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The Timbavati Gabbro of the Kruger National Park

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The structure, geochemistry and isotope geochemistry of the Timbavati Gabbro, a suite of basic, intrusive sills located within and outside the Kruger National Park, are discussed. The available information is integrated into a single genetic model for the Timbavati intrusions — this model involves melting of upper mantle material and accumulation of the magma in an intermediate magma chamber from which batches of magma escaped at various times to form the different phases of the Timbavati Gabbro. Both fractional crystallisation and assimilation of country rock played a part in the geochemical evolution of the Timbavati Gabbro. The age of the Timbavati Gabbro appears to be quite young, predating the rocks of the Karoo Sequence by a relatively short time.

Key words: Timbavati Gabbro, petrogenesis, basic rocks, geochronology, geochemistry, structure, olivine gabbro, gabbro, quartz gabbro.

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Introduction

Outcrop of medium- to coarse-grained gabbroic rocks are present for a considerable distance in a north-south direction in the Kruger National Park (KNP). These rocks have been observed within the granitic and gneissic rocks that underlie much of the KNP, especially its central and western portions. Their distribution is illustrated in Fig. 1 and from this it can be seen that they are also present in places outside the park. These basic rocks, previously referred to as Tsange gabbros (Bristow, Armstrong & Allsopp 1982) have been named Timbavati Gabbro by the South African Committee for Stratigraphy (SACS, 1980). They have a clear surface expression, outcrop well in some places and may form prominent koppies, *e.g.* at Tsange lookout and at Ship Hill (Skipberg) (Fig. 2). Elsewhere they indicate their presence by the development of turf-like soils and distinctly sparser vegetation than the surrounding country.

Although of great interest to other disciplines such as botany and pedology,

the gabbros also present pertinent and stimulating geological problems. Quite a number of geologists have described them in the past and various opinions have been expressed as to their origin and affinities. Yet little clarity exists as to whether the Timbavati Gabbro intrusions are manifestations of the Karoo volcanicity which caused the extensive basalt and rhyolite successions of the Lebombo Ranges or whether they represent either a younger or an older magmatic event.
It is with the view to obtaining further information about the Timbavati Gabbro to improve our understanding of these rocks and perhaps draw firmer conclusions about its genesis, that the study was undertaken on which this paper is based. Three aspects of the Timbavati Gabbro have been given specific attention; these are the structure and shape of the intrusions, their trace element geochemical and isotopic composition and their age. Separate papers have appeared or are being written on each of these aspects (Walraven 1984; Walraven & Armstrong *in prep.)*. This paper represents a summary of this work in which these aspects are brought together and reviewed in context with earlier views and ideas.

Previous Work

One of the earliest references to the Timbavati Gabbro was made by Brandt in 1948 in his geological study of the northeastern Transvaal. He referred to it as the "Wildtuingang" or Game Park Dyke and considered it to be an irregularly trending north-south dyke. Visser & Verwoerd (1960) later described the gabbro in the explanatory notes of map sheet 22; they noted the relative freshness of the gabbro and considered it to be related to the Karoo dolerite, *i.e.* of late Karoo age. Their view was later opposed by Saggerson & Logan (1970) who grouped the Timbavati with their so-called "Older Basic Instrusions" of the north-eastern Transvaal. Evidence corroborating a pre-Karoo age for the Timbavati Gabbro was supplied by Clubley-Armstrong (1979) who mapped an area near Pretoriuskop and found clear indications of the gabbro being discordantly overlain by the Karoo strata.

Age determinations have provided further indications of an older age for the Timbavati rocks. $^{39}Ar/^{40}Ar$ step-heating age determinations done on four samples of gabbro from the vicinity of Orpen have resulted in ages ranging between 1 072±4 Ma and 1 123±5 Ma (Burger & Walraven 1978, 1980). Some of the samples showed evidence of strong overprinting at 696±4 Ma. Bristow *et al.* (1982) carried out Rb-Sr whole-rock determinations on the Timbavati Gabbro and obtained an age of 1 454±50 Ma and an initial $^{87}Sr/^{86}Sr$ ratio of 0,7050.

The sill-like nature of the Timbavati Gabbro was made clear during recent mapping in areas adjoining the KNP (Michaluk 1983). Gordon-Welsh (1980) interpreted the thickness of the sill in the vicinity of Orpen to be in the order of 200 m while Clubley-Armstrong (1979) made estimates of the thickness in the vicinity of Pretoriuskop ranging between 300 m and 480 metres.

Schutte (1974a, 1974b) recognised three gabbro types in the Timbavati intrusive, olivine gabbro, gabbro and quartz gabbro, which both he and Clubley-Armstrong (1979) considered to have originated by differentiation and fractional crystallisation after intrusion. Bristow *et al.* (1982) noted the relatively high initial $^{87}Sr/^{86}Sr$ ratio of the Timbavati (Tsange) Gabbro and

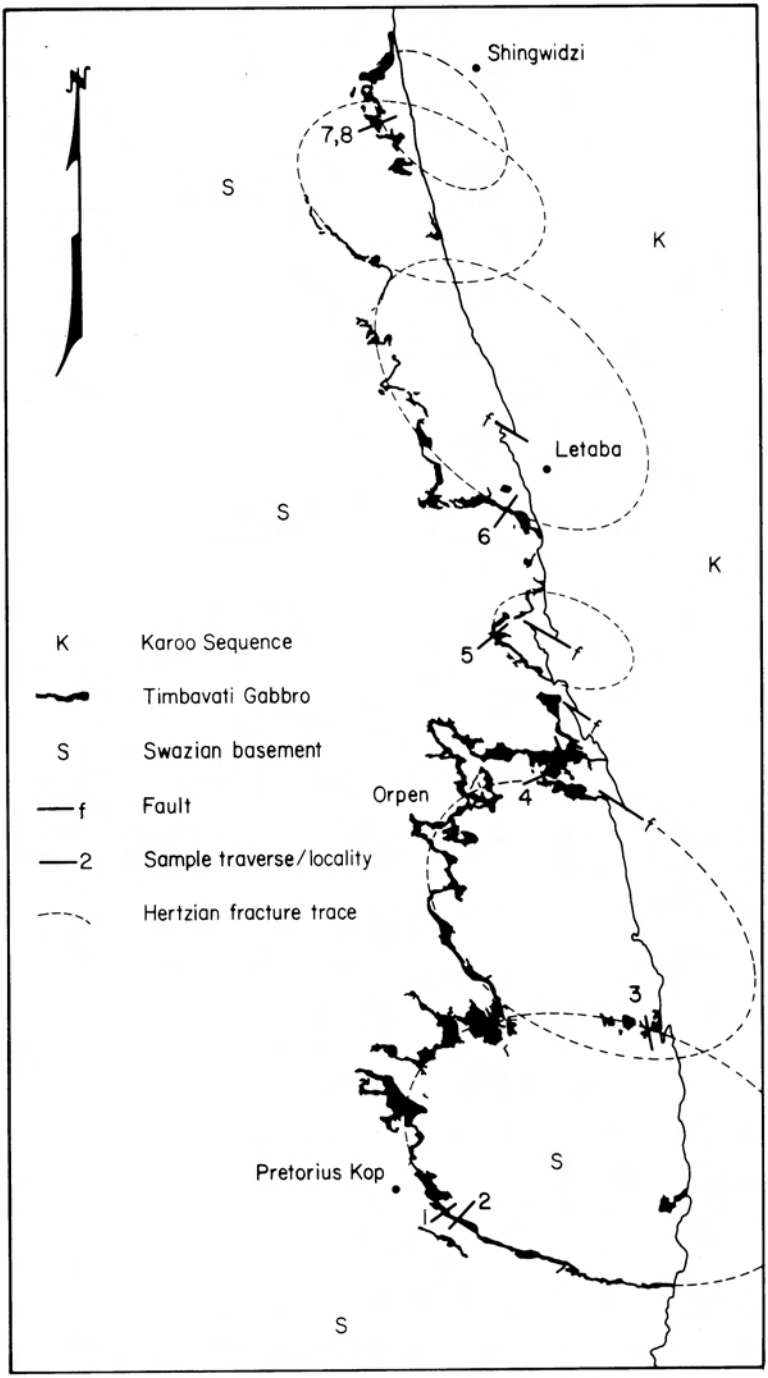

Fig. 1. Locality map and sketch plan of the Timbavati Gabbro showing its extent and outline as well as the sample traverses and the conical fracture traces. (Reproduced with permission of the Honorary Editor, Geological Society of South Africa).

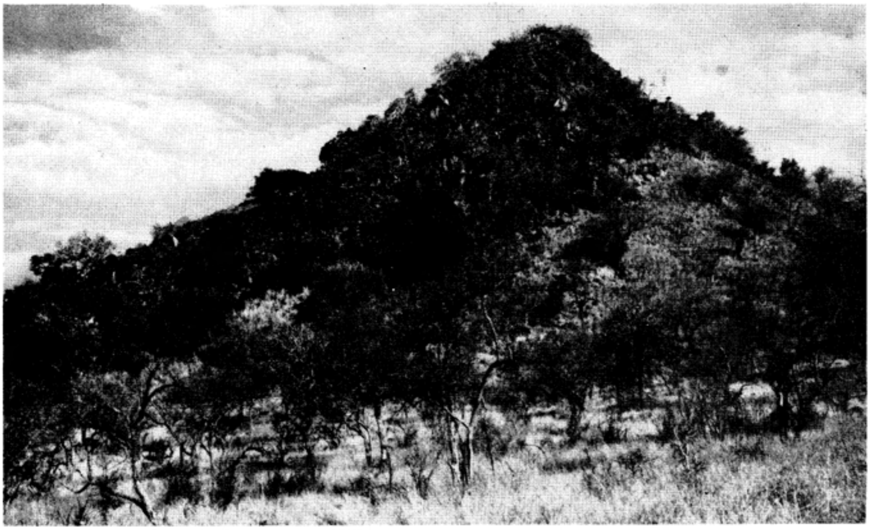

Fig. 2. View of Ship Hill (Skipberg) from the north. This is a prominent hill in the vicinity of Pretoriuskop, consisting of the gabbro phase of the Timbavati Gabbro. A contact with Archaean granite can be seen to the south-west of the hill. (photograph by I.C. Schutte).

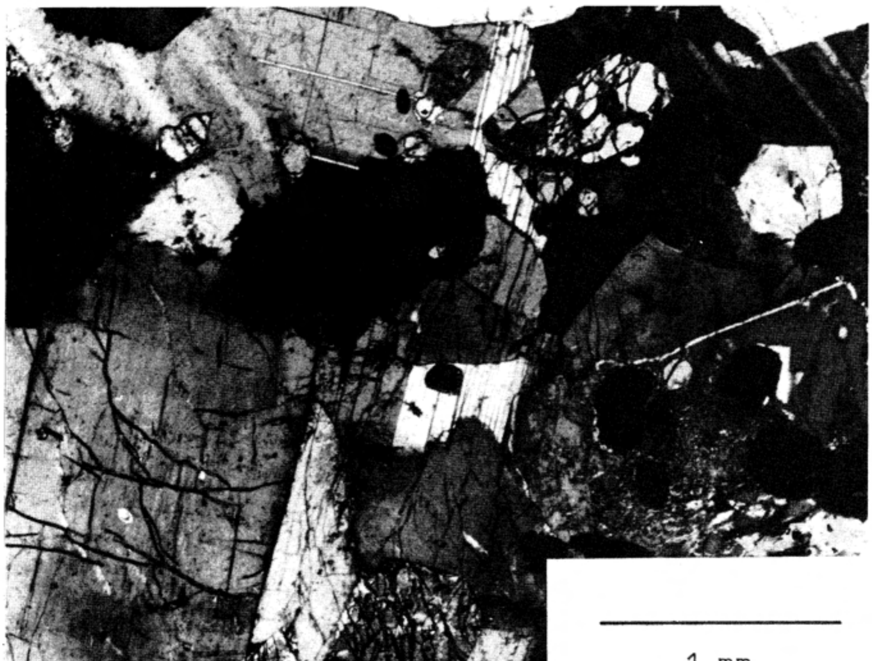

Fig. 3a. Microphotograph of the olivine gabbro phase of the Timbavati Gabbro. Crossed polarisers.

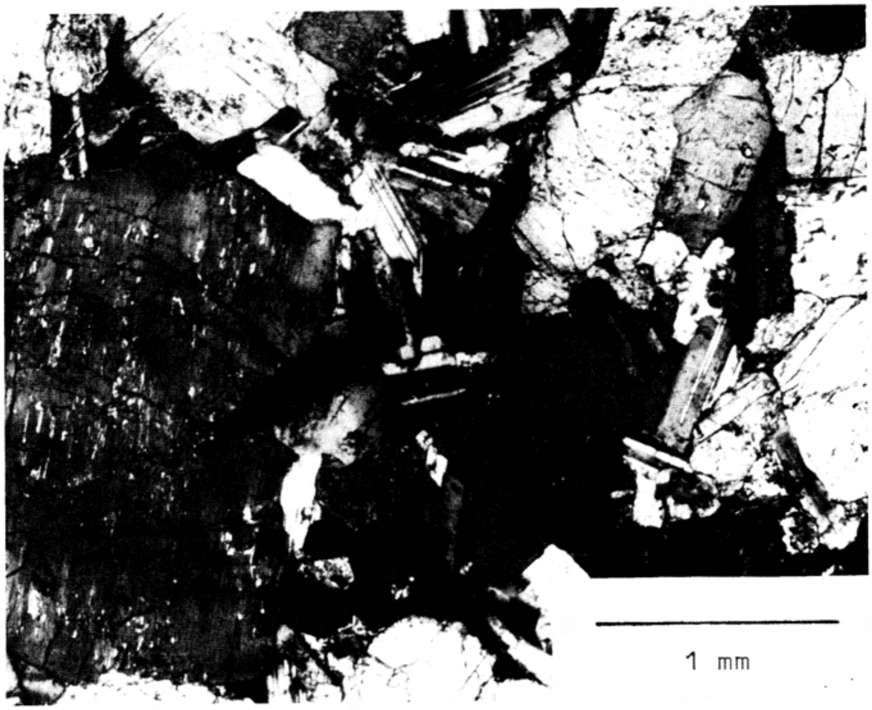

Fig. 3b. Microphotograph of the gabbro phase of the Timbavati Gabbro. Crossed polarisers.

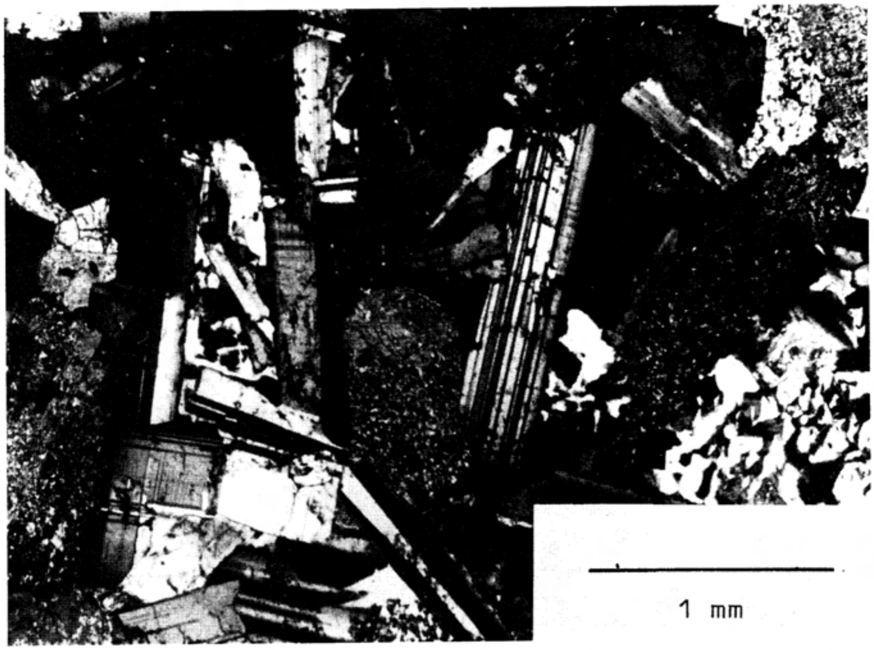

Fig. 3c. Microphotograph of the quartz gabbro phase of the Timbavati Gabbro. Crossed polarisers.

consider this to indicate a strongly radiogenic mantle having existed in this part of south-eastern Africa for some considerable time.

Petrography of the Timbavati Gabbro

Petrographic examination of the Timbavati Gabbro has confirmed the observations of Schutte (1974a, 1974b) that there are three gabbro types making up the sills. It has also demonstrated that this applies to the entire extent of the Timbavati Gabbro, both within as well as outside the Kruger National Park. A slightly finer grained phase, which represents a chilled margin of the gabbro intrusions, has been found in a few localities. The three gabbro types are an olivine-rich variety, a quartz-free gabbro with relatively little olivine and a quartz-bearing gabbro with no olivine.

1. Olivine gabbro
The olivine gabbro is medium- to coarse-grained and consists of olivine, clinopyroxene, plagioclase and orthopyroxene with minor magnetite, ilmenite and biotite (Fig. 3a). Olivine is abundant as fine-grained, rounded crystals between 0,2 mm and 0,3 mm in diameter. Larger olivines, about 1 mm in diameter, are also present. Clinopyroxene occurs as crystals 2 mm to 3 mm in diameter typically enclosing the fine-grained olivine poikilitically. Plagioclase has crystallised late and occurs interstitially. Orthopyroxene forms large crystals, up to 1,5 mm in diameter.

2. Gabbro
The gabbro is generally coarse-grained with large orthopyroxene crystals of 2 mm to 3 mm diameter. Clinopyroxene forms smaller crystals, about 1 mm to 1,5 mm in diameter (Fig. 3b). Olivine is present both as small (about 0,2 mm) and large crystals (about 1 mm) which vary in proportion from sample to sample. Plagioclase forms small, late-crystallised, interstitial laths. Biotite, magnetite and ilmenite make up a small proportion of the gabbro; the former usually represent alteration products of olivine. Very minor quantities of chalcopyrite and pyrite are also found in the gabbro.

3. Quartz gabbro
The quartz gabbro has a sub-ophitic texture similar to that observed in Karoo dolerite and consists of clinopyroxene and plagioclase, the latter forming laths of 1 mm to 2 mm length (Fig. 3c). Slightly finer grained orthopyroxene is also present as well as quartz, amphibole, biotite, ilmenite, magnetite, chalcopyrite and pyrite. The plagioclase, clinopyroxene and orthopyroxene show evidence of deuteric alteration and the pyroxenes have crystallised later than the plagioclase. Quartz and feldspar tend to occur interstitially and are intergrown to form micrographic textures in places.

Structure of the Timbavati Intrusives

Although, as noted in the foregoing section, the Timbavati Gabbro was at times interpreted as a dyke, its sill-like nature became clear once more detailed field work was carried out. The Timbavati sills generally dip towards the east at angles between 20 and 30 degrees. Initial mapping in the KNP by Schutte (1974a, 1974b) and Clubley-Armstrong (1979) illustrated the irregular shape of the sills, resulting in a surface expression unrelated to the topography of the region. Later mapping in the region adjoining the park (Michaluk 1983) completed the picture and showed the outcrop pattern of the sills to consist of a series of connected arcuate segments (Fig. 1). Since these arcuate shapes imply that the related sill segments must be conical in shape, it was suggested that the Timbavati Gabbro was emplaced along a series of north-south linked conical fractures (Walraven 1983). The surface intersection traces of these fractures are included in Fig. 1.

Conical fractures may form when brittle materials are subjected to localised stress and form part of a group of fractures generally known as Hertzian fractures (Hertz 1881; Auerbach 1891). Hertzian fracture cones tend to have a characteristic conical ring shape centred around the point of application of the stress; the slopes of the cones generally flatten away from the stress point. Hertzian fracturing has been invoked as a geological agent by various researchers such as Frank & Lawn (1967) and Lawn & Wilshaw (1975). Bahat (1979, 1980) carried out experiments using brittle materials such as glass and perspex and the results of these studies have been applied to both the Great Dyke of Zimbabwe (Sharpe & Bahat 1981a) and the Bushveld Complex (Sharpe & Snyman 1980; Sharpe & Bahat 1981b).

Interpretation of the shape of the Timbavati Gabbro intrusions as resulting from emplacement along Hertzian fractures would imply the existence of local stress points at a number of localities along an approximately north-south line. Estimates of the probable depths of such stress points are in the middle to lower crust and rising mantle diapirs have been considered as the possible causes of the local stresses (Walraven 1983). Upward movement of the diapirs would have continued through the crust up to the point where the internal volatile pressure exceeded the confining pressure; explosive pressure release took place at this point (Nicolaysen & Ferguson 1980). Conical fractures then formed, extending upwards and outwards from the points of stress to provide pathways for the later intrusion of magma from which the Timbavati Gabbro crystallised.

The north-south alignment of the diapirs would suggest control by a major structural feature (Ben-Evram & Mart 1981), possibly a major fault parallelling the south-eastern margin of the African continent, representing a crustal weakness extending south of the East African Rift Valley.

Major and Trace Element Geochemistry

Bristow *et al.* (1982) presented major and trace element data for three samples of Timbavati Gabbro. Some compositional variation is evident from their data although perhaps not quite what could be expected from the petrographical range described by Schutte (1974a, 1974b). The major and trace element data of this study were collected to examine the geochemical variations of the Timbavati Gabbro *per se* and also in order to be able to make geochemical comparisons between the Timbavati Gabbro and other basic igneous rocks, such as those of the Bushveld Complex and the Karoo Sequence. Samples of Timbavati Gabbro were collected along a number of traverses across the Timbavati sills in various parts of the KNP (see Fig. 1 for the location of the traverses). Samples intended for isotopic analysis and geochronological determinations were also collected during the sampling programme. The major and trace element data were carried out for the

author at the laboratories of the Geological Survey in Pretoria.
The distribution of major and trace elements in the Timbavati Gabbro strongly support the existence of three petrographic rock types; it also shows a distinct lack of intermediate compositions between the three gabbro types. The compositional gaps are very clearly shown by histograms of element concentrations, especially those of CaO, MgO and Ni (see Fig. 4). Petrographically the three groups defined by the histograms correspond to the olivine gabbro (high Ni and MgO and low CaO), the gabbro (intermediate concentrations) and the quartz gabbro (low Ni and MgO and high CaO). Statistical examination of the geochemical data (mainly cluster analysis and discriminant analysis have been used) results in further, clear illustrations of the existence of, and differences between, the three gabbro types. The cluster analysis resulted in a complete separation of the quartz gabbro samples from the gabbro and olivine gabbro samples and only two misgroupings between the gabbro and olivine gabbro samples. Even more striking distinction between the three gabbro types was obtained from the

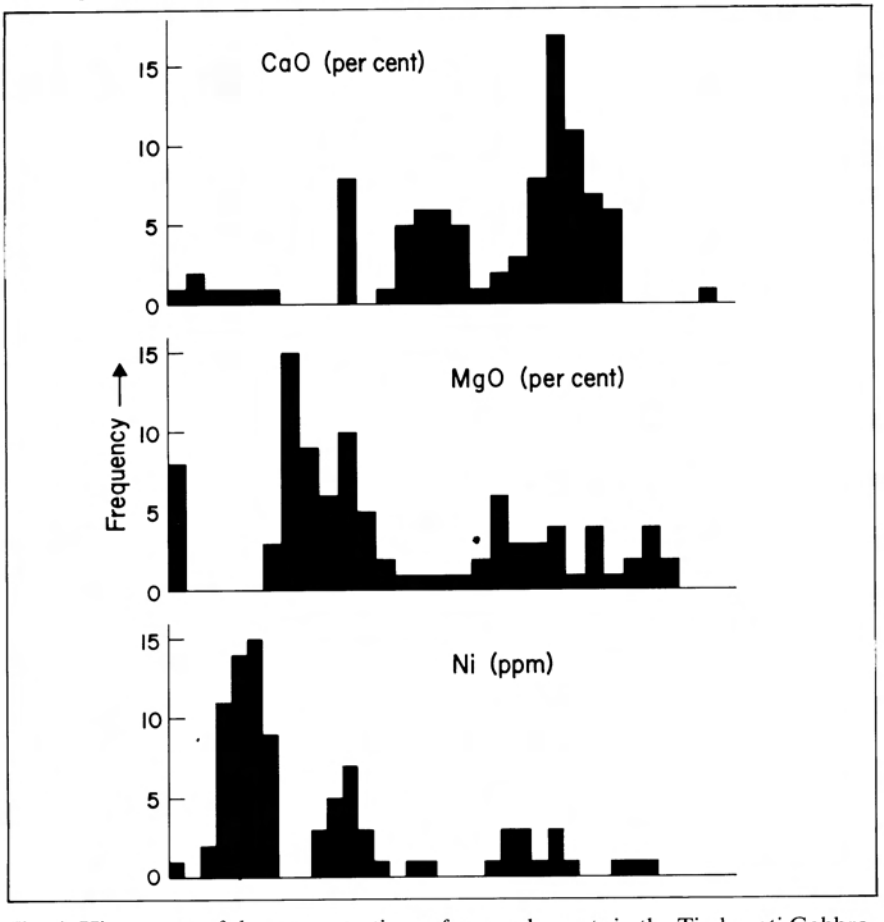

Fig. 4. Histograms of the concentrations of some elements in the Timbavati Gabbro. (Reproduced with permission of the Honorary Editor, Geological Society of South Africa).

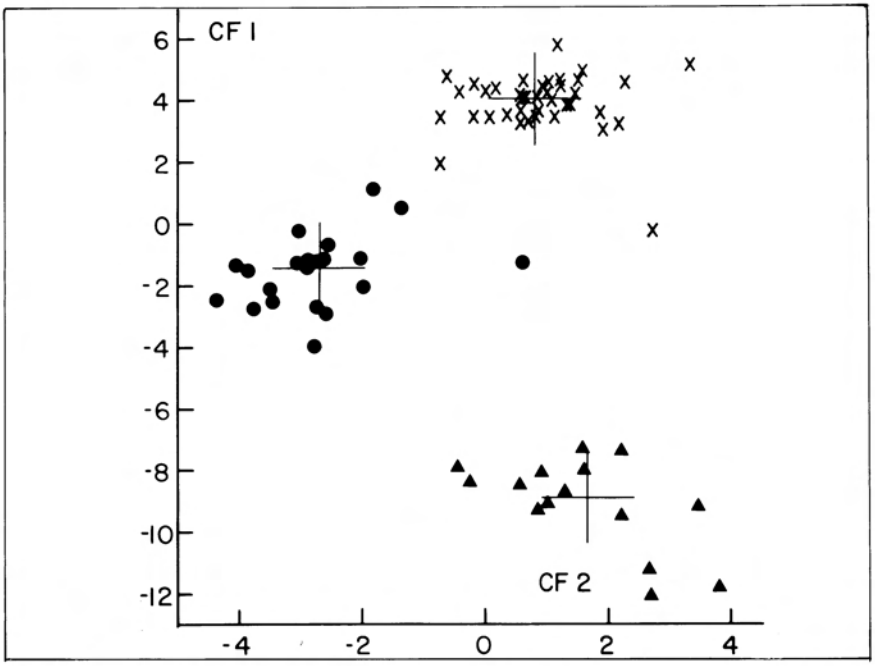

Fig. 5. Territorial map using canonical function 1 plotted against canonical function 2, showing the discriminated classes within the Timbavati Gabbro. Crosses represent quartz gabbro, circles gabbro and triangles olivine gabbro. (Reproduced with permission of the Honorary Editor, Geological Society of South Africa).

canonical discriminant analysis of the geochemical data. As illustrated in Fig. 5 extremely good classification and discrimination was obtained from this analysis with very clear distinctions between the three gabbro types. The chemical compositions of the class means of each of the three rock types is shown on Table 1.

Having confirmed and characterised the differences between the three gabbro types within the Timbavati Gabbro, it became possible to examine the distribution of these rock types throughout the various Timbavati sills. This examination revealed that many of the Timbavati Gabbro sills are composite in that they consist of more than one gabbro type. In addition the contacts between the different gabbro types within the composite sills are also in general sharp. These relationships are illustrated in Fig. 6 which depicts the chemical variations along three of the traverses across the Timbavati sills. In the case of traverse 4 the composite sill consists of intrusions of olivine gabbro alternating with quartz gabbro. Along traverse 5 the lower part of the sill is made up of olivine gabbro while the upper part consists of quartz gabbro. A somewhat different pattern is seen along traverse 7 where at least three separate intrusions of quartz gabbro can be recognised, each displaying a degree of upward fractionation evidenced by decreasing concentrations of elements which tend to concentrate in early-crystallising solids and increasing concentrations of those elements which tend to remain in the magma.

Table 1 *Average chemical compositions of the three gabbro types*

	Olivine Gabbro	Gabbro	Quartz Gabbro
SiO_2	47.82	51.86	52.46
TiO_2	0.52	0.51	0.74
Al_2O_3	7.07	9.54	14.22
Fe_2O_3	2.44	2.12	2.13
FeO	10.15	8.52	7.92
MnO	0.20	0.20	0.18
MgO	23.98	16.88	8.69
CaO	5.56	8.00	10.45
Na_2O	1.14	1.57	2.19
K_2O	0.40	0.38	0.62
P_2O_5	0.04	0.06	0.09
Ba	106	136	220
Rb	11	11	23
Sr	79	111	164
Y	9	10	17
Zr	62	59	81
Nb	4	4	5
Co	71	42	12
Zn	63	58	62
Cr	4473	2481	673
Ni	597	289	121
V	100	129	176
Cu	95	75	102

Major elements expressed as per cent; trace elements as parts per million

These observations quite clearly point to the conclusion that the Timbavati Gabbro was not formed as a result of the intrusion of a single magma, but rather by the multiple intrusion of a number of different magma types. Examination of the variations of the concentrations of various trace and major elements with indices of differentiation combined with theoretical modelling of fractional crystallisation suggests that a deep-seated intermediate magma chamber was involved in the formation of the magmas for the different intrusions (Walraven 1984). Partial melting of mantle material resulted in an olivine tholeiitic magma which accumulated in an intermediate magma chamber and there crystallised and differentiated to produce different magma compositions. The estimated depth of the intermediate magma chamber was probably less than about 27 kilometres. Comparison of the bulk chemical composition of the olivine gabbro and the olivine crystals themselves suggest that the latter are not in equilibrium but are probably xenocrystic in origin. This conclusion is corroborated by the rounded texture of the olivine crystals in the olivine gabbro and in turn means that the olivine had previously crystallised at depth and was incorporated into a subsequent batch of magma which intruded to form the olivine gabbro.

Geochronology of the Timbavati Gabbro

Although earlier work of Bristow *et al.* (1982) indicated an age of 1 454 Ma for the Timbavati Gabbro, the possibility could not be excluded that their data define a mixing line rather than an isochron, especially in view of the

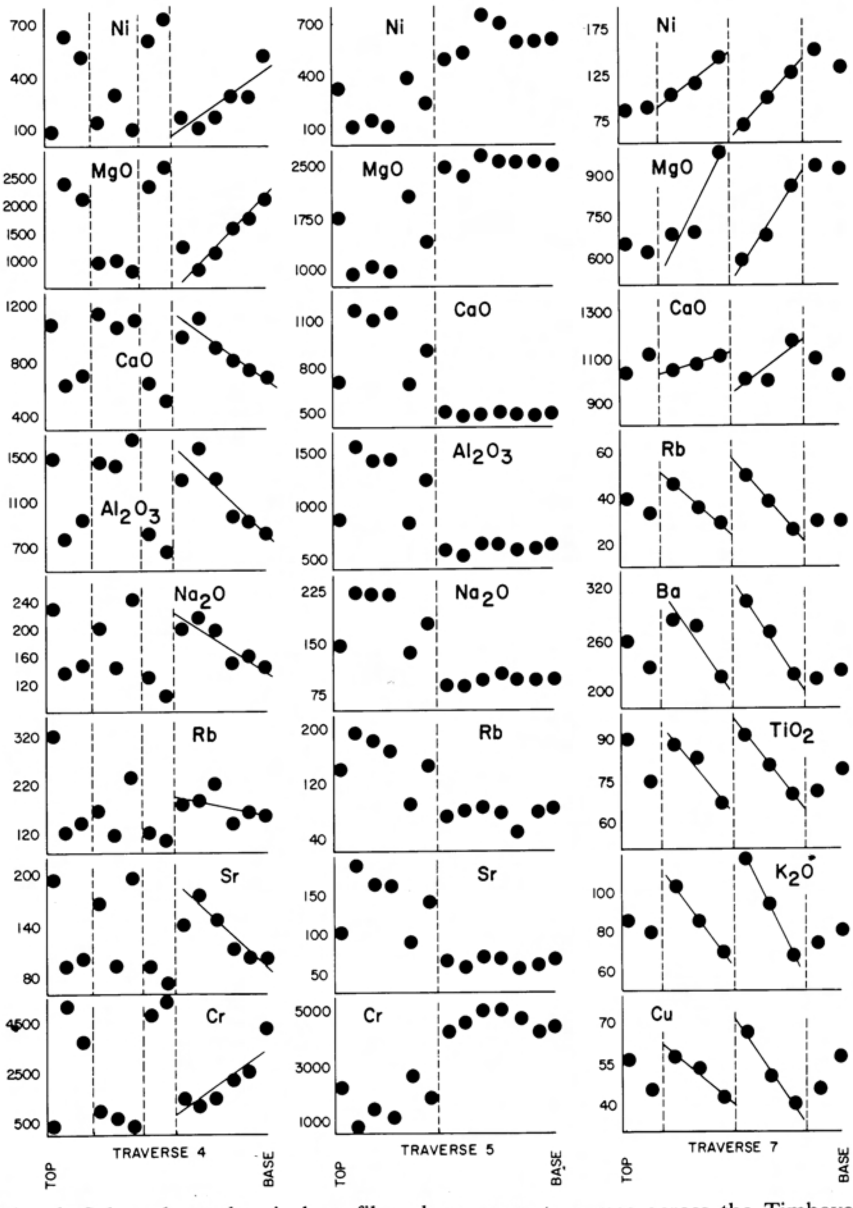

Fig. 6. Selected geochemical profiles along some traverses across the Timbavati Gabbro. Concentration breaks are shown as dashed vertical lines. Oxide concentrations are in per cent x100; element concentrations in ppm. (Reproduced with permission of the Honorary Editor, Geological Society of South Africa).

different intrusions involved. Walraven & Armstrong *(in prep.)* carried out both Rb-Sr and Pb-Pb isotopic analyses on the two suites of samples collected for istopic analyses as well as on a number of other samples. The results of the Rb-Sr analyses are summarised in Fig. 7 and it can be seen that the data define a number of sub-parallel trends rather than one single isochron. The general trend of the data agrees with the 1 454 Ma isochron of Bristow *et al.* (1982) but each of the individual gabbro types, quartz gabbro, gabbro and olivine gabbro, plot along a separate line having a flatter slope. The data points within each rock type scatter too greatly to allow a precise determination of the age of the Timbavati Gabbro on any of the rock types.

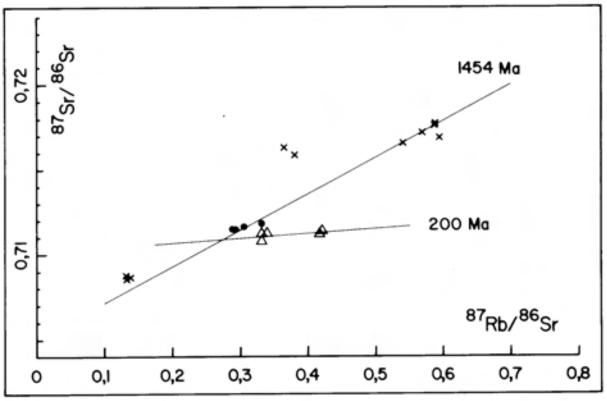

Fig. 7. Rb-Sr diagram of the analysed samples of Timbavati Gabbro. Included for reference are the 1 454 Ma isochron of Bristow *et al.* (1982) and a 200 Ma reference line. Crosses represent quartz gabbro, circles gabbro and triangles olivine gabbro.

Although further work is still in progress to establish this more conclusively, the Pb-Pb data obtained for the same samples tend to suggest that this age may be as low as Carboniferous to Permian, *i.e.* that the Timbavati Gabbro may be of Karoo age. This would imply that the 1 454 Ma age does not represent a real event but could possibly be a result of mixing of the Timbavati magma with older material having a higher ratio of $^{87}Sr/^{86}Sr$.

Discussion

Both the geochemical as well as the Rb-Sr isotopic data provide clear evidence of multiple intrusion involving at least three distinct magma types. This is quite clear not only from the distinct chemical compositions of the three main rock types — olivine gabbro, gabbro and quartz gabbro — but also from the separate trends that these rocks follow on the Rb-Sr diagram in Fig. 7. These features are quite at variance with those to be expected in a single magmatic intrusion which crystallised fractionally after emplacement. Such an intrusion could conceivably produce the range of rock types, in terms of petrography and geochemistry, that is seen in the Timbavati Gabbro, but would not result in the distinct lack of chemical compositions intermediate between the three main rock types. It would furthermore not be possible to explain the origin of the sub-parallel trends shown by the different gabbro types on the Rb-Sr diagram. A single intrusion would be expected to result in data points plotting on a single straight line.

Multiple intrusion is furthermore very clearly suggested by the abrupt compositional changes seen along some of the traverses crossing the

Timbavati sills. Once again, a single intrusion could be expected to produce a different pattern, consisting of smoothly varying chemical compositions, and the sharp breaks observed are suggestive of the contacts between different intrusions. The multiple alternations between gabbro types along some of the traverses suggest that interfingering of the later magmas may have taken place.

If multiple intrusion is accepted for the emplacement of the Timbavati Gabbro, it remains to be considered whether the different magmas were genetically related. If the geochemical variations did not form after intrusion of the gabbros they may be ascribed either to the formation of separate batches of magma by melting of various parts of the Earth's mantle or to changes that took place within a single batch of magma which formed by melting of mantle material and was subsequently modified either in situ or elsewhere. In the latter case portions of this magma were removed and intruded to form the different types of Timbavati Gabbro.

Consideration of the overall chemical similarity of the various gabbro types suggests that a model involving separate melting events is not a likely explanation and the alternative model of melting followed by subsequent changes in an intermediate magma chamber seems more acceptable. The geochemical modelling carried out by Walraven (1984) suggests that the olivine gabbro intruded first, followed by the gabbro and finally by the quartz gabbro. It also showed, however, that simple cooling and fractional crystallisation of this magma will not result in the observed chemical differences. The Rb-Sr data are also not in agreement with such a simple model. The main problem relates to the abundant presence of olivine in the olivine gabbro. Walraven (1984) showed the olivine to be out of chemical equilibrium with rock in which it occurs and therefore not likely to have crystallised from it. It was consequently suggested that the olivine represents a crystal cumulate of an earlier melt and that the olivine was incorporated into the first of the batches of magma that was emplaced to form the Timbavati Gabbro.

Both the geochemical and the isotopic data contain indications that assimilation of country rocks also played a part in modifying the chemical composition of the Timbavati magmas. The Rb-Sr data show this most clearly in the sub-parallel trends displayed by each of the gabbro types and the fact that the gabbro and quartz gabbro have increasingly higher $^{87}Sr/^{86}Sr$ ratios, suggesting that rather radiogenic material, such as the granite and gneiss typical of the area, may have been involved.

A final consideration that must be made concerns the mechanisms which controlled the movement of the different magma batches to their eventual place of intrusion. While it is not possible to reach definitive conclusions, the tectonism involved in producing the Hertzian fractures may have played a part. If mantle diapirs were in operation at the time of magma generation, they can be held responsible not only for causing the initial fracturing but also, by means of the stress patterns they generated, for the opening up of conduits and previous fractures to allow magma movement and intrusion to form the sills. Since different diapirs must have been operative to form the various fractures, differences between the stress patterns would have resulted and emplacement of later magma batches partly along new fractures and partly along the existing fractures, would have taken place.

The isotopic work, although still to be finalised, suggests that the Timbavati Gabbro may not be as old as was considered by Bristow *et al.* (1982) but is possibly, as indicated by the preliminary results of the lead isotopic work, slightly older than the Karoo Sequence. The Rb-Sr data are considered to clearly indicate the effects of assimilation of crustal material characterised by a higher $^{87}Sr/^{86}Sr$ ratio than the basic magma. Such assimilation, which probably took place while the magma resided in the intermediate magma chamber, but may also partly have occurred during the movement of the individual magma batches to their final site of intrusion, became more pronounced in the later batches of magma. Each of the individual gabbro types display some spread of the Rb-Sr data points; although the scatter within each is too great to allow an accurate estimate of the age, the approximate ages indicated by the slopes range from 200 Ma to about 650 Ma. The preliminary age indicated by the lead isotopic data is in the order of about 400 Ma which agrees with the rather wide bracket suggested by the Rb-Sr data.

Conclusions

The three aspects of the Timbavati Gabbro that have been examined during this investigation can be unified into a coherent model in which all the known and observed features of this intrusion can be incorporated. The model involves a period of magma generation in the upper mantle regions of the Earth coupled to upward movement of mantle diapirs. A substantial quantity of magma of tholeiitic composition was formed during the melting and this magma accumulated in an intermediate magma chamber. The action of the mantle diapirs resulted in the formation of conical fractures, also known as Hertzian fractures, in the crustal rocks thereby providing intrusion conduits for the magma. In addition to providing the fractures and intrusion conduits, the diapirs probably controlled the movement of batches of magma from the intermediate magma chamber to the final intrusion sites. Three main episodes of magma movement can be distinguished and in the periods between the individual batches the magma evolved by fractional crystallisation as well as assimilation of the rocks surrounding the magma chamber. This evolution is evident in the geochemistry of the Timbavati Gabbro, which ranges from olivine gabbro through gabbro to quartz gabbro.

It is also evident from the $^{87}Sr/^{86}Sr$ ratios of the gabbro types which increase systematically from the olivine gabbro through the gabbro to the quartz gabbro.

The first batch of magma, which was emplaced as the olivine gabbro, passed through and incorporated olivine from a cumulate which had crystallised in the magma chamber from an earlier magma. The second batch of magma incorporated very little olivine and was emplaced as the gabbro. The third and final batch of magma assimilated a greater amount of country rock and was emplaced as the quartz gabbro. Generation of new fractures and re-opening of previous fractures by the mantle diapirs resulted both in single intrusions as well as multiple intrusion so that some of the Timbavati Gabbro sills have sharp, abrupt changes of chemical composition.

The age of the Timbavati Gabbro appears to be slightly greater than that of the Karoo Sequence which disconformably overlies it. Thus the Timbavati Gabbro may represent a magmatic event which preceded the Karoo volcanicity but was probably part of the same major tectono-magmatic episode.

Acknowledgements

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