this deep graben immediately north of Waterfall Gorge.

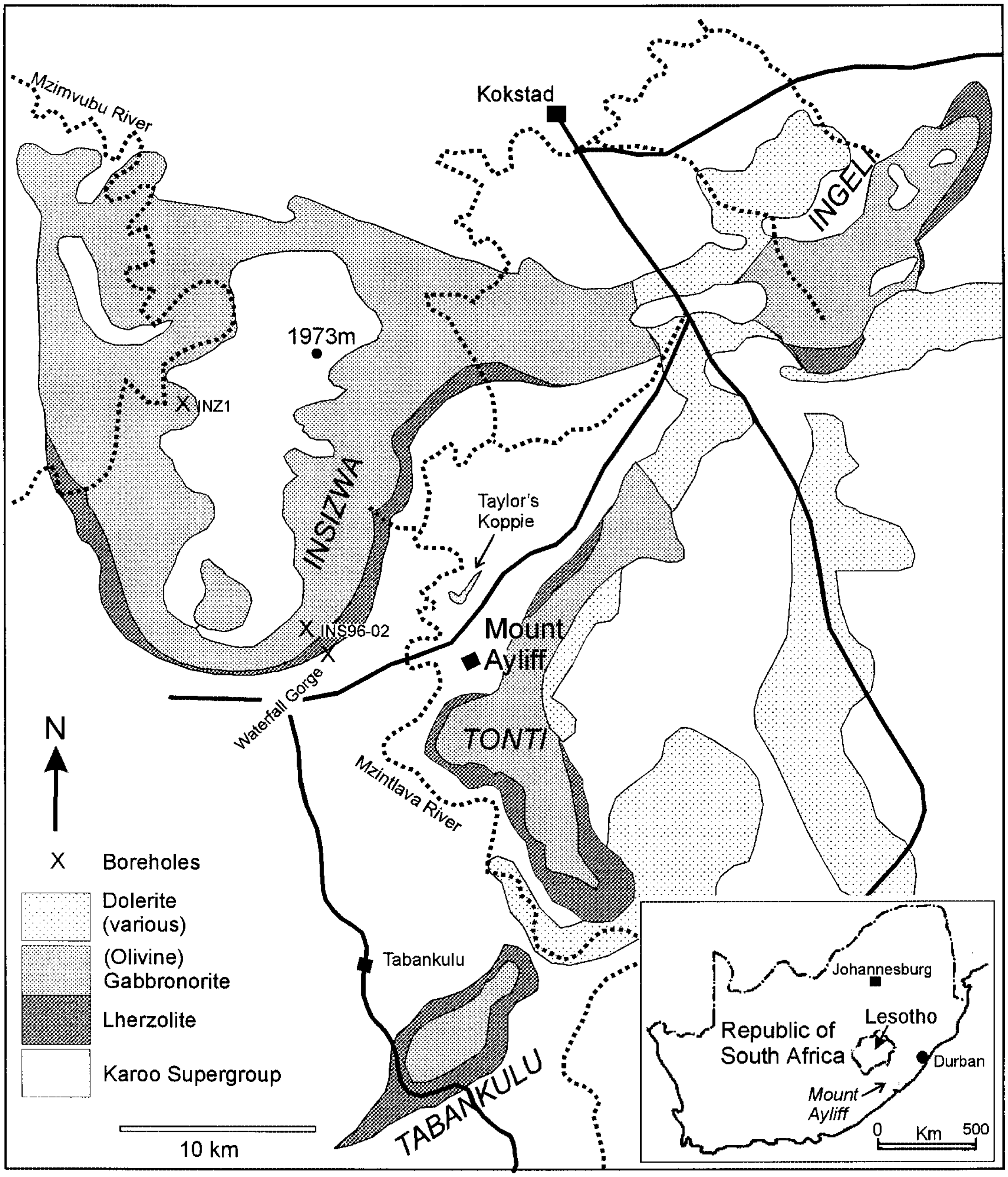


FIG. 1. Geological map of the four lobes of the Mount Ayliff Intrusion, Insizwa, Tonti, Tabankulu and Ingeli, showing the locations of the defunct Waterfall Gorge copper mine, the borehole (INZ1) documented here and borehole INS96–02 (Maier *et al.* 2002). Data are taken from various sources, including Scholtz (1936), Dowsett & Reid (1967) and Sander & Cawthorn (1996). Inset shows the location of the Mount Ayliff Intrusion within South Africa.

Stratigraphic Section Through the Insizwa Lobe

The stratigraphy and petrography of the rocks types comprising the Mount Ayliff intrusion have been documented in detail (Scholtz 1936, Lightfoot & Naldrett 1984a, 1987, Lightfoot *et al.* 1984, Cawthorn *et al.* 1991, 1992). One difference in terminology is proposed here. The term picrite has been extensively used with reference to the olivine-rich samples, but it is a name not considered appropriate by Streckeisen (1976). These rocks are dominated by olivine, with similar proportions of plagioclase, clinopyroxene and orthopyroxene. A more suitable name is lherzolite, which Streckeisen (1976) recommends for rocks with greater than 40% olivine. In this study, rocks with less than this proportion are termed olivine gabbronorite. In fact, the distinction is relatively straightforward, both in the field and chemically, since 40% olivine corresponds to rocks with about 25% MgO. Most samples have values significantly above or below this value, as discussed below, and so the division is sensible in terms of rocks in this body. From the base upward, the lithologies identified in the drill core and field are a basal olivine microgabbronorite (<0.5 m), lower olivine gabbronorite (50 m), lherzolite (400 m), and upper olivine gabbronorite (700 m). Within the latter are three thin layers highly enriched in olivine. Very leucocratic dioritic and gabbroic patches are irregularly distributed in the uppermost 50 m of the lobe. The core was supplemented with field samples for the uppermost 300 m to provide a complete section through this part of the lobe.

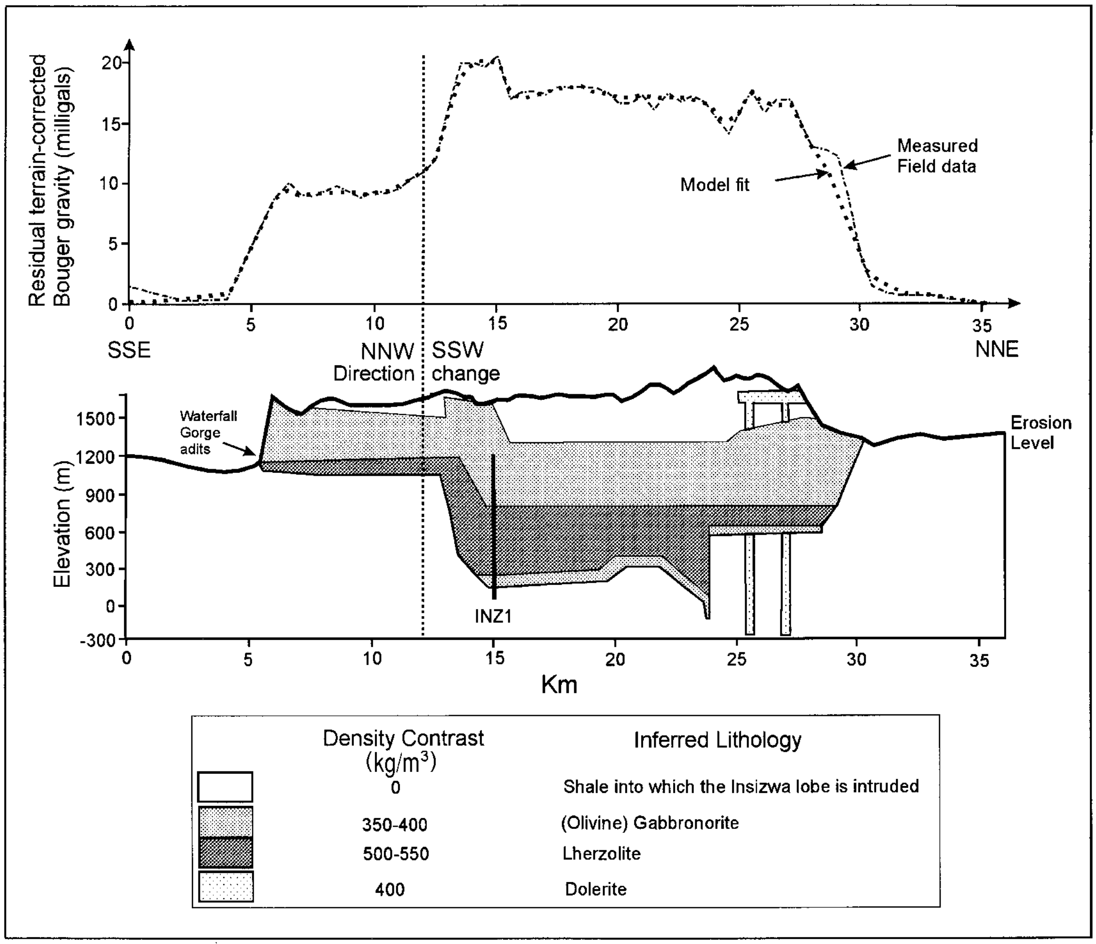


FIG. 2. Interpretation of the gravity profile from south to north across the Insizwa lobe (Sander & Cawthorn 1996), showing locations of Waterfall Gorge and borehole INZ1. Density contrasts are quoted relative to shale of the Karoo Supergroup. The location of the gravity traverse is shown in Figure 3.

The following description of rock types relates to the drill core, INZ1, but is very similar to all previous descriptions.

Basal olivine microgabbronorite

There is a thin (<0.5 m), relatively fine-grained zone in contact with hornfels, in which irregular grains of olivine (0.5 mm) are embedded in anhedral clinopyroxene and orthopyroxene, together with small laths of plagioclase. Chromite inclusions occur in the olivine grains, and anhedral magnetite and ilmenite occur in the matrix. Scarce biotite is very irregularly distributed, as anhedral to poikilitic grains.

Lower olivine gabbronorite

At its base, this 50-m-thick unit is essentially a slightly coarser-grained version of the underlying olivine microgabbronorite. Small, euhedral to anhedral grains of olivine (1.0 mm) are present within orthopyroxene and clinopyroxene that may ophitically enclose euhedral plagioclase. The irregularity of the outline of the olivine grains is not related to the immediately surrounding mineral. Thus, a euhedral edge of a grain may be in contact with orthopyroxene, and small, euhedral grains of plagioclase may be partially embedded in the margins of olivine grains. Chromite is a minor phase both within and outside olivine grains. Upward, the grain-size increases, and olivine becomes more euhedral and abundant.

Lherzolite

There is a transition from olivine gabbronorite to lherzolite over about 1 m, above which the proportion of olivine increases to 80%. The three other silicate minerals poikilitically enclose olivine in grains that can be several mm across. Chromite is a ubiquitous minor phase both within and outside olivine grains.

Upper olivine gabbronorite

The transition to the upper olivine gabbronorite takes place over about 10 m. The texture in the upper olivine gabbronorite is slightly different from the lower one, in that the olivine is less regular in shape, and plagioclase grains are larger and euhedral. In the lower unit, plagioclase, clinopyroxene and orthopyroxene are present in approximately equal proportions, but in the upper unit, plagioclase is distinctly more abundant. Elsewhere, troctolitic rocks have been reported at the top of the lherzolite unit (*e.g.,* in the Tabankulu lobe: Lightfoot & Naldrett 1984a), but have not been observed here. The proportion of olivine is quite variable, with one thin layer nearly 6 m thick containing 60% olivine, some 30 m above the base of the olivine gabbronorite; second (2 m thick) and third (6 m) layers, 100 and 300 m higher in the succession, contain up to 30% olivine.

WATERFALL GORGE SILL

Numerous sills of variable thickness occur above and beneath the four lobes. There are also dykes in the area that cut the lobes, but proving the age relationships of the sills and the dykes to the main lobes is not possible. Most sills and dykes consist of dolerite, typically with about 7% MgO, indicating that they are similar to the typical Karoo basalts (Marsh & Eales 1984). However, one sill (Waterfall Gorge sill) is fundamentally different. It contains 14% MgO and contains hopper olivine grains. As such, it is relevant to the debate about the composition of the parental magma to the Insizwa lobe (discussed below), and is described in detail. The Waterfall Gorge sill (<3 m) occurs 400 m southwest of the Waterfall Gorge adits, about 20 m below the basal contact of the Insizwa lobe. Only the upper contact is exposed, where it intrudes an older dolerite sill. The latter has a typical ophitic texture of clinopyroxene enclosing small laths of plagioclase. Some clinopyroxene grains have a core of orthopyroxene. There are scattered, subrounded olivine grains (Fig. 4A), and magnetite is a common microphenocryst phase. The margin of the Waterfall Gorge sill forms an optically unresolvable matrix that contains three generations of olivine grains.

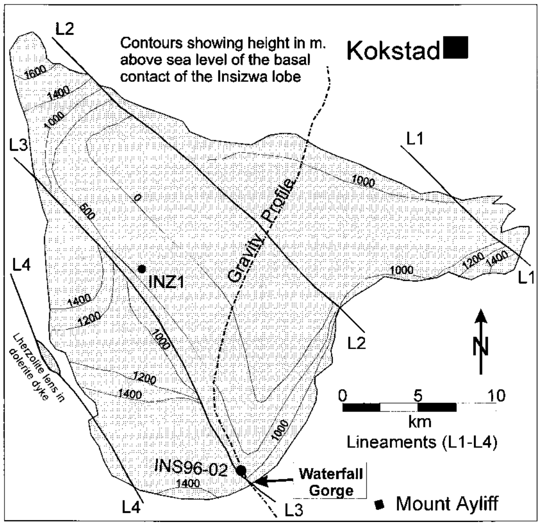
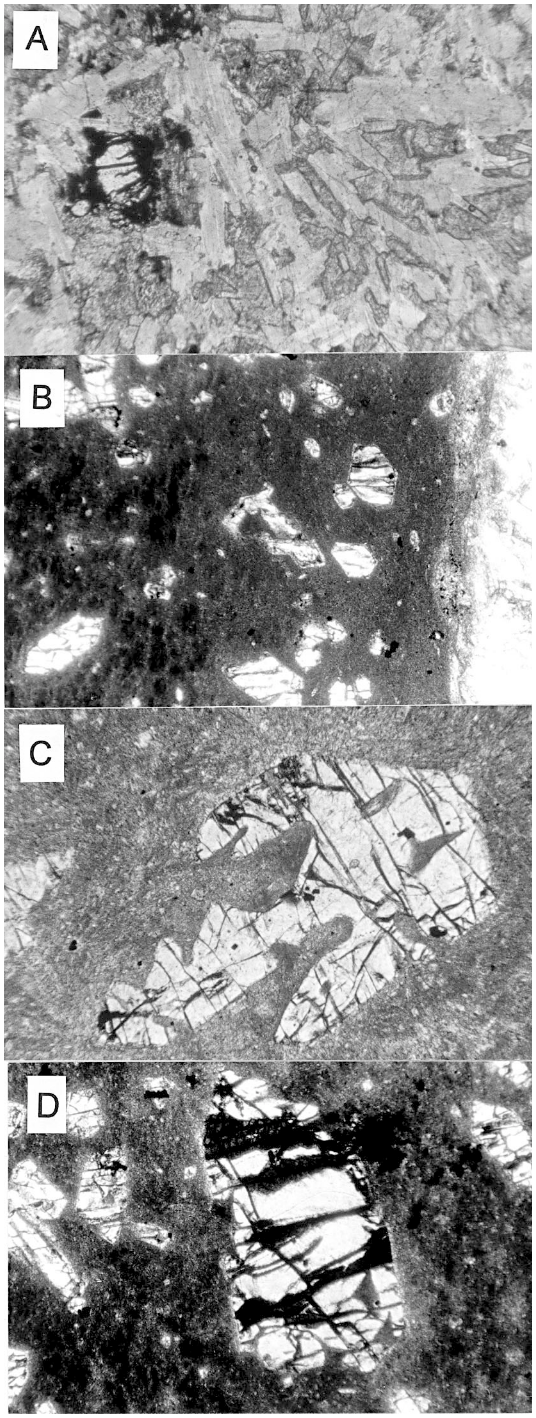


FIG. 3. Interpretation of the elevation above sea level of the basal contact of the Insizwa lobe (Sander & Cawthorn 1996). Major structural lineaments, L1–L4, are based on air photo and gravity information. L4 contains a dolerite dyke that bulges into a wide lens, the center of which consists of lherzolite. The location of the gravity traverse (Fig. 2) is shown. Boreholes INZ1 (this study) and INS96–02 (Maier *et al.* 2002) are shown.



The two most common forms are hopper and equant grains (Figs. 4B, C). The equant type increases in abundance inward until it reaches 10%, whereas the hopper grains are not observed more than a few cm from the edge of the sill. The equant grains range from 0.1 to 0.4 mm, whereas the hopper grains reach 1 mm. The third type of olivine is extremely scarce, and occurs as anhedral macrocrysts (Fig. 4D), which are up to 2 mm in size. Chromite is present as minute octahedra inside the equant olivine grains, but is absent in the crystalline component of the hopper olivine. However, it is present in the matrix that is enclosed by the hopper olivine, and also in the general matrix. These general relationships are shown in Figure 5.

GEOCHEMISTRY

Whole-rock X-ray-fluorescence analyses were undertaken by Randgold Exploration, as part of their exploration program, and further analyses were made in the Department of Geology, University of the Witwatersrand. Electron-microprobe analyses of olivine were undertaken by Randgold Exploration (Armitage 1992), but the numbers of grains analyzed and core–rim compositional variability were not recorded, and so further data were obtained at the Department of Geology, University of Bloemfontein, on olivine, chromite and glass. Rb–Sr isotope analyses were performed at the Hugh Allsopp Laboratory, University of the Witwatersrand, on whole-rock powders and mica and plagioclase separates.

Whole-rock compositions

Representative compositions are given in Table 1. The composition of the upper contact of the Waterfall Gorge sill (Table 1, WGS–R) contains 14% MgO, which is considerably higher than typical Karoo basalt and dolerite (Table 1, KB and KD, from Marsh & Eales 1984). Debates about the representativity of such compositions as liquids *versus* cumulus-enriched magmas demand that it cannot be assumed that the liquid had such a high level of Mg. To investigate whether there was cumulus enrichment of olivine in this sample, the

FIG. 4. Photomicrographs of the Waterfall Gorge sill intruded below the Insizwa lobe. A. Dolerite host to Waterfall Gorge sill, showing ophitic plagioclase in clinopyroxene, and scarce, but large, olivine grains, showing some alteration around the edges. B. Contact of dolerite with fine-grained sill (vertically, at right). The fine-grained sill contains euhedral microphenocrysts of olivine in a glassy matrix. C. Hopper olivine grains in glassy matrix. D. Large anhedral olivine grains in glassy matrix with euhedral microphenocrysts. Widths of photographs: A, 3 cm, B, 2.5 mm, C 1 mm, D 3 mm.

TABLE 1. REPRESENTATIVE WHOLE-ROCK COMPOSITIONS FROM THE INSIZWA LOBE AND UNDERLYING WATERFALL GORGE SILL

Height	SiO_2	TiO_2	Al_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	S	LOI	Total	Sr	Zr	Ni	Cu	V	Cr
1148.0	68.70	0.62	15.90	3.75	0.04	1.81	2.12	2.40	3.33	0.16	b.d.	0.83	99.25	634	246	18	41	50	n.a.
1098.0	51.00	0.94	14.60	9.72	0.13	8.71	10.70	2.10	0.28	0.16	0.03	1.05	98.32	154	81	105	99	166	274
1048.0	50.80	0.54	15.90	7.97	0.16	11.00	10.50	1.60	0.38	0.11	0.15	0.50	98.58	174	48	82	79	127	410
998.0	49.80	0.72	15.10	8.53	0.15	10.30	10.80	2.30	0.32	0.12	0.06	0.81	98.01	181	67	148	78	141	342
948.0	49.20	0.52	15.20	8.63	0.16	12.20	10.30	2.10	0.17	0.08	0.05	1.03	98.64	200	41	186	75	113	342
885.7	51.02	0.75	16.30	8.63	0.14	8.12	11.69	2.81	0.45	0.11	b.d.	0.77	99.84	226	39	76	41	253	390
834.0	52.00	0.55	19.20	5.53	0.07	7.50	12.40	2.30	0.29	0.09	b.d.	0.39	99.71	262	53	95	20	171	342
813.0	46.40	0.46	11.30	12.20	0.16	19.80	7.82	1.40	0.19	0.08	0.04	1.32	99.79	141	33	531	35	158	1300
795.0	46.10	0.40	11.30	12.20	0.14	19.80	7.23	1.40	0.16	0.07	0.02	1.15	98.61	140	27	581	32	136	1300
767.0	52.80	0.50	14.90	8.24	0.11	9.30	11.20	1.90	0.22	0.08	0.02	0.63	98.97	254	20	107	47	179	410
744.0	50.00	0.24	16.80	7.38	0.10	10.30	12.80	1.60	0.09	0.04	0.04	0.05	98.49	239	20	193	64	267	342
714.0	49.60	0.36	17.70	7.48	0.10	9.30	12.80	2.00	0.14	0.05	0.02	0.73	99.44	240	28	124	35	191	479
690.0	49.70	0.29	19.10	7.45	0.07	9.60	11.90	2.00	0.13	0.05	0.02	0.78	100.25	249	24	155	23	134	410
670.0	46.40	0.32	16.70	9.31	0.12	12.00	11.20	1.70	0.12	0.05	0.04	0.14	97.04	225	25	241	94	157	342
669.6	48.44	0.40	16.99	8.69	0.14	9.94	11.43	2.57	0.3	0.05	b.d.	0.85	98.84	231	17	180	40	158	521
627.0	50.60	0.26	15.80	7.95	0.08	11.20	11.70	1.20	0.12	0.04	0.03	0.15	97.93	242	27	160	42	115	479
618.3	48.03	0.31	15.91	9.48	0.14	11.83	11.25	2.07	0.23	0.04	b.d.	1.35	99.60	217	10	229	56	187	800
609.0	46.30	0.08	17.10	9.82	0.06	14.40	10.40	1.00	0.05	0.01	0.04	1.09	99.23	243	10	236	94	68	410
597.8	49.40	0.23	16.04	8.77	0.14	11.62	13.08	2.11	0.09	0.02	b.d.	0.89	101.43	208	b.d.	169	24	286	890
596.5	48.57	0.23	17.10	6.91	0.11	9.84	13.75	2.21	0.17	0.01	b.d.	0.79	98.93	225	b.d.	156	20	371	904
593.0	46.41	0.26	14.20	11.33	0.17	14.09	10.19	1.94	0.20	0.03	b.d.	1.39	98.96	192	7	249	74	227	803
592.0	46.90	0.44	5.14	14.60	0.26	19.00	10.50	0.80	0.09	0.02	0.51	1.34	97.48	83	12	628	689	672	684
574.6	44.62	0.28	12.68	13.20	0.19	17.73	9.96	1.35	0.11	0.03	b.d.	1.37	100.07	160	9	300	66	275	686
557.0	52.20	0.19	15.60	7.28	0.08	13.10	9.98	1.10	0.09	0.02	0.06	0.50	99.34	206	10	75	56	174	752
541.4	45.11	0.18	18.07	8.03	0.12	13.65	12.39	1.17	0.20	0.03	b.d.	1.28	99.35	196	6	123	84	232	959
519.1	44.22	0.17	14.31	9.47	0.12	18.54	11.01	0.92	0.17	0.03	0.09	2.10	100.02	149	7	226	137	273	1328
516.0	45.70	0.09	13.80	9.72	0.01	18.60	11.10	0.60	0.04	0.01	0.10	0.56	99.16	161	10	210	137	212	1026
498.2	43.90	0.15	15.77	8.27	0.12	16.39	12.47	0.78	0.13	0.01	0.10	1.79	98.87	149	b.d.	275	241	272	1405
498.0	47.40	0.12	14.40	7.60	0.06	15.80	12.20	0.50	0.06	0.01	0.01	0.00	97.31	151	12	131	35	46	1231
493.5	39.22	0.09	5.18	16.61	0.21	33.74	3.44	0.21	0.11	0.02	0.30	1.90	98.90	55	b.d.	1470	486	140	2792
480.0	47.90	0.08	18.30	5.72	0.03	13.10	13.70	0.60	0.05	0.01	0.06	0.13	98.73	183	10	135	199	148	889
474.0	45.50	0.05	17.00	7.02	0.04	17.00	12.10	0.60	0.04	0.01	0.08	0.04	98.63	172	10	191	279	116	1094
467.1	43.23	0.12	17.34	7.92	0.10	17.62	11.17	1.14	0.13	0.02	0.06	1.14	99.06	162	b.d.	229	219	172	1600
462.0	44.50	0.08	15.20	8.21	0.08	19.80	9.90	0.80	0.04	0.01	0.06	0.42	98.14	157	16	298	152	102	1232
456.0	41.00	0.18	2.95	15.40	0.18	35.90	2.17	0.40	0.07	0.04	0.01	0.74	97.34	46	16	621	23	150	2189
418.5	39.26	0.11	3.04	16.28	0.19	37.26	2.08	0.46	0.15	0.02	b.d.	2.56	99.62	37	123	1546	79	101	2100
381.4	39.35	0.37	1.86	16.33	0.19	36.12	2.37	0.40	0.31	0.06	b.d.	3.43	98.99	31	19	2096	123	170	3871
362.9	39.05	0.15	2.66	14.84	0.18	39.13	1.99	0.44	0.18	0.03	b.d.	3.06	100.08	22	30	1583	n.a.	583	2936
362.9	39.64	0.26	2.11	14.77	0.18	38.22	1.71	0.50	0.28	0.07	b.d.	2.74	98.86	28	11	1652	27	514	2293
317.0	41.00	0.19	2.49	14.50	0.08	37.20	1.79	0.50	0.09	0.04	0.08	1.75	98.03	27	16	1666	58	120	3898
291.0	41.50	0.15	2.59	14.40	0.10	38.10	2.08	0.30	0.05	0.02	0.08	1.48	99.19	26	12	1118	79	64	3215
288.9	40.54	0.17	2.91	14.45	0.19	38.73	1.85	0.55	0.205	0.03	b.d.	0.88	98.92	35	12	1513	30	81	3797
282.0	41.40	0.15	2.24	14.30	0.16	37.90	1.76	0.30	0.08	0.03	0.05	1.40	98.15	26	10	1240	39	41	3420
255.0	41.00	0.12	2.39	13.60	0.12	39.30	1.33	0.40	0.04	0.01	0.06	1.87	98.68	26	10	1472	54	59	3625
235.7	40.31	0.15	2.91	14.54	0.18	38.74	2.03	0.43	0.17	0.03	b.d.	0.97	98.86	32	10	1737	81	45	3966
233.0	40.90	0.18	2.92	12.90	0.23	38.10	2.23	0.50	0.06		0.09	1.36	97.96	28	20	1662	76	20	2599
231.0	40.90	0.12	2.89	14.00	0.14	37.80	2.01	0.30	0.07	0.03	0.03	1.81	98.53	26	10	1623	30	48	3352
222.6	40.47	0.15	2.95	13.62	0.17	39.38	2.10	0.46	0.15	0.04	b.d.	0.91	98.90	29	9	1661	15	53	3474
180.0	41.60	0.14	2.79	14.70	0.16	36.70	2.00	0.40	0.06	0.02	0.01	1.61	98.56	26	10	1520	17	65	3762
154.5	40.29	0.13	4.37	14.25	0.18	35.18	2.95	0.83	0.20	0.02	b.d.	1.91	98.74	54	11	1610	68	100	935
143.0	39.69	0.15	2.50	15.09	0.17	37.87	2.16	0.34	0.17	0.05	b.d.	2.45	98.98	33	10	2045	106	71	952
132.0	43.10	0.17	2.75	12.10	0.14	37.70	1.99	0.50	0.12	0.03	0.05	0.99	98.26	31	25	1832	67	89	3488
130.0	39.60	0.12	3.07	12.88	0.18	40.12	2.04	1.30	0.12	0.00	b.d.	2.97	100.98	93	38	1120	45	115	2662
118.0	40.94	0.20	2.98	13.14	0.15	38.74	2.43	0.58	0.23	0.02	b.d.	0.89	98.85	30	15	2272	35	60	4215
105.2	42.72	0.20	8.80	11.00	0.14	30.80	4.60	1.78	0.20	0.03	b.d.	1.36	100.42	87	21	1447	52	89	5093
102.0	43.10	0.29	3.06	13.20	0.12	36.00	2.33	0.50	0.26	0.05	0.04	1.50	98.96	33	25	1575	74	115	2941
78.0	42.78	0.30	6.99	12.42	0.16	30.84	3.87	1.50	0.37	0.09	b.d.	0.95	98.90	71	39	1282	55	106	2443
75.0	42.90	0.20	3.54	14.20	0.20	32.40	3.12	1.00	0.20	0.10	0.02	0.74	97.04	33	25	1119	88	130	2804
66.0	42.98	0.37	6.57	14.64	0.19	28.91	3.90	1.23	0.34	0.10	b.d.	1.01	98.63	84	40	1245	56	166	4212
61.0	43.08	0.41	7.33	14.55	0.19	27.74	4.68	1.29	0.41	0.07	b.d.	0.77	98.92	91	36	1128	43	131	2966
55.0	45.40	0.40	6.76	14.20	0.13	26.70	4.70	1.00	0.25	0.08	0.05	1.88	99.94	92	23	1093	44	145	2120
49.0	50.90	0.52	15.00	9.83	0.06	11.20	9.68	1.50	0.50	0.09	0.10	0.92	99.12	133	63	217	68	153	684
43.0	46.26	0.47	11.96	12.18	0.17	17.96	7.90	1.75	0.41	0.06	b.d.	1.37	99.15	102	50	498	62	168	1238
30.0	52.00	0.58	14.50	9.77	0.08	7.93	10.60	1.50	0.49	0.09	0.08	0.91	97.38	161	56	108	123	222	410
26.0	50.53	0.64	14.79	10.83	0.17	12.23	9.48	2.27	0.62	0.09	b.d.	1.04	101.50	138	76	243	56	167	554
17.0	49.50	0.56	13.20	10.10	0.17	12.40	9.76	1.90	0.51	0.14	0.12	1.06	98.19	130	60	256	78	56	410
7.0	46.50	0.46	8.25	11.80	0.22	22.20	6.61	1.30	0.26	0.05	0.07	1.29	97.64	86	39	699	61	112	1915
1.0	53.00	0.58	14.50	8.89	0.08	7.93	10.60	1.50	0.49	0.09	b.d.	1.70	98.38	161	46	108	123	222	240
0.0	63.90	0.81	17.90	7.60	0.11	2.82	0.74	1.20	4.44	0.12	b.d.	0.61	96.19	188	132	59	40	56	n.a.
R	48.92	0.66	12.77	11.53	0.19	14.44	8.96	1.29	0.50	0.10	n.a.	n.a.	99.36	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
G1	48.80	0.55	17.06	6.26	0.09	10.53	11.67	1.77	0.74	0.18	n.a.	n.a.	97.65	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
G2	48.55	0.62	16.74	6.10	0.08	10.22	13.84	1.58	0.72	0.08	n.a.	n.a.	98.53	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
G3	51.20	0.66	18.28	5.38	0.13	7.74	13.52	0.99	0.17	0.10	n.a.	n.a.	98.17	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
KB	51.50	0.95	15.69	9.98	0.16	7.01	10.69	2.17	0.70	0.16	n.a.	n.a.	99.01	192	94	94	87	240	283
KD	51.76	1.00	15.23	9.99	0.20	6.86	10.57	2.28	0.56	0.17	n.a.	n.a.	98.62	208	97	87	92	243	275

Height (in m) refers to height above base of Insizwa lobe in borehole INZ1. Samples below 900 m are from drill core, samples above 900 m are from field outcrop. WGS- prefix precedes samples R, G1, G2, and G3, and refers to Waterfall Gorge sill, R: whole-rock composition, G: glass composition. KB and KD are average Karoo basalt ($n = 32$) and dolerite ($n = 17$) from Eales *et al.* (1984). Total iron is expressed as FeO. Compositions are expressed in wt.% and ppm Sr, Zr, Ni, Cu, V and Cr concentrations. Abbreviations: n.a.: not analyzed, b.d.: below limit of detection.

glass and fine matrix at the edge of the sill were analyzed by electron microprobe using a defocused beam (Table 1, WGS–G1, G2 and G3). MgO contents range from 7 to 10%. Figure 5 shows a schematic diagram of one section of the contact of this sill to the overlying dolerite, including the MgO contents of this quenched matrix. We conclude that the liquid that produced this sill did contain more Mg than average Karoo basic magma.

Typical compositions of samples from the drill core and overlying field outcrops of the Insizwa lobe are given in Table 1. Heights are quoted in m above the base of the lobe. Up to the level of 900 m, the samples are from the drill core. Above this position, samples were collected in the field, and their elevations are less precise than for those from the core. The vertical variation in whole-rock composition is shown in Figure 6A. The major variation in mineralogy lies in the proportion of olivine, as is demonstrated by the range in Mg contents. The basal chill contains 7.9% MgO, and is similar to typical Karoo basic magma (Marsh & Eales 1984). Upward, the Mg content increases, consistent with increasing proportion of olivine. There is a sharp break at 50 m between the lower olivine gabbronorite and the lherzolite. The lherzolite contains between 25 and 40% MgO, corresponding to 50 to 80% olivine. At the top of the lherzolite (at 450 m), there is an abrupt decrease to less than 20% MgO in the upper olivine gabbronorite. A thin olivine-rich layer occurs 30 m into the gabbronorite, and contents vary irregularly between 10 and 20% MgO up to a height of 600 m, where there is another olivine-rich layer. Above this level, there is an irregular decrease from 11 to 8% MgO at a height of 800 m, where there is another thin olivine-enriched layer. Above this layer, almost to the top of the body, the MgO content remains about 8%.

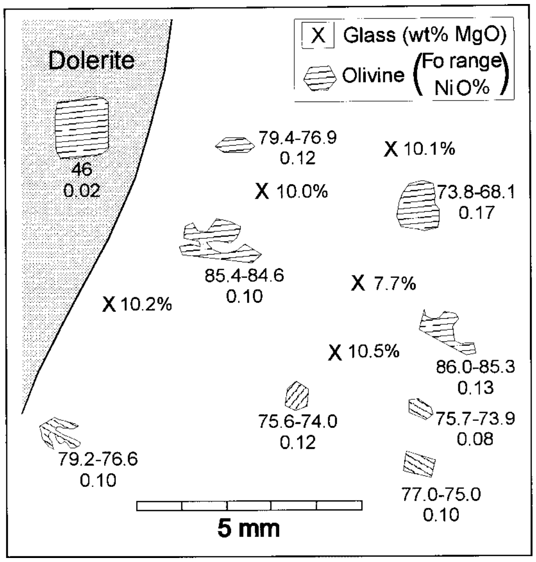


FIG. 5. Sketch of contact of fine-grained Waterfall Gorge sill showing olivine textures and compositions. Below each olivine grain, the Fo and wt% NiO are indicated. The contact with the host dolerite occurs on the left, and the dolerite has large grains of olivine. Close to the contact are hopper and equant olivine grains up to 2 mm in size. One example of a very rare, irregular shape of olivine is shown at center right, and has lower Fo, but higher Ni content than the hopper and equant olivine grains. Also shown, as crosses, are electron-microprobe data for wt% MgO of the glass and fine-grained mesostasis, obtained with a defocused beam.

Titanium, being an incompatible element with respect to the main minerals present, shows the inverse trend to Mg (Fig. 6A). At the base, the value of 0.6% TiO_2 is slightly lower than that of the Karoo basic magma. Contents decrease upward as the proportion of olivine increases. In the lherzolite, the concentration is low but very variable, from 0.1 to 0.3% TiO_2, reflecting varying proportions of intercumulus magma. At the top of the lherzolite, there is no significant increase in Ti, indicating that the overlying gabbronorites are also largely cumulate rocks with a relatively small proportion of intercumulus magma. In the uppermost part of the succession, concentrations increase, possibly reflecting a combination of a larger proportion of intercumulus liquid and a higher Ti content of that more evolved intercumulus liquid.

Plots of other elements reflect the same features, namely that with the exception of the basal few meters, these rocks are orthocumulates, dominated by olivine through the lherzolite, and plagioclase, pyroxenes and minor olivine through the upper sections.

The Cu, Ni and S contents of these rocks are also shown in Figure 6A. Close to the base, values for S are about 0.1%, and in the lherzolite, contents decrease. A slight increase occurs in the upper olivine gabbronorite. Two zones with higher values (0.3 and 0.5% S) are encountered within the upper olivine gabbronorite, both of them where there is an increase in the proportion of olivine. The uppermost olivine-rich layer does not show an increase in S. Copper shows a parallel trend to S, with values falling from 100 ppm at the base to a very few tens of ppm in the lherzolite. Like S, Cu also increases at the base of the upper olivine gabbronorite, and further increases in the lower two olivine-rich layers. The data for Ni reflect the abundance of olivine in the samples, and so parallel the trend for Mg (Fig. 6A).

Olivine compositions

The olivine compositions in the Waterfall Gorge sill are quite variable. Representative compositions of the various generations of olivine are presented in Table 2. Figure 5 shows a schematic diagram of one section of the contact of this sill with the overlying dolerite, including the morphologies and forsterite and Ni contents of the olivine grains. The hopper grains show a total range from Fo_{86} to Fo_{77}, although only one is below Fo_{82}. Variation between core and rim is small (1–2.5 mole % Fo) and not systematic. The equant grains show a total range in composition from Fo_{79} to Fo_{74}, with core-to-rim variation similar to that in the hopper grains. Only one megacryst was analyzed; it is reversely zoned from Fo_{68} to Fo_{74}. In contrast, olivine from the adjacent dolerite sill shows a range from Fo_{44} to Fo_{47}, and grains are largely unzoned. Because of their high iron content, we suggest that the scarce megacrysts in the Waterfall Gorge sill are xenocrysts, possibly derived from the adjacent dolerite, with some degree of re-equilibration producing the reversed zonation.

Representative compositions of olivine grains from the Insizwa lobe are given in Table 2 and Figures 5 and 6B. Analyses of cores and rims of three to five grains were undertaken on samples reported in Table 2. Armitage (1992) did not report the number of individual

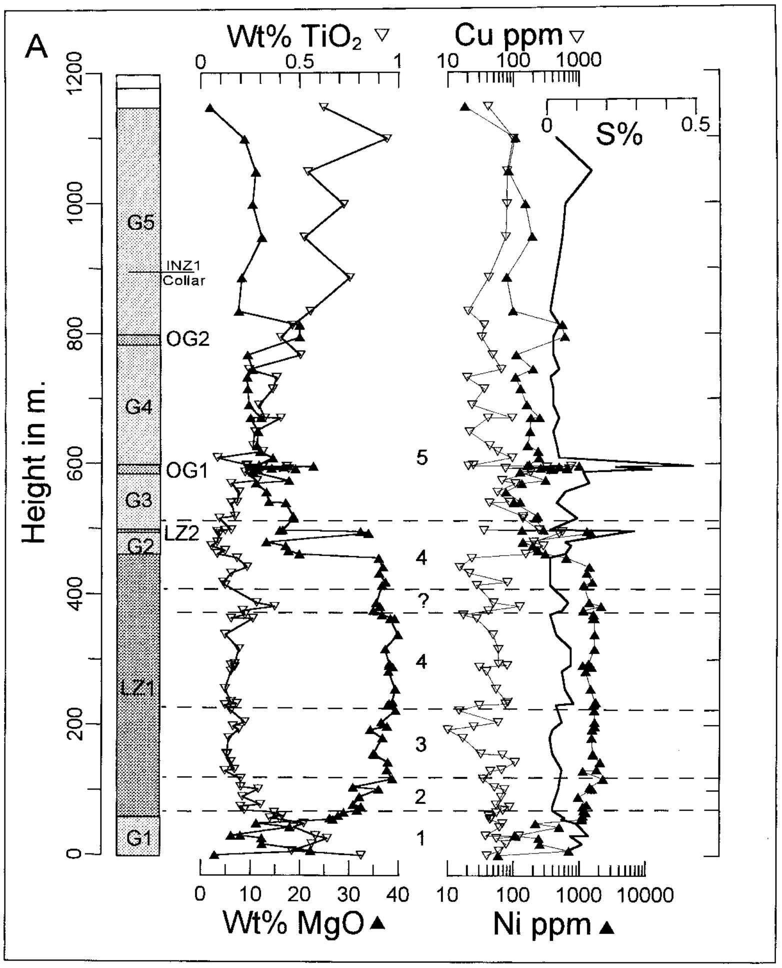


FIG. 6. Plot of concentration of various geochemical parameters (Tables 1, 2) *versus* height through the Insizwa lobe. In the column on left, the darker shading, denoted LZ, refers to lherzolite, the medium density shading, denoted OG, refers to olivine-rich gabbronorite, and the paler shading, denoted G, pertains to gabbronorite with minor olivine. The horizontal dashed lines and the fields denoted 1 to 5 represent possible different magmatic events, as defined by the initial $^{87}Sr/^{86}Sr$ (R_o) values and discussed in the text. All data are for whole rocks, except R_o values, for which most data are for plagioclase separates (Table 4). A. Wt% Mg and Ti, and Ni and Cu (ppm) content of whole rock. B. Fo content of olivine, wt% NiO in olivine, and initial $^{87}Sr/^{86}Sr$ in plagioclase separates and whole rocks.

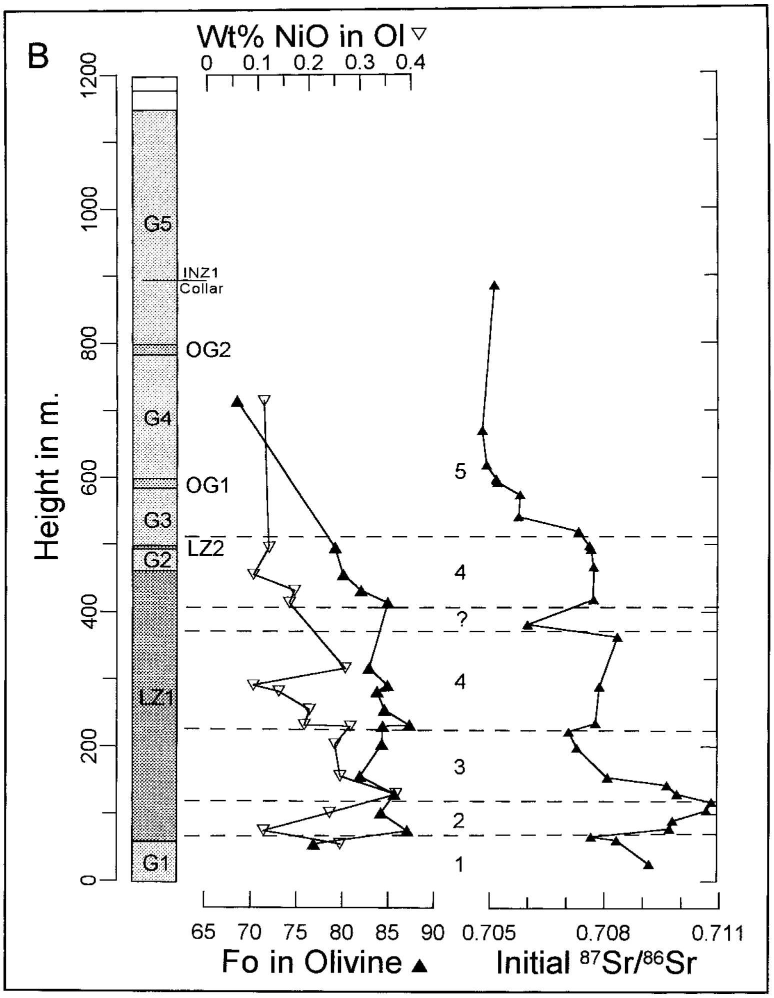


FIG. 6B.

analyses per sample. In the case of olivine in lherzolite and upper olivine gabbronorite, there is minimal variation in the Fo value between core and rim. In the lherzolite, variation within a single grain was found to be generally less than 0.4%, whereas combining compositions of all olivine grains from a single sample gives a variation of 0.7%. However, in the lower olivine gabbronorite, zoning is present. Single grains show variations in Fo of up to 8%. In Figure 6B, only the core compositions for such grains are shown. Ni is quite variable, even in single grains of olivine from the lherzolite, with variation as much as 0.06% being recorded.

The range of Fo and Ni in olivine as a function of height is shown in Figure 6B. From the base upward for 50 m, Fo increases from 75 to 85%. Through the lherzolite, it shows no systematic pattern, ranging between 87 and 81%. From close to the top of the lherzolite, Fo regularly decreases, and decreases further from 79 to 67% through the upper olivine gabbronorite. The pattern for Ni in olivine is much more variable. Within the lherzolite, values range from over 0.25 to less than 0.07% Ni. In the upper gabbronorite, values are less than 0.1% NiO.

Chromite compositions

The compositions of chromite from the Waterfall Gorge sill are given in Table 3. It contains 47–49% Cr_2O_3, 8–12% Al_2O_3, and 1.5–3.2% TiO_2. There is no systematic difference among grains, whether they occur in the olivine or within the matrix. They have the distinctive characteristics of chromite found in the lower half of the Mount Ayliff Intrusion, in having a very high Cr/Al ratio and being Ti-rich (Cawthorn *et al.* 1991).

Rb–Sr isotope data

Thirty-three samples (11 whole-rock samples, one mica and 21 plagioclase separates) have been analyzed for Rb and Sr isotopes, and the data are given in Table 4. For calculation of the initial $^{87}Sr/^{86}Sr$ (R_o) value, we assume an age of 183 Ma, comparable to the entire basaltic lava sequence found in the Karoo Supergroup (Duncan *et al.* 1997, Marsh *et al.* 1997). We have confirmed this age for the Insizwa lobe by analyzing separated biotite from the sample 100 m above the base (Table 4). Assuming a value for R_o of 0.71 (as determined from the plagioclase separate from that sample) an age is obtained for the mica of 178 ± 2 Ma. What is important in this study is the calculated R_o values for the 32 samples. In view of the generally low Rb/Sr ratio (0.01 to 0.03 for plagioclase and up to 0.2 for whole rock), even a large error in this age will have little effect on the calculated R_o values. The R_o ratios are plotted in Figure 6B. All values of the initial ratio lie well above that of typical mantle at 183 Ma, but this observation is true for many of the Karoo basalts and dolerites (Bristow

TABLE 2. OLIVINE COMPOSITIONS FROM THE INSIZWA LOBE AND UNDERLYING WATERFALL GORGE SILL

HeightIn m	SiO_2	FeO	MnO	MgO	NiO	CaO	Total	Fo %
713C	38.75	27.13	0.36	33.69	0.07	0.04	100.06	68.9
713R	38.35	27.81	0.34	33.38	0.13	0.07	100.13	68.2
403C	39.68	13.42	0.16	46.23	0.13	0.07	99.73	86.0
403R	39.40	14.05	0.18	46.07	0.15	0.10	100.08	85.4
254C	41.10	11.40	0.17	47.05	0.14	0.06	100.22	88.0
254R	40.69	11.89	0.20	47.02	0.20	0.06	100.14	87.6
174C	39.61	12.57	0.10	47.51	0.15	0.08	100.17	87.1
174R	39.71	12.79	0.07	47.28	0.15	0.04	100.13	86.8
WGS-X-C	38.21	27.89	0.38	33.4	0.15	0.21	100.24	68.1
WGS-X-R	37.95	23.87	0.27	37.65	0.17	0.06	98.82	73.8
WGS-H-C	38.62	18.63	0.21	41.25	0.13	0.15	99.32	85.4
WGS-H-R	38.63	20.87	0.12	39.66	0.06	0.11	100.02	84.6
WGS-H-C	38.92	18.89	0.45	41.82	0.11	0.22	100.07	79.2
WGS-H-R	38.69	21.17	0.32	39.43	0.09	0.07	99.97	76.6
WGS-E-C	38.59	20.74	0.46	39.71	0.10	0.11	100.02	77.0
WGS-E-R	38.38	22.36	0.58	38.52	0.07	0.04	100.02	75.0
WG-DOL	34.31	42.97	0.66	21.88	0.02	0.06	99.98	47.2

Height refers to height above base of Insizwa lobe in borehole INZ1. WGS refers to Waterfall Gorge sill. X, H and E refer to grain shapes: xenocrysts, hopper and equant. DOL refers to dolerite into which WGS is intruded. C and R refer to core and rim of grains. Total iron is expressed as FeO. The raw data are expressed in wt.%, and the composition of the olivine, in mol.% Fo. In all cases, a typical pair of core (C) and rim (R) compositions is given, rather than averages of all analytical data.

TABLE 3. CHROMITE COMPOSITIONS FROM WATERFALL GORGE SILL

Location	1	2	3	4	5
TiO_2 wt%	2.60	2.73	3.16	2.39	1.53
Al_2O_3	11.62	11.67	11.27	8.15	12.20
Fe_2O_3	4.63	2.46	3.40	6.36	6.82
Cr_2O_3	48.12	49.73	48.23	49.09	46.93
V_2O_3	0.46	0.42	0.57	0.45	0.33
FeO	27.67	27.61	28.40	27.51	26.95
MnO	0.31	0.34	0.23	0.25	0.30
MgO	4.18	4.16	3.66	4.08	3.85
NiO	0.05	0.07	0.03	0.04	b.d.
ZnO	0.34	0.46	0.40	0.45	0.42
CaO	0.13	0.11	0.21	0.04	0.28
Total	100.14	99.78	99.65	98.85	99.72
Ti *apfu*	0.53	0.56	0.65	0.51	0.31
Al	3.72	3.75	3.64	2.70	3.88
Fe^{3+}	0.95	0.50	0.70	1.35	1.38
Cr	10.35	10.72	10.46	10.92	10.00
V	0.10	0.09	0.13	0.10	0.07
Fe^{2+}	6.29	6.30	6.52	6.47	6.08
Mn	0.07	0.08	0.05	0.06	0.07
Mg	1.69	1.69	1.50	1.71	1.55
Ni	0.01	0.02	0.01	0.01	0.01
Zn	0.07	0.09	0.08	0.09	0.08
Ca	0.04	0.03	0.06	0.01	0.08

Location of grains: 1, 2 and 3 in matrix, 4 in hopper olivine, 5 in equant olivine grain. Cation proportions are expressed in atoms per formula unit (*apfu*) containing 32 oxygen anions.

TABLE 4. Rb–Sr ISOTOPE DATA FROM THE INZ1 BOREHOLE AND THE WATERFALL GORGE SILL

Height in m	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ ±2SE	R_o at 183 Ma
885.7P	5.28	404.1	0.0378	0.705190 ±20	0.70510
669.6P	0.80	421.2	0.0055	0.704792 ±20	0.70478
618.3W	2.60	214.3	0.0351	0.704984 ±58	0.70490
597.8W	1.10	206.3	0.0154	0.705179 ±20	0.70514
596.5W	0.59	227.0	0.0075	0.705176 ±28	0.70516
593.0W	2.01	187.0	0.0311	0.705270 ±42	0.70519
574.6W	3.62	225.0	0.0466	0.705900 ±20	0.70578
541.4W	7.04	226.2	0.0901	0.705965 ±20	0.70574
519.1P	2.00	356.1	0.0162	0.707351 ±18	0.70731
498.2P	1.67	324.2	0.0149	0.707629 ±26	0.70759
493.5P	1.30	329.2	0.0114	0.707671 ±18	0.70764
467.1P	1.58	313.2	0.0146	0.707744 ±24	0.70771
418.5P	0.77	472.7	0.0047	0.707707 ±30	0.70770
381.4W	5.76	28.4	0.5864	0.707480 ±60	0.70598
362.9W	3.32	22.3	0.4308	0.709427 ±86	0.70833
288.9P	1.37	377.5	0.0105	0.707891 ±28	0.70786
267.5P	0.24	345.0	0.0020	0.707731 ±22	0.70773
235.7W	3.05	28.3	0.3116	0.708543 ±58	0.70776
222.6W	2.95	26.8	0.3177	0.707852 ±68	0.70706
198.1P	0.81	254.8	0.0092	0.707298 ±22	0.70728
177.5P	1.04	279.2	0.0108	0.707555 ±28	0.70753
154.5P	0.61	286.3	0.0062	0.708090 ±34	0.70807
143.0P	3.91	306.0	0.0370	0.709712 ±30	0.70962
130.0P	8.59	333.3	0.0746	0.710066 ±30	0.70988
118.0P	0.12	292.1	0.0012	0.710781 ±18	0.71078
105.2P	0.35	288.3	0.0036	0.710657 ±35	0.71065
90.0P	3.15	366.9	0.0249	0.709832 ±32	0.70977
78.0P	0.98	294.1	0.0096	0.709718 ±30	0.70969
66.0P	0.17	381.5	0.0013	0.707654 ±48	0.70765
61.0P	2.72	368.7	0.0214	0.708365 ±20	0.70831
43.0W	14.93	99.16	0.4358	0.710741 ±26	0.70964
26.0P	21.62	283.8	0.2205	0.709713 ±26	0.70916
WGSW	9.34	168.0	0.1608	0.706617 ±52	0.70621
Biotite–Plagioclase Model Age Determination					
118.00B	341.20	6.812	150.40	1.091213 ±30	178±2 Ma

The Rb–Sr data were obtained at the Hugh Allsopp Laboratory using standard techniques outlined elsewhere (Eales *et al.* 1990). The total method blanks were <100 pg for Rb and <1 ng for Sr and have no influence on the results. The $^{87}Sr/^{86}Sr$ ratio was determined on the spiked sample. Spiked and unspiked runs of SRM–987 yielded ratio of 0.71023. Letters P, B and W after each height refer to plagioclase and biotite separates, and whole-rock compositions respectively. WGS is Waterfall Gorge sill.

et al. 1984), with most values in the range 0.704–0.706. Our data from the drill core show that at the base, the initial ratio is 0.7092 and decreases upward through the lower olivine gabbronorite to 0.7076. At the base of the lherzolite, the ratio abruptly increases to 0.7095 and continues to increase upward to a value of 0.7105, above which it decreases slightly. There is an abrupt decrease to 0.708 at 120 m, and the ratio shows only small variation through the overlying 300 m, with one exception at 0.706. Rocks in the lowest 50 m of the upper olivine gabbronorite have this same value, but above the first olivine-rich layer at 495 m, the ratio decreases, and in the upper olivine gabbronorite, it falls to 0.705. Data for the upper 300 m are scarce, but the four determinations indicate a uniform value of 0.705.

A single sample from the Waterfall Gorge sill (WGS) has a R_o value of 0.70621.

INTERPRETATION

A number of interrelated issues require discussion. These include: 1) the composition of the parental magma(s), 2) the significance of R_o values, and whether there has been multiple injection, 3) the near-constant composition of olivine through a long vertical section of lherzolite, 4) the formation of immiscible sulfide liquid, 5) the relationship between the lherzolite in the borehole and that at Waterfall Gorge, and 6) the location of feeders.

Parental magma(s)

By definition, magmas may contain entrained crystals, and so it is necessary to distinguish between composition of magma and that of true liquid. Eales & Marsh (1979) suggested that all intrusive rocks in the Karoo Province that contain more than 7% MgO result from olivine accumulation, and cited rocks from Insizwa as examples. This conclusion was contested by Cawthorn (1980), who suggested that at least for the lower part of the Insizwa lobe, the liquid was more magnesian. Lightfoot & Naldrett (1984a, b) and Lightfoot *et al.* (1984) concluded that for the Waterfall Gorge section, the magma became stratified prior to intrusion, and that injection occurred from a continuously zoned column of magma. They suggested that the least fractionated liquid had 6–7% MgO. This argument rested heavily on their observation that the most magnesian olivine is Fo_{82}, which they assumed had not re-equilibrated with cooling magma. Cawthorn *et al.* (1992) studied eleven profiles through the lherzolite from all four lobes of the Mount Ayliff Intrusion. They found olivine compositions similar to that of Lightfoot & Naldrett (1984b), but re-interpreted the data in terms of the effect of reaction with trapped residual liquid (Barnes 1986), which lowered the Fo content. Cawthorn *et al.* suggested that the primary olivine may have been as magnesian as $Fo_{84–86}$, a conclusion that would have required its formation from a liquid with more than 7% MgO. Using geochemical constraints based on samples from a drill hole 1 km northwest of Waterfall Gorge, Maier *et al.* (2002) also concluded that the parental magma was of typical Karoo basalt composition.

On the basis of variations in R_o, it is possible that a series of liquids existed, and that different vertical sections record formation from different magmas. The data presented here extend the basis upon which interpretation about compositions of parent liquid may be inferred. Mg contents of the various magmas can best be constrained by reference to olivine compositions. The values of Fo_{84} to Fo_{86} mentioned above were *calculated* (Cawthorn *et al.* 1992) on the basis of the effect of reaction with trapped liquid (Barnes 1986). In the drill core (Fig. 6B), *actual* compositions reach Fo_{87}. These olivine grains may also have reacted with trapped liquid, and hence the primary compositions may have been even more magnesian.

A graphical comparison of the relation between olivine composition and MgO and FeO content of liquid was given by Revillon *et al.* (1999). For liquids with 8, 9, 10 and 11% FeO, crystallization of olivine of composition Fo_{87} requires 9.2, 10, 11.2 and 12.4% MgO, respectively (Fig. 7). If the original composition of cumulus olivine, prior to reaction with trapped liquid, contained higher Fo, an even more magnesian liquid must be invoked. In Figure 7, we have plotted the composition of typical Karoo basic magma. As emphasized by Cawthorn (1980) and Cawthorn *et al.* (1992), this liquid would crystallize olivine $Fo_{<80}$. We note that the most primitive compositions of olivine in four studies of the Insizwa lobe are $Fo_{82.5}$ for Waterfall Gorge

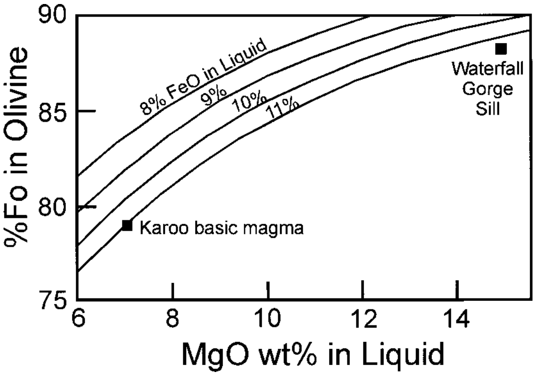


FIG. 7. Plot of wt% MgO in liquid *versus* calculated Fo content of olivine, for different FeO concentrations in the liquid (from Revillon *et al.* 1999). The composition of typical Karoo basic magma (Marsh & Eales 1984) and the sill below Waterfall Gorge (documented here) are shown. Note that the composition of Karoo magma would crystallize olivine $Fo_{<80}$.

(Lightfoot *et al.* 1984), Fo_{83} from an outcrop from the western edge of the Insizwa lobe in the Mzimvubu River valley (Cawthorn *et al.* 1992), $Fo_{85.0}$ for the drill core 1 km to the northwest of Waterfall Gorge (Maier *et al.* 2002), and $Fo_{87.6}$ for the drill core described here. We suggest that all of these compositions indicate crystallization from a more magnesian magma than typical Karoo basalt.

We have documented the existence of a chemically distinct thin sill that has a chilled margin composition with about 14% MgO. In order to test whether this composition contained accumulated olivine, we determined the composition of the quenched glass to have 7.7–10.2% MgO (Fig. 5, Table 1). Also, the hopper olivine grains attain Fo_{86} (Fig. 5). We note that there are common olivine phenocrysts, together with the hopper olivine, that show a range of composition less magnesian than Fo_{80}. Such crystals formed subsequently to the hopper grains, at a stage when the cooling rate was slower, and also when the MgO content of the remaining liquid was lower. The zonation shown by these grains demonstrates that growth occurred during continued fractionation of the magma. Within a few cm of the edge of the sill, cooling was sufficiently fast to preclude significant subsolidus homogenization of the grains or re-equilibration with trapped liquid. We therefore conclude that a magnesian magma with at least 10–12% MgO must have existed in the Insizwa chamber and was also capable of being emplaced as a thin sill. This conclusion does not preclude the involvement of other liquids with a lower Mg content, as is discussed below.

Significance of R_o values

The R_o values are a powerful tool in understanding magmatic processes, especially in terms of crustal contamination and magma addition. We suggest that there are five isotopically identifiable sections recognizable in Figure 6B. In most cases, bases of these sections can also be recognized by abrupt changes in mineralogy or changes in olivine composition, and so we suggest that they reflect addition of magma rather than later contamination or alteration.

Section 1 (*0–60 m*): The samples from the chill zone, the lower olivine gabbronorite and the very base of the lherzolite have values of 0.7092, decreasing upward to 0.7077. The values for the basal samples are slightly higher than 0.707 to 0.7086 quoted by Lightfoot *et al.* (1984) for the basal succession at Waterfall Gorge. Cawthorn (1980) and Lightfoot *et al.* (1984) argued for local contamination in the feeder zone of the first magmas to be injected, which might have produced the enriched values at the very base, with a decreasing proportion of contamination upward. It is difficult to quantify such a hypothesis, since the R_o value of the uncontaminated magma is not constrained.

Section 2 (*60–130 m*): At a height of 60 m, there is an abrupt and very significant increase in R_o to greater than 0.710. The Fo content of the olivine also increases markedly to over 86%. We suggest that this break indicates addition of a second, relatively magnesian magma, but nevertheless from an isotopically enriched or contaminated mantle source. In this instance, we do not believe that contamination by local crust is a viable mechanism, because the rocks are shielded from the country rocks by 60 m of igneous rocks, and because we know of no local rock with a high enough Sr content or R_o value that could produce these high values in the lherzolite without considerably modifying the bulk composition of the resultant magma.

Section 3 (*130–230 m*): Over a vertical height of 100 m, there is a steady decrease in R_o from 0.710 to 0.707. Two possibilities could be considered. The first magma (section 1) may have had a value of less than 0.707, and so there could have been prolonged mixing between it and the second magma to produce the observed range of values in this section. One observation inconsistent with this hypothesis relates to olivine compositions. The olivine formed by the first magma at the base of the lherzolite is Fo_{79}. At the top of section 3, the olivine has only decreased from Fo_{87} to Fo_{84}, a range that is not consistent with mixing with the earlier magma. The alternative (preferred) process would involve addition of magma, similar to the second magma in terms of Mg, but with a lower R_o value.

Section 4 (*230–490 m*): At 230 m, there is a small increase in both R_o and Fo content of olivine. The former is sustained for over 100 m, whereas the latter shows an upward decrease, possibly due to fractionation. This break at 230 m is taken to indicate another addition of magma. There is one anomalous R_o value at 380 m, for which no olivine compositions are available. Major- and trace-element compositions show no anomalous behavior at this level, and so its significance is difficult to evaluate. It could represent addition of a small pulse of magma, but its composition cannot be constrained other than that it had low R_o. A small pulse is envisaged because the sample at 414 m has an R_o value and Fo content consistent with the underlying rocks from section 4.

Above 400 m the olivine compositions show a systematic trend of differentiation, not obvious in the underlying succession. The upper part of this interval also shows the evolution of the rock type to the upper olivine gabbronorite. We note that the R_o value of 0.7075 and Fo content of olivine of 80% at the top of the lherzolite correspond to the entire ultramafic section at Waterfall Gorge (Lightfoot *et al.* 1984).

Section 5 (*490–900 m*): Above 490 m, there is a steady decrease in R_o value, ultimately to 0.7055. Such lower values are comparable to those reported for typical basalt and dolerite samples from the Karoo Province (Bristow *et al.* 1984). Thus, we suggest that there has been addition of a substantial volume of magma, typical of the Karoo Province, that slowly mixed with the resident magma while the succession from 490 to 600 m height accumulated. We note that the lowest of the olivine-rich layers in the upper gabbronorite falls in section 4, but that the upper two olivine-rich layers occur within section 5, and so could represent further injections of typical Karoo basic magma. The R_0 value for the upper gabbronorite at Waterfall Gorge of 0.7056 (Lightfoot *et al.* 1984) is the same as observed here for this section.

General implications: The R_0 values recorded in the lherzolites are considerably higher than typical mantle, and in most cases significantly higher than observed in the Karoo magmas (Fig. 8). Samples from the upper 700 m have values that lie close to 0.705 and are comparable to many values from the Karoo basalts. These samples could represent such magma, consistent with the observed mineralogy in the olivine gabbronorite. Such a model raises a question as to what happens to the residual magma to the lherzolites. If significant volumes of residual magma to section 2 to 4 had mixed with magma from event 5, the mixed R_0 value would exceed that of average Karoo basalt of 0.705. Only limited mixing is indicated by the change in R_0 from 490 to 520 m (Fig. 6B). Thus, the residual magma from events 2 to 4 is not accounted for in the vertical profile of Figure 6. A considerable volume of this residual magma may thus have flowed through the chamber and was either erupted or intruded as sills elsewhere. High values of R_0 would be distinctive fingerprints in any such rocks. Possible candidates might be the early Karoo lavas, such as the Kraai River and Pronksberg Basalts (Fig. 8).

Olivine compositions in the lherzolite

From a height of 50 to 350 m, the olivine composition varies slightly in terms of its Fo content, but lies within the range Fo_{87} to Fo_{81}. If such changes were the result of differentiation, the required proportion of fractionation can be seen by reference to Figure 9. Starting with a liquid containing 14% MgO, some 15% olivine fractionation would be required to cause the observed decrease in Fo content. The fact that 300 m of lherzolite shows this limited range of olivine composition suggests that large volumes of magma existed or passed through the chamber during the formation of this vertical sec-

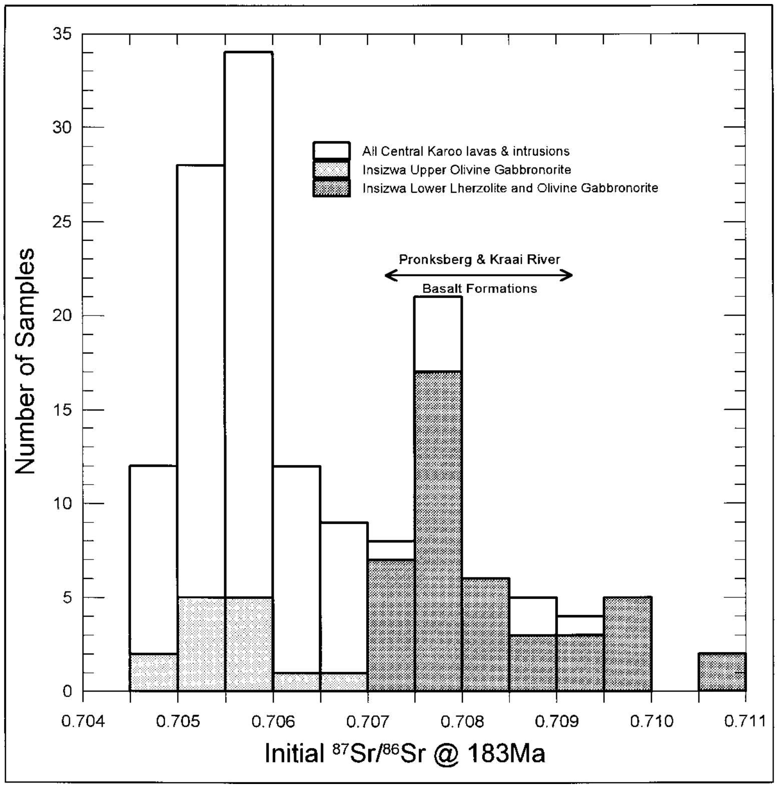


FIG. 8. Histogram of initial $^{87}Sr/^{86}Sr$ (R_0) values for Karoo basaltic rocks and the Insizwa lobe. Data are from Bristow *et al.* (1984), Lightfoot *et al.* (1984), Marsh *et al.* (1997), Maier *et al.* (2002) and Table 5.

tion. This section cannot be the result of progressive crystallization of a single body of magma, a conclusion supported by the changing R_o values.

Formation of an immiscible sulfide liquid

The existence of, and search for further, Ni–Cu–PGE mineralization in the Mount Ayliff Intrusion have led to numerous studies and models being presented for the origin of the ore at Waterfall Gorge (Scholtz 1936, Cawthorn 1980, Lightfoot *et al.* 1984, Sander & Cawthorn 1996). The textures and chemical composition of the sulfides strongly indicate that they have formed from an immiscible sulfide liquid generated from the host magma (Lightfoot *et al.* 1984). The demonstration that the S isotopic ratio is close to a mantle value (Jensen 1967) eliminates the possibility that sulfide immiscibility was triggered by addition of sulfur from a sedimentary source. Other possibilities for triggering immiscibility include contamination by siliceous material, magma mixing and fractionation. Various geochemical parameters can provide constraints on such processes.

Within the main body, identifying the separation of a sulfide liquid depends upon comparison of the Ni content of olivine as a function of Fo. Such a comparison is made in Figure 10. There are samples for which the Ni content of olivine indicates prior separation of sulfide, whereas other samples contain an undepleted Ni content. Electron-microprobe analysis of olivine for Ni is less precise than an X-ray fluorescence analysis for Ni of a whole rock, and so a method is presented here that allows for a more accurate assessment of sulfide separation based on the results from whole-rock analysis.

MgO and Ni contents of whole rocks are plotted in Figure 11. The different units in the vertical section are clearly distinguishable in this diagram. Here, it clearly emerges that these rocks are mixtures of cumulus olivine and trapped liquids in different proportions. Nevertheless, whether they are liquids or cumulates, samples that are depleted or enriched in magmatic sulfide can be recognized on such a plot. Basic magmas that have formed an immiscible sulfide liquid will be depleted in Ni (and Cu) relative to sulfide-undersaturated magmas, which may be recognized in both quenched liquid and subsequently crystallized olivine compositions. The Waterfall Gorge sill contains 14% MgO, with Ni and Cu contents of 137 and 84 ppm. This Ni value is distinctly lower than expected for a rock with 14% MgO, for which values of 300–500 ppm would be predicted (*e.g.,* Duke & Naldrett 1979). The olivine compositions in this sill are even more definitive. The hopper olivine grains have a range from Fo_{86} to Fo_{76} and yet typically contain 0.1% NiO. These Ni contents are atypically low for olivine with that range of Fo contents (Fig. 10), unless the magma has previously lost an immiscible sulfide liquid. The partition coefficient for Ni between olivine and silicate magma, for a liquid with 14% MgO, is about 6 (Duke & Naldrett 1979). Hence, the Waterfall Gorge sill, with 137 ppm Ni, would be expected to crystallize olivine with about 800 ppm Ni or 0.1% NiO. Thus the presumed liquid and olivine primocrysts, shown in Figure 11, appear to be in equilibrium (and both are Ni-depleted). The irregular large grain of olivine found in the sill has a lower Fo content (Fo_{74-68}), but higher Ni content (0.17% NiO) than the other two types of olivine. Such a composition supports the interpretation that these olivine grains are xenocrysts, and are derived from a rock from which prior removal of sulfide had not taken place. These geochemical observations strongly suggest that this sill formed from a magma that has lost an immiscible sulfide phase. In terms of total mass, the sill is trivial, being only 3 m thick, but it illustrates that a magma chamber existed in which sulfide immiscibility occurred.

The composition of typical Karoo basic magma is shown in Figure 11 (denoted K). Given its MgO, FeO and Ni contents (6.9%, 10.9% and 90 ppm), it is possible to calculate the composition of olivine that would form from it. Using the Mg–Fe exchange (Roeder & Emslie 1970) and the Ni partition coefficient (Duke & Naldrett 1979), a composition $Fo_{78.5}$ with 1150 ppm Ni is obtained and shown in Figure 11. All compositions that are mixtures of such a cumulus olivine and this liquid ought to lie on the tieline between the two, which is what is observed for the samples from the lower olivine gabbronorite. The proportion of cumulus olivine is quite small. Based on the values for R_o discussed previously, we suggest that the lowest samples in this profile have undergone assimilation of crust. But there is no observable or geochemical evidence to suggest that such

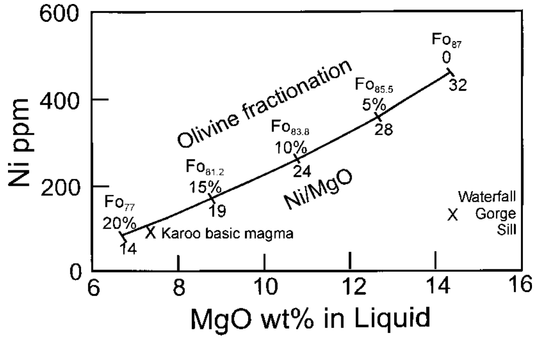


FIG. 9. Plot of wt% MgO *versus* Ni in ppm in liquid showing an olivine fractionation trend, the starting composition for which is postulated to be the most magnesian liquid responsible for the lherzolite. The observed composition of the Waterfall Gorge sill is Ni depleted (Table 1), and an inferred undepleted composition is used for this calculation. The composition of the Karoo basic magma is from Marsh & Eales (1984). The percent of olivine fractionation, the Fo content of the olivine and the ratio of Ni/MgO are shown.

contamination triggered the formation of an immiscible sulfide liquid.

The samples from the main lherzolite do not plot on this Karoo basalt – Karoo olivine trend in Figure 11, and so cannot have formed from such magma. The most magnesian olivine in this succession is Fo_{87} with 2200 ppm Ni. We suggest that this olivine formed from magma with 14% MgO and 450 ppm Ni (Fig. 9). These two compositions are shown in Figure 11. Accumulation of olivine into such a liquid composition ought to produce a linear array of bulk compositions plotting along this tieline. The data for the lherzolites in Figure 11 show no systematic trend. Many samples with a limited range of Mg contents, from 35–40% MgO, show Ni contents ranging from 1000 to 2400 ppm. We suggest that the samples that plot at lower Ni contents than the anticipated tieline contain olivine formed from magma already depleted in a Ni-sulfide phase. The few samples that plot above the tieline are inferred to contain a magmatic sulfide component.

The samples from the lower olivine-enriched layer of the upper gabbronorite (with 30% MgO) in the upper olivine gabbronorite lie on the same trend as the lherzolite samples in Figure 11, whereas the samples from the upper, less olivine-rich layer (20% MgO) lie nearer to the typical Karoo basalt trend. Three samples from the upper olivine gabbronorite are enriched in Ni. However, these samples are also enriched in Cu by a few hundred ppm, and obviously contain a magmatic sulfide component.

Samples from the upper olivine gabbronorite have less Ni than predicted by either trend (Fig. 11). This decrease is due to the change in cumulus mineralogy, and the fact that pyroxenes contain relatively less Ni compared to Mg than olivine. For example, a liquid with 7% MgO (and 10% FeO) would be in equilibrium with olivine, orthopyroxene and clinopyroxene containing 42, 30 and 15% MgO, respectively. If the liquid had 90 ppm Ni, and the partition coefficients are 11, 4 and 2, those same minerals would contain 990, 360 and 180 ppm, respectively. These idealized compositions of mafic minerals are plotted in Figure 11, and show that a rock with cumulus pyroxenes will contain less Ni for a given MgO content than a rock with cumulus olivine. Thus the apparently low Ni content for the MgO content in the upper olivine gabbronorites is probably due

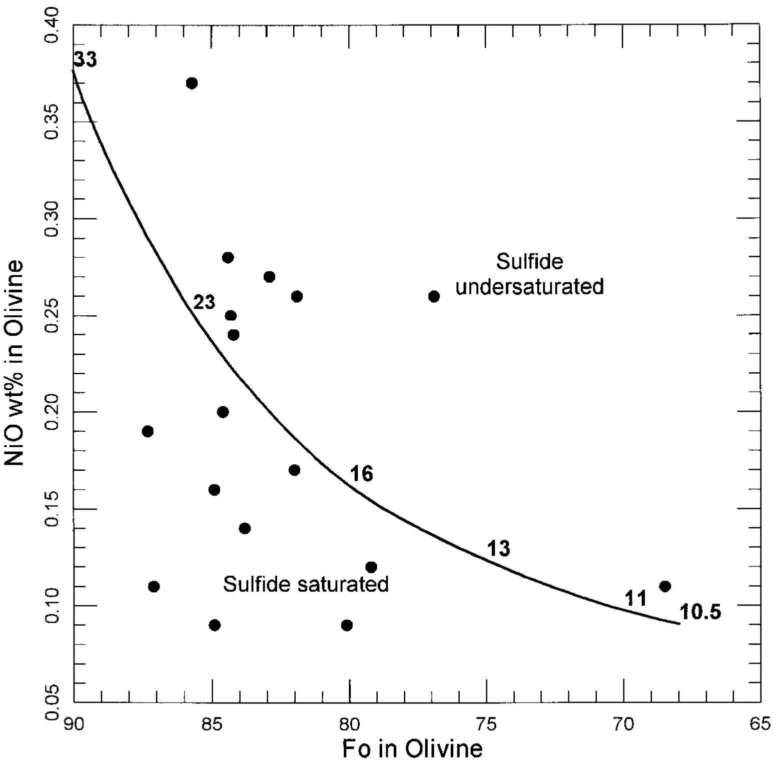


FIG. 10. Plot of Fo *versus* Ni in olivine from the borehole, showing that some olivine fractions are Ni- depleted. The general curve for sulfide saturation is from Duke & Naldrett (1979). Numbers along the curve are for Ni/MgO values.

to the different assemblage of minerals that is accumulating, and not to sulfide separation.

Also plotted on Figure 11 are lines of constant Ni/MgO. This ratio is less than 30 for typical Karoo basalt, its coexisting olivine, and hence also any mixtures between them. The proposed magma to the main lherzolite and its Ni-undepleted olivine composition have a ratio close to 40. Samples of lherzolite that are depleted in Ni, plot with lower Ni/MgO values than those samples that are undepleted, and hence this ratio is a useful guide to sulfide-mineralization events. However, this ratio will also change with olivine fractionation of a basic magma, as is shown in Figure 9. Magma with 14% MgO and 450 ppm Ni has a Ni/MgO value of 32. During fractionation, the ratio will decrease to 14 at the stage at which the composition has evolved to 7% MgO, which requires 20% fractionation.

These principles can be applied to data in Figure 12, which shows the variation in Ni/MgO as a function of height within the lobe. The basal 50 m show values of 14 to 32, consistent with olivine accumulation into a typical Karoo basalt composition. At 50 m, there is an abrupt increase in this ratio to 40, consistent with addition of magnesian magma. At 120 m, there is another

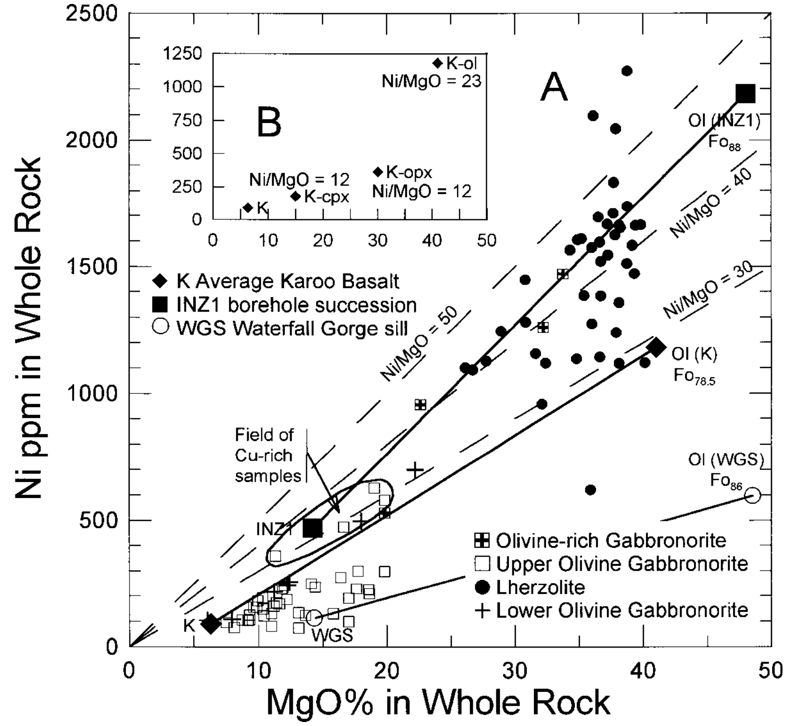


FIG. 11. A. Plot of wt% MgO *versus* Ni in ppm for whole rocks from the borehole. Points K and WGS are average Karoo basic magma (Marsh & Eales 1984), and the Waterfall Gorge sill. The latter composition has also been adjusted to the Ni content expected for an MgO content of 14%, and is denoted INZ1. This composition is considered to represent the magma that produced the lherzolite by olivine accumulation. The compositions of olivine in equilibrium with these three compositions are indicated as Ol(K), Ol(WGS) and Ol(INZ1), and their Fo contents are indicated. Tielines between magma and olivine compositions are shown as solid lines. Dashed lines of constant Ni/MgO are shown. Four samples of the upper olivine gabbronorite (shown as open square) that contain high Cu contents, and hence also high Ni contents, are encircled. Note that the samples from the lherzolite do not plot on the Ni-undepleted tieline, INZ1 to Ol(INZ1), between proposed magma and olivine, but show a wide range in Ni contents at near-constant MgO content. B. The inset shows the compositions of olivine (K-ol), orthopyroxene (K-opx) and clinopyroxene (K-cpx) in equilibrium with Karoo basic magma (K), together with their respective Ni/MgO values, and illustrates why the upper olivine gabbronorites in general have low Ni/MgO values compared to olivine-enriched rocks, even though they might have formed from a magma of similar composition.

abrupt increase and then a decrease in the Ni/MgO value, from 58 to 27, over a very short vertical interval. The anomalously high value of 58 suggests the presence of a small proportion of sulfide, and the anomalously low value of 28 suggests that the magma was depleted in Ni by the sulfide-forming event. Low values are not sustained upward in the succession above 120 m, suggesting that only a very small volume of magma underwent the sulfide depletion. Close to this level, there is a change in the value of R_0 from 0.7108 to 0.70706. Such a change probably reflects addition of new magma or mixing between two magmas. From 130 m to 300 m, the Ni/MgO ratio slowly decreases from over 40 to 30, consistent with fractionation. The ratio then increases to 40, indicative of magma replenishment. At 390 m, there is an abrupt but vertically restricted increase to a high value of 58. This anomaly coincides with an anomalously low value for R_0 (Fig. 6), and so may again reflect magma addition, and the formation of an immiscible sulfide liquid, but on a very limited scale. Above this level, near the top of the lherzolite, the Ni/MgO ratio shows a decrease to 10. We showed above that this decrease reflects the change in cumulus mineralogy, with pyroxenes becoming dominant. Apart from three very limited sections, the Ni/MgO ratio remains constant to the top of the intrusion. The three spikes all correspond to the presence of olivine-rich layers. In the case of the lower two, there is an increase in Cu, indicating the presence of sulfide, whereas the upper layer has a smaller Ni/MgO value and does not have a high Cu content associated with it.

Based on this Ni/MgO trend, it is possible to identify four intervals in the core that record the formation of sulfide. In the case of the stratigraphically lower two, they occur entirely within lherzolite, but occur at levels where magma addition is postulated on the basis of

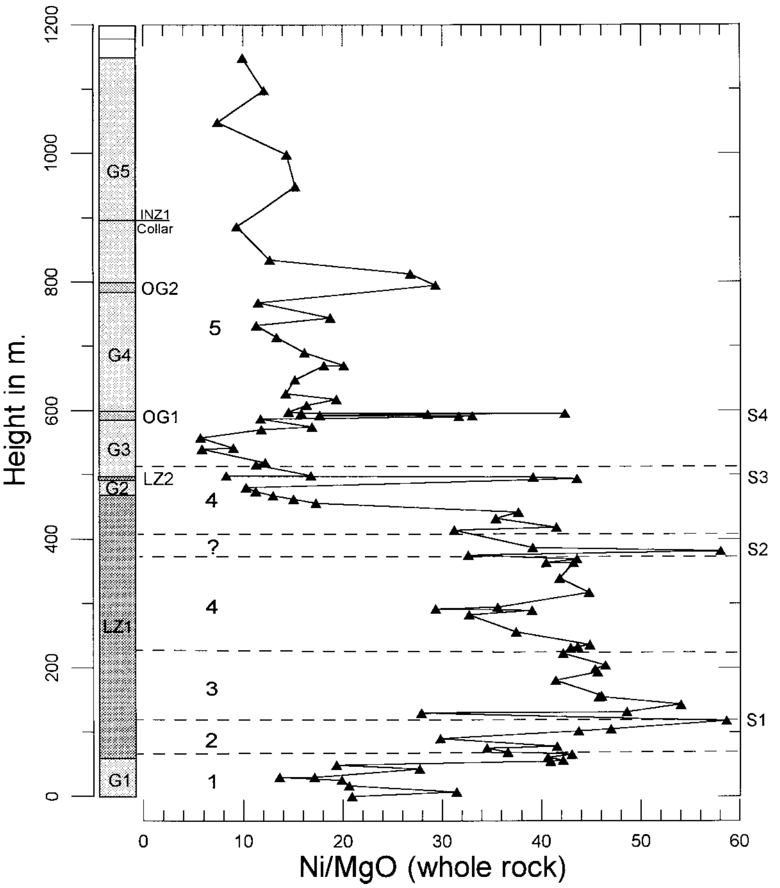


FIG. 12. Plot of whole-rock Ni/MgO *versus* height in the intrusion. Four zones that contain abnormally high Cu content (in sulfides that also contain high Ni) are shown as S1–S4. Numbers 1–5 refer to proposed distinct magmatic events

breaks in R_o values. The added magma may have been sulfide-saturated. However, mixing between it and the resident, sulfide-undersaturated magma may have resulted in sulfide-undersaturation. The upper two coincide with olivine-bearing zones in the upper gabbronorite. Again, the added magma may have been sulfide-saturated, but the ensuing mixing caused sulfide-undersaturation.

Relationship between the drill-hole section and Waterfall Gorge area

The presence of small deposits of massive and disseminated Ni–Cu–PGE sulfides at the base of the Insizwa lobe at Waterfall Gorge has been the motivation for several exploration programs. Most have focused on the immediate vicinity of Waterfall Gorge (see, for example, the location of boreholes drilled in a recent exploration program, indicated by Ferré *et al.* 2002 and Maier *et al.* 2002). The borehole described here, INZ1, was drilled on the basis of a gravity anomaly far from Waterfall Gorge in the interior of the Insizwa lobe. Another drill core, INS96–02, documented by Maier *et al.* (2002) from 1 km northwest of Waterfall Gorge, provides valuable geometrical information, shown in Figure 13. Sander & Cawthorn (1996) suggested that there was a graben oriented north–northwest immediately north of Waterfall Gorge (Fig. 3). The three vertical sections, INZ1, INS 96–02 and Waterfall Gorge are almost collinear (Fig. 1), and lie very close to the line of the proposed edge of the graben (Fig. 3). Nevertheless, in Figure 13, one can see that the basal contact of borehole INS 96–02 occurs at about 400 m above mean sea-level, whereas at Waterfall Gorge the elevation is over 1000 m. A difference of over 600 m in elevation over such a short horizontal distance is very strong evidence for the existence of such a graben structure (Fig. 13). We suggest that the lower olivine gabbronorite (denoted G1 in Fig. 13), the lherzolite (denoted LZ1), the immediately overlying olivine gabbronorite (denoted G2) and the next layer of lherzolite (denoted LZ2) are common to both INZ1 and INS96–02, although relative thicknesses vary. Lherzolite layer LZ1 has a distinctly higher R_o and slightly higher Fo content than LZ2. On the basis of these two criteria, we suggest that only upper lherzolite LZ2 is present at Waterfall Gorge. Olivine gabbronorite layer, G3, has a distinctly lower R_o value than the underlying rocks, and the break in this ratio

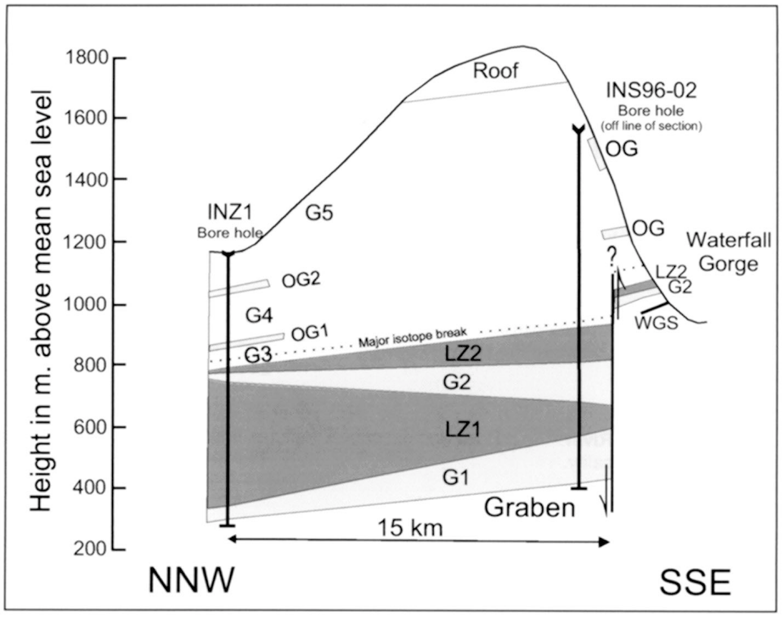


FIG. 13. Schematic cross-section, from north–northwest to south–southeast, from the borehole INZ1 to Waterfall Gorge, illustrating the variation in elevation of the base of the intrusive and the thickness of the lherzolite layers. The section crosses a proposed lineament, L3 in Fig. 3, causing the abrupt change in height of the basal contact. The possible correlations of the various units in the boreholes INZ1 and INS96–02, and Waterfall Gorge are indicated. Note that the lowest lherzolite unit (LZ1) is confined to the graben, and the lherzolite found at Waterfall Gorge is correlated with LZ2.

permits correlation across all three sections. The olivine-rich layers in the upper half of the Insizwa lobe are harder to correlate in these three sections, partly because there are fewer mineral compositional, geochemical and isotopic data with which to constrain such correlation.

Location of feeders

Ferré *et al.* (2002) used the anisotropy of magnetic susceptibility to try to determine directions of magma flow and hence the direction to possible feeders to the Insizwa lobe. They suggested that the small dyke at Taylor's Koppie (Fig. 1), just north of the village of Mount Ayliff, might have been the feeder to the Insizwa lobe. Their conclusion is based on an inferred northwest–southeast flow direction in rocks of the Insizwa lobe. The orientation of this dyke is northeast–southwest. We debate whether any flow fabric in the middle of a thick, layered body defines the source or feeder, or whether it reflects convection cells within the cooling sheet. Based on an air-photo interpretation, Sander & Cawthorn (1996) identified a strong north–northwest structural control. They also located a dyke with this orientation, immediately west of the present outcrop of the Insizwa lobe, that swelled to produce a lherzolite lens (Fig. 3). We therefore prefer to postulate the existence of feeder dykes with this orientation. Such observations, when combined with the abrupt changes in gravity anomaly across the lineaments shown in Figure 1, suggest that they may have acted as feeders. We also note that Maier *et al.* (2002) did not favor Taylor's Koppie as a feeder to the Insizwa lobe on the basis of its evolved PGE content compared to samples from their drill core.

Potential for Mineralization

Where olivine-rich rocks are exposed close to the base of the different lobes, minor sulfide mineralization has been reported (Scholtz 1936, Dowsett & Reid 1967, Lightfoot & Naldrett 1984a, 1987, Cawthorn *et al.* 1992). In many of these cases, the olivine compositions show evidence of variable degrees of Ni-depletion, suggesting prior separation of a sulfide fraction. Hence, we conclude that the magmatic system is close to sulfide saturation. The forsterite content of olivine in INZ1 is slightly greater than in INS96–02, and considerably more so than at Waterfall Gorge and Tabankulu. Hence, we postulate that feeders may lie close to INZ1, and that exploration in proximity to such vertical structures may offer further opportunities for locating sulfide orebodies.

Maier *et al.* (2002) concluded that the mineralization potential for Insizwa is minimal, because the proposed low-Mg parental magma is depleted in PGE. However, here we have shown that the magma parental to the lherzolite layers contained about 14% MgO, because of their high forsterite content. The only example of this magma, in a 3-m-thick sill near Waterfall Gorge, is extremely Ni-depleted compared to magmas that entered the main chamber of the Insizwa lobe, and so its PGE content cannot be used to determine the true Ni–Cu–PGE potential of the parental magma proposed here.

Summary

We have obtained geochemical information from a deep borehole drilled into the center of the Insizwa lobe of the Mount Ayliff Intrusion to provide further information about parental magmas and sulfide potential of this body, which is related to the basalt outpourings forming the Karoo Province. Olivine compositions reach Fo_{87}, and so are far too magnesian to have formed from a typical Karoo basic magma. This observation is supported by data from the Waterfall Gorge sill, which contains 14% and has hopper olivine grains attaining Fo_{86}. This sill is Ni-depleted, providing evidence for prior formation of sulfide. Thin zones in the 400-m-thick lherzolite of the Insizwa lobe also show signs of Ni-depletion.

On the basis of initial $^{87}Sr/^{86}Sr$ values, five different intrusive episodes are recognized. Highly anomalous and distinctive values in excess of 0.71 are identified in the lherzolite. We suggest that the lower part of the lherzolite in the drill-core section represents the localized lower part of the intrusion, formed from primitive magma or magmas injected into a graben. Subsequent injections of magma extended across the graben and reached Waterfall Gorge, but were not as magnesian or as contaminated as the earlier magmas. Fifty m below the top of the lherzolite in the drill core, there is evidence for a sulfide-forming event that may be the same as that seen at Waterfall Gorge.

The most magnesian olivine compositions so far reported in the Mount Ayliff Intrusion are found in this drill core, which is located close to a postulated feeder system, and we suggest that this area offers further opportunities for the discovery of Ni–Cu–PGE mineralization.

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