

Deep-crustal layered mafic complexes in the Mesoproterozoic oceanic-arc of the Tugela Terrane, South Africa

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ABSTRACT

Layered mafic intrusions are important in understanding the generation of continental crust in oceanic arcs. The Mesoproterozoic (c. 1200 Ma) Tugela Terrane in southeast South Africa is made up of a series of thrust slices of varied rock-types purported to have been derived in oceanic arcs prior to accretion onto the southern margin of the Archean Kaapvaal Craton. They are not ophiolites. Mafic intrusions in two adjacent thrust slices are known as the Tugela Rand and Mambula Complexes. Both intrusions are intensely layered on scales of centimetres to several tens of metres but clear cyclic units are not apparent and crystal fractionation is limited indicating these were open systems with magma chamber through-flow. Tugela Rand is made up of dominantly olivine-bearing rocks ranging from dunite and pyroxenite to gabbro. In contrast, Mambula is dominantly gabbroic with only rare olivine-bearing rocks and is more evolved with layers of titaniferous-magnetite. Primary magmatic structures in both complexes include graded bedding, slumping and erosion features. Relatively high pressure of formation is indicated by the aluminous nature of the pyroxenes and corona textures by reaction between plagioclase and olivine. Chromitites in Tugela Rand range from massive to podiform with the rare orbicular variety indicating complex controls on chromite accretion. They include the high-Al compositional variety. There are no other similar chromitite occurrences in South Africa. The complexes, together with their enclosing rock-types, draw striking parallels with the lower arc crust observed in the late Cretaceous Kohistan arc complex in NE Pakistan. The Tugela Rand Complex shares many similarities with the Chilas Complex in that terrane, while the Mambula Complex is considered to be a more evolved derivative of the same magma. This study shows that generation of juvenile continental crust formation in mature island arc systems may have been firmly established by the Mesoproterozoic.

1. Introduction

Subduction of oceanic lithosphere beneath other sections of oceanic lithosphere has been the cornerstone of plate tectonics since the early Proterozoic or even the Archean. The generation of juvenile continental crust in intra-oceanic arcs is now recognized as an important related process (Couzinié et al., 2024; Gazel et al., 2015; Lutfi et al., 2023). Evaluation of this concept becomes more difficult in the ancient geological history but certain terranes allow further understanding of the process. One such area is the Mesoproterozoic Natal-Namaqua Metamorphic Province, an extensive belt of igneous rocks and metamorphic derivatives that lies in the southeast and western margins of the Archean Kaapvaal Craton in southern Africa. It is lithologically and chronologically linked to the extensive proto-Kalahari Craton and includes the Maud belt in Antarctica, metamorphic complexes in

Mozambique and the Sinclair Group in Namibia that formed the locus of the supercontinent of Rodinia. Lithologies in the Natal-Namaqua Metamorphic Province are highly diverse and include granites, high-grade metamorphic rocks and volcanic sequences that are linked to volcanic arcs spanning several episodes (Cornell et al., 2006; Macey et al., 2022).

In the geological history of southern Africa, ultramafic and mafic complexes provide insight into the source of volcanism and the prevailing tectonic settings. This study examines two well preserved layered intrusions in the Natal sector of the Natal-Namaqua Province and focuses attention on their possible role in the evolution of oceanic arcs in the Mesoproterozoic. These are known as the Tugela Rand and Mambula Complexes, and this study presents the first detailed geological maps of them, together with field, mineralogical and compositional data offering insight into the tectonic and magmatic evolution of the Tugela Terrane

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in which the complexes occur.

2. Tectonic setting

The Natal-Namaqua Province surrounds the Kaapvaal Craton to the west, south (underlying Phanerozoic rocks) and east and comprises a wide variety of rock types including mafic and felsic volcanic rocks and intrusive granitoids. Although continuity between the eastern and western sectors of the orogenic belt is generally accepted, a fundamental difference is that the Natal sector represents almost entirely mantle-derived juvenile crust extracted after 1.5Ga (Eglington et al., 1989) whereas the western segment reflects more varied sources (McCourt et al., 2006; Thomas and Eglington, 1990). The principal aim of this

work is to provide further context to this observation.

The south-eastern sector of the Natal-Namaqua Province, the KwaZulu-Natal sector (Fig. 1a), comprises three distinct tectonic units known, from north to south, as the Tugela, Mzombe and Margate Terranes (Blereau and Spencer, 2023; Thomas, 1989; Thomas et al., 1993). The most southerly is the Margate Terrane at granulite facies and is dominated by granitoid gneiss and mafic gneisses with subordinate supracrustals including metapelite and carbonate. The youngest concordant detrital zircon age from the metapelite has been dated at 1207 ± 33 Ma and the oldest granitoid at 1181 ± 15 Ma (McCourt et al., 2006). Arc magmatism in the Margate Terrane continued until ~ 1120 Ma accompanied by intrusions derived from melting of pre-existing arc crust (Spencer et al., 2015). North of the Margate Terrane and adjacent

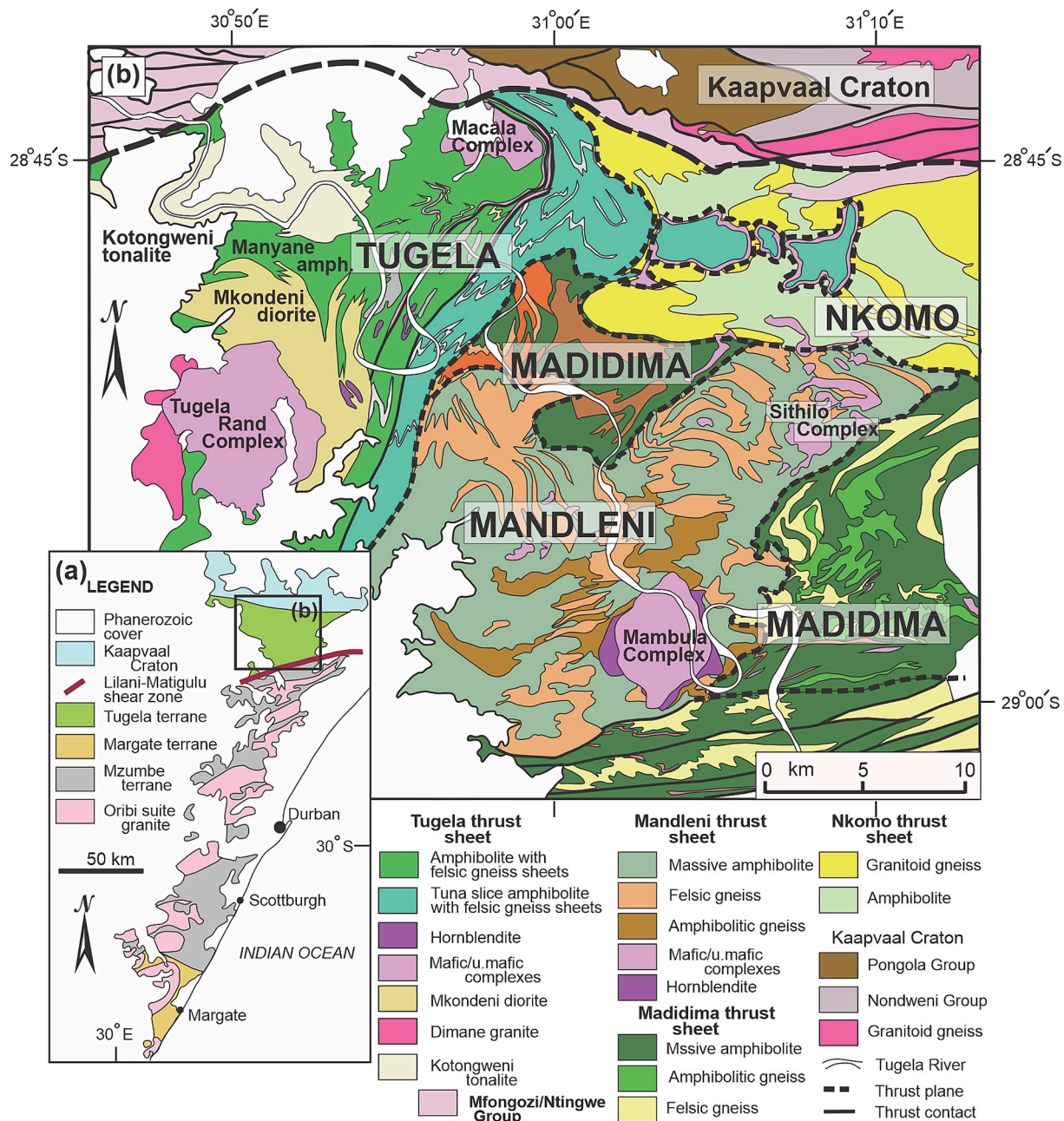


Fig. 1. Simplified geological maps of (a) the Natal sector of the Natal-Namaqua belt (after McCourt et al. (2006), and Cornell et al. (2006)), and (b) the Tugela Terrane after Matthews and Charlesworth (1981). Gravity modelling (Barkhuizen and Matthews, 1990) indicates that the Lilani-Matigulu shear zone (in (a)) marks the southern margin of the Kaapvaal Craton beneath the Tugela Terrane and also the tectonic contact between the Mzombe and Tugela Terranes. A series of tectonostratigraphic packages (or thrust sheets) make up the Tugela Terrane with the Nkomo sheet the lowest, followed by the Madidima and Mandleni thrust sheets and the structurally highest Tugela thrust sheet. Outlines of the Tugela Rand and Mambula Complexes are from this work.

to it are amphibolite to granulite facies gneissic supracrustal rocks of the Mzumbe Terrane extending for over 200 km and comprising older gneissic supracrustals intruded by granites and tonalitic gneisses. Volcanic-arc geochemical signatures characterize the grey gneisses.

The most northerly component of the Natal belt is the Tugela Terrane (Fig. 1b), an imbricated thrust complex emplaced onto the southern boundary of the Kaapvaal Craton and mapped in detail by Matthews and Charlesworth (1981). A series of four westerly plunging thrust sheets, known from east to west as the Nkomo, Madidima, Mandeleni and Tugela collectively comprise the Tugela Terrane. These thrusts are dominated by amphibolite-gneiss, ultramafic and mafic intrusions and felsic schists (Matthews and Charlesworth, 1981). The amphibolite rocks of the Tugela Terrane are interpreted as original sea-floor basalt and as a result the sequence was considered to be part of an ophiolite (Matthews, 1972). The structural complexity of the thrust sheets is illustrated in the Madidima sheet in which five episodes of deformation represent the continuum of arc-continent convergence (Abu Sharib et al., 2021).

The highest structural package of the Tugela Terrane is the Tugela thrust sheet in which the Tugela Rand ultramafic/mafic complex is located. The complex was first recognized by du Toit (1931) and later described by Dix (1981). The Mambula Complex with extensive deposits of titaniferous magnetite is located in the Mandleni thrust sheet and was first described by du Toit (1918) and mapped in part by Bristow (1981). The Tugela Terrane, thrust onto the southern margin of the Archean Kaapvaal Craton and the associated accreted arc terranes making up the Natal province, were formed between 1250 and 1070 Ma (McCourt et al., 2006).

3. Methods

Mapping of the Tugela Rand and Mambula complexes was carried out in five field seasons over the period 1982–1990 using high resolution 1:5000 aerial photographs prepared specifically for this project. 259 samples were collected, and sample locations are shown on the geological maps in the Supplementary Data File. Approximately 2 kg samples were used for whole rock major and trace element analyses for field samples. Drill-core samples from Tugela Rand (TR8) were 150 g of half core. Drill-core samples from Mambula (MBH) were taken as composite chips for each rock unit to give a total of 500 g for each sample. Major elements were analysed using fusion disks made from Li metaborate Spectroflux 105 and the Panalytical Axios XRF at Wits University and the PW1404 XRF at the University of KwaZulu-Natal. Trace elements were determined on 50 mg of powdered sample by ICP-MS using the Thermo iCAP in the mass spectrometry facility at Wits University after HF-HNO₃ dissolution in Teflon pressure vessels held at 160 °C for 24 h and dried down twice using pure concentrated HNO₃ to decompose fluorides. The dried sample was taken into solution with 5 % HNO₃ containing the internal standard Rh, Re, Bi and In. Zr was also analysed by XRF on pressed pellets for comparison with the ICP-MS data, to ensure that complete dissolution of trace amounts of zircon in the samples had been achieved.

Isotopic measurements were carried at the Carnegie Institution of Washington. Approximately 200 mg of sample was dissolved in a 2:1 mixture of HF-HNO₃ in a sealed Teflon vessel after the addition of isotopically enriched tracers of ⁸⁷Rb, ⁸⁴Sr, ¹⁴⁹Sm and ¹⁵⁰Nd. Chemical separation methods followed those described by Walker et al. (1989). Sr isotopic compositions were corrected for fractionation and instrument bias to yield a value of ⁸⁷Sr/⁸⁶Sr = 0.71025 for standard NBS 987. Nd was measured as NdO and fractionation corrected with data reported to a value of ¹⁴³Nd/¹⁴⁴Nd of 0.511860 for the La Jolla Nd reference standard (Wilson and Carlson, 1989).

Electron microprobe analyses were carried out in the Geology Department at Rhodes University using a Cameca SX-100 and a Jeol Superprobe at the University of Cape Town. Analytical conditions were a 2-µm spot and beam current of 20 nA. Primary standards were

accredited minerals and ZAF correction was online. In-house standards were used to ensure accuracy.

Compositional data are given in Tables 1 and 2 and in Supplementary Data Files. The compositional parameter Mg# for silicate rocks containing ferromagnesian minerals is molar MgO/(MgO + FeO). Wt% FeO is calculated as 0.9 total Fe.

4. Tugela Rand Complex

The Tugela Rand Complex is a mafic/ultramafic intrusion, sub-circular in map view (Fig. 2), exposed over 16 km in a north-south direction and approximately 12 km wide, covering 80 km² in exposed areal extent. It comprises a wide variety of rock types ranging from dunite and pyroxenite to gabbro and troctolite. The intrusion is enclosed within amphibolite of the Tugela thrust slice as well as the Mkondene diorite/quartz norite. It is intruded on the west side by the Dimane granite. Gabbroic rocks and dunite/wehrlite are the dominant lithologies with extensive chromitite layers in some parts of the complex. Nowhere are contacts with the country rock exposed and in the north-east pyroxenites are in close association with diorite. Distinct cyclic units are not observed on a local scale but the full range of rock types is preserved in many areas. The complex is intensely lithologically layered on scales from a few cm to 10's m with overall attitude dipping to the south and striking approximately east-west. Apparent strike directions are affected by the extreme topography of the area.

4.1. Structure of the complex

The dip of the layering to the south increases from relatively low angles (~10°) in the northern part of the complex, progressively increasing towards the south eventually becoming sub-vertical and then reversed in the extreme south with dip angles to the north of about 60°. There is also faulting throughout the complex with the central dunite unit entirely fault bounded. In the north the layers are parallel to the margins of the complex and in the north-west of the complex a border group of olivine-amphibole gabbro grades into amphibolite with no evidence of a chilled contact. Throughout the rest of the complex the lithological layers project to intersect the boundary at a high angle. On the east side a pegmatoidal gabbro-norite appears to be situated at the margin as a facies variation of the layering. Tectonic duplication of layering is apparent in some areas.

4.2. Lithologies

The Tugela Rand Complex is remarkable in the range of mafic and ultramafic lithologies present. The most abundant rock-type, overall, is gabbro with allied types including olivine-bearing, anorthositic, and noritic varieties. Dominantly olivine rock-types are also in abundance and range from massive dunite (now serpentinized on surface) in the centre of the complex, to wehrlite, harzburgite and lherzolite, together with feldspathic variants in layers throughout the complex. Troctolite is the dominant lithology in the south. Pyroxenites include ortho- and clinopyroxenite and websterite together with feldspathic and olivine-bearing varieties. In some cases these represent differentiated units, but the layered packages seldom extend more than several hundred metres suggesting high degrees of compartmentalisation and interaction between discrete crystal-melt packages. Some of these packages appear to be bounded by *syn*-depositional growth faults.

Local successions of basal wehrlite grading into plagioclase-bearing clinopyroxenite and overlain by gabbro or anorthosite provide clear evidence of a fractionated sequence and definitive way-up. Such sequences are 10–30 m in thickness and are common throughout the complex. Orthopyroxenite and websterite grade upwards into norite or gabbro-norite respectively on a repeated basis. Repeated minor scale layered sequences such as wehrlite interspersed by layers of clinopyroxenite are likewise common (Fig. 3a). Plagioclase is locally abundant in

Table 1
Major and trace elements of the Tugela Rand Complex.

Sample	TR82/80	TR82/11	TR82/50	TR82/42	TR82/87	TR82/27	TR8 110.16	TR82/16–1	TR8 114.8	TR8 238.6	TR8 225
Area	W.central	South	W.central	East	West	North	N east	Central	N east	N east	N east
Domain	D2	D5	D3	D3	D3	D2A	D2A	D1	D2A	D2A	D2A
Rock-type	Ol.gab	Troct	Ol.gab	Ol. Clinop	ol.Web	Webst	Pyrox	Wehr	Dunite	Dunite	Dunite
Setting	Field	Field	Field	Field	Field	Field	Core TR8	Field	Core TR8	Core TR8	Core TR8
wt%											
SiO ₂	51.07	47.33	49.83	49.69	49.80	52.97	52.46	43.50	44.59	41.82	41.5
Al ₂ O ₃	22.31	25.35	12.10	4.88	5.22	4.23	3.68	6.00	2.33	1.58	1.49
Fe ₂ O ₃	0.39	0.39	0.69	0.72	0.76	1.09	1.16	1.33	1.42	1.63	1.64
FeO*	3.17	3.15	5.61	5.81	6.12	8.81	9.43	10.75	11.5	13.18	13.31
MnO	0.06	0.05	0.14	0.15	0.16	0.21	0.22	0.20	0.22	0.23	0.18
MgO	7.24	8.16	14.77	19.45	20.23	24.66	29.46	33.10	36.56	40.56	41.6
CaO	12.07	12.6	14.4	16.68	15.4	6.91	2.64	4.53	3.02	1.15	0.13
Na ₂ O	2.92	1.98	1.48	0.50	0.38	0.36	0.01	0.18	0.46	0.03	0.38
K ₂ O	0.12	0.18	0.08	0.02	0.00	0.02	0.01	0.04	0.00	0.02	0
TiO ₂	0.12	0.13	0.38	0.40	0.37	0.37	0.23	0.18	0.12	0.11	0.08
P ₂ O ₅	0.03	0.03	0.02	0.02	0.01	0.02	0.01	0.03	0.02	0.03	0.03
Cr ₂ O ₃	0.05	0.22	0.24	0.70	0.71	0.49	0.55	0.38	0.34	0.50	0.53
NiO	0.01	0.03	0.03	0.09	0.08	0.12	0.14	0.20	0.22	0.26	0.27
TOTAL	99.57	99.61	99.76	99.11	99.24	100.26	99.99	100.42	100.81	101.1	101.14
* FeO calculated as 0.9Fe total											
ppm											
Li	1.347	1.755	3.439	1.612	1.212	1.178	1.227	2.85	1.291	0.236	0
P	66.7	103.6	44.4	47.2	26.5	18.9	19.40	63.0	49.8	59.1	57.536
Sc	14.734	4.663	45.754	60.542	50.378	33.904	27.061	11.798	14.744	6.375	5.813
Ti	682	807	2089	2251	2097	1948	1164	908	525	359	301
V	55.0	30.9	162.3	202.9	194.0	157.1	116.5	58.9	63.3	46.1	41.0
Cr	247	1446	1487	4688	4576	2966	3109	1633	1731	2252	2280
Co	30.3	34.2	48.7	60.2	85.2	103.2	90.2	116.7	122.5	118.8	137.4
Ni	100	271	198	696	577	783	945	1230	1350	1472	1511
Cu	3.34	67.8	22.0	350.5	283.6	310.0	298.1	217.9	229.1	117.7	135.789
Zn	21.95	24.92	33.88	35.36	36.66	65.17	71.83	67.82	69.22	81.77	74.92
Rb	0.785	3.237	1.835	0.884	0.379	0.351	0.641	0.715	0.224	1.044	0.14
Sr	1158.9	440.3	306.2	64.3	48.4	26.7	12.5	194.7	15.0	4.9	2.7
Y	2.199	2.034	7.486	9.337	8.369	6.216	2.642	2.217	1.836	1.013	0.968
Zr	2.607	9.378	12.365	13.477	13.09	9.311	5.069	3.937	3.411	3.489	2.866
Nb	0.027	0.318	0.029	0.06	0.009	0.247	0.075	0.19	0.069	0.184	0.143
Cs	0.14	0.141	0.606	0.036	0.181	0.093	0.047	0.154	0.021	0.095	0.005
Ba	93.9	76.3	38.5	9.362	5.426	6.202	5.933	38.786	4.321	9.846	2.434
La	1.672	1.461	1.04	0.857	0.775	0.825	0.413	1.683	0.26	0.474	0.401
Ce	2.687	2.919	3.192	2.82	2.328	2.554	0.649	2.618	0.62	0.893	0.864
Pr	0.319	0.367	0.577	0.539	0.414	0.437	0.088	0.272	0.103	0.118	0.122
Nd	1.478	1.632	3.469	3.405	2.586	2.555	0.497	1.445	0.594	0.560	0.604
Sm	0.391	0.383	1.192	1.309	1.000	0.843	0.191	0.423	0.204	0.154	0.170
Eu	0.332	0.295	0.463	0.484	0.375	0.287	0.069	0.214	0.082	0.050	0.058
Gd	0.445	0.399	1.434	1.674	1.352	1.063	0.289	0.479	0.280	0.182	0.209
Tb	0.068	0.059	0.229	0.276	0.229	0.178	0.056	0.071	0.049	0.028	0.030
Dy	0.426	0.373	1.465	1.811	1.549	1.190	0.438	0.432	0.355	0.197	0.204
Ho	0.086	0.074	0.298	0.372	0.323	0.251	0.103	0.088	0.076	0.043	0.041
Er	0.231	0.202	0.789	0.966	0.881	0.729	0.335	0.236	0.229	0.124	0.119
Tm	0.032	0.030	0.114	0.140	0.127	0.114	0.058	0.036	0.036	0.020	0.018
Yb	0.206	0.192	0.703	0.865	0.811	0.727	0.414	0.237	0.247	0.144	0.123
Lu	0.029	0.027	0.099	0.123	0.114	0.111	0.069	0.036	0.039	0.023	0.020
Hf	0.125	0.265	0.554	0.606	0.554	0.449	0.206	0.164	0.137	0.126	0.109
Ta	0.002	0.047	0.007	0.010	0.0005	0.009	0.010	0.044	0.009	0.011	0.010
Pb	0.405	1.048	0.343	0.466	0.590	1.150	0.839	0.921	0.539	0.495	0.500
Th	0.005	0.145	0.005	0.018	0.016	0.031	0.025	0.020	0.015	0.063	0.043
U	0.004	0.063	0.003	0.007	0.007	0.010	0.015	0.009	0.008	0.030	0.016

Abbreviations: Ol. Gab – olivine gabbro; Troct. – troctolite; Ol.Clinop. – olivine clinopyroxenite; Pyrox.- pyroxenite; Wehr. - wehrlite.

all pyroxenites and is an interstitial phase in coarse-grained dunites (Fig. 3b). Medium-scale layering is present in the northern area of the complex where layers of orthopyroxenite are separated by olivine norite dipping to the south (Fig. 3c). Fine-scale layering occurs in all gabbroic rocks (Fig. 3d) with graded bedding a supporting way-up direction indicator. The layering also exemplifies the mush-state of the cumulates with abundant cross-bedding (Fig. 3e) and slump structures (Fig. 3f) common. The semi-consolidated state of the crystal mushes which reflect the early physical state in the chamber is illustrated by the downward trails of blocks of pyroxenite sinking through a plagioclase cumulate (Fig. 3g). Chromitite layers are observed in the central dunite and appear as massive seams up to 1.5 m thick, or as repeated thinner layers and as fine-scale layering (Fig. 3h). Massive chromitites

commonly contain sub-spherical silicate inclusions (originally olivine crystals or aggregates) 0.5–2 cm in diameter, which enclose microchromite crystals. Thin chromitite layers are in places tabular, approaching podiform type, and commonly drape over and enclose blocks of dunite (Fig. 3i). These blocks are usually slightly elongate and invariably rounded.

5. Mambula Complex

The Mambula Complex (Fig. 4) is sub-circular in plan, slightly elongate, 7 km in length and 5 km wide. It is contained within amphibolitic gneisses commonly with highly sheared steep wall-rock boundaries although these are rarely exposed. The dominant lithology

Table 2
Major and trace elements of the Mambula Complex.

Sample	WMB82/6	MB35	MB45	MB015	358.2	225.34	WMB82/1	121.67	WMB82/26	MB91/1	MB023
Area	Central	North	North	Southeast	South	South	Central	South	North	North	North
Rock-type	Pyrox.	Pyrox.	Mag.	Gab.	Pyrox.	Anorth.	Gab.	Gab.	Anorth.	Troct.	Anorth.
Setting	Field	Field	Field	Field	Core	Core	Field	Core	Field	Field	Field
wt%											
SiO ₂	49.48	47.78	11.31	48.48	51.09	46.70	51.53	46.02	52.22	49.64	52.66
Al ₂ O ₃	5.10	5.58	8.64	17.19	11.25	18.04	16.46	16.36	29.00	19.78	28.57
Fe ₂ O ₃	1.43	1.26	6.23	1.15	1.05	1.50	0.86	1.48	0.06	0.72	0.12
FeO*	11.59	11.34	56.07	9.34	8.46	12.14	6.95	11.97	0.49	5.81	0.94
MnO ₂	0.32	0.24	0.29	0.21	0.21	0.15	0.17	0.16	0.01	0.11	0.01
MgO	15.62	14.48	4.50	9.31	11.69	6.10	7.99	6.40	0.15	9.76	0.30
CaO	14.39	16.79	2.72	10.83	13.19	9.66	12.47	12.62	11.71	11.17	12.02
Na ₂ O	0.80	0.52	0.44	2.25	1.77	3.32	2.83	2.94	4.37	2.86	4.71
K ₂ O	0.02	0.04	0.07	0.29	0.13	0.54	0.21	0.26	1.61	0.16	0.20
TiO ₂	1.14	1.34	11.37	1.10	0.72	1.84	0.54	1.91	0.06	0.22	0.16
P ₂ O ₅	0.01	0.02	0.01	0.01	0.02	0.01	0.00	0.01	0.02	0.01	0.02
Cr ₂ O ₃	0.00	0.06	0.06	0.03	0.12	0.00	0.02	0.01	0.02	0.02	0.01
NiO	0.00	0.01	0.02	0.01	0.03	0.01	0.01	0.01	0.00	0.02	0.00
TOTAL	99.91	99.47	101.75	100.21	99.73	100.00	100.04	100.15	99.71	100.27	99.72
* FeO calculated as 0.9Fe total											
ppm											
P	68.6	58.7	21.5	47.3	80.9	35.1	45.4	35.5	36.3	61.8	100.8
Sc	86.2	68.4	14.2	36.6	40.9	18.4	38.2	42.0	0.1	21.9	1.2
V	221	419	2760	275	161	433	223	509	2.0	72.2	13.784
Cr	9.19	360.5	75.2	88.0	695.7	31.24	130.8	13.75	0.661	83.9	1.967
Co	57.9	67.5	194.0	56.7	42.2	62.1	40.4	64.6	28.7	55.2	4.9
Ni	15.1	111.0	70.1	103.8	217.4	34.0	49.3	71.4	3.0	131.7	21.3
Cu	8.653	154.6	13.477	32.73	8.252	49.04	3.384	76.84	4.033	54.80	16.631
Zn	72.43	55.66	335.13	85.78	56.73	73.13	43.17	83.28	2.24	24.60	5.09
Rb	0.231	1.022	0.658	2.48	0.714	2.66	1.537	2.339	32.614	2.185	0.681
Sr	73	32	113	345	682	710	348	626	911	471	567
Y	22.39	19.597	2.453	11.368	14.651	4.061	10.292	11.277	0.132	3.159	1.291
Zr	24.638	26.128	16.383	18.682	20.816	6.420	13.494	16.153	4.210	4.297	1.651
Nb	0.101	0.296	1.347	0.156	0.142	0.233	0.112	0.256	0.261	0.117	0.438
Ba	30.4	71.2	47.7	167.2	84.5	158.5	86.3	144.3	400.7	108.9	94.0
La	1.508	1.713	0.490	1.448	2.102	1.452	1.452	2.069	0.931	0.878	1.582
Ce	6.066	5.363	1.069	3.927	6.779	3.158	4.507	5.268	1.623	1.972	3.476
Pr	1.300	1.067	0.188	0.665	1.318	0.440	0.716	0.929	0.161	0.277	0.363
Nd	8.620	6.725	1.063	3.843	8.324	2.211	4.115	5.281	0.509	1.443	1.383
Sm	2.947	2.495	0.347	1.360	2.642	0.707	1.371	1.726	0.270	0.456	0.327
Eu	1.049	0.878	0.169	0.654	1.026	0.499	0.607	0.808	0.410	0.333	0.414
Gd	3.133	3.328	0.444	1.648	2.495	0.666	1.418	1.889	0.092	0.496	0.314
Tb	0.610	0.583	0.072	0.301	0.460	0.120	0.274	0.319	0.008	0.087	0.042
Dy	3.875	3.631	0.473	1.945	2.732	0.722	1.808	1.988	0.025	0.541	0.23
Ho	0.794	0.736	0.096	0.401	0.539	0.149	0.374	0.397	0.004	0.112	0.045
Er	2.056	1.95	0.255	1.096	1.374	0.392	1.004	1.028	0.012	0.294	0.115
Tm	0.303	0.279	0.037	0.167	0.202	0.060	0.154	0.151	0.001	0.045	0.016
Yb	1.852	1.743	0.233	1.040	1.223	0.366	0.946	0.917	0.008	0.271	0.101
Lu	0.274	0.247	0.036	0.155	0.176	0.053	0.140	0.134	0.002	0.040	0.014
Hf	1.167	1.378	0.573	0.791	0.942	0.291	0.575	0.714	0.092	0.165	0.05
Ta	0.019	0.034	0.095	0.018	0.007	0.036	0.012	0.023	0.028	0.011	0.038
Pb	1.014	0.748	0.367	2.765	1.301	1.217	0.794	1.735	3.069	0.384	3.321
Th	0.033	0.098	0.018	0.019	0.037	0.017	0.024	0.025	0.177	0.030	0.07
U	0.011	0.048	0.016	0.006	0.014	0.008	0.011	0.01	0.118	0.014	0.095

Abbreviations: Pyrox. – pyroxenite; Mag. – magnetite; Gab. – gabbro; Anorth. – anorthosite.

is gabbro and anorthositic gabbro but the defining characteristic of the complex is the extensive layering developed by pyroxenites and magnetites. At least 22 magnetite layers or concentrations of magnetite within pyroxenite of 1 m or more in thickness, are observed. The thickest magnetite layer exposed in the Tugela River is over 10 m thick.

The generalized sequence in a unit is gabbro overlain by pyroxenite, in turn overlain by anorthosite or magnetite. In some cases, particularly in the north, magnetite clearly overlies anorthosite. In other occurrences magnetite layers appear to overlie pyroxenite but are invariably separated by a thin anorthosite layer.

Although hypothetical, it is possible that an ultramafic sequence, similar to that of Tugela Rand underlies the currently exposed section of Mambula (see Fig. 4).

5.1. Structure of the complex

In the northern part of the complex layering is parallel to the margins but to the south the layers appear to intersect the walls of the intrusion at a high angle, although actual contacts are nowhere exposed. No chill margin is exposed but along the western margin emplacement breccias consisting of blocks of fine-grained melagabbro contained within coarser-grained leucogabbro are indicative of a dynamic emplacement process (Fig. 5a). The most primitive lithology of the complex is troctolite that occurs in the northern area where the layers dip inwards (to the south and south-west). Dip angles of the layering in the southern part of the complex point to this centre with radial strike directions and project to the margins at a high angle. The structural configuration indicates an overall asymmetric form with the thickest part in the south as shown in the hypothetical cross-section. However, this does not take into account significant tectonic complexities such as layer-parallel

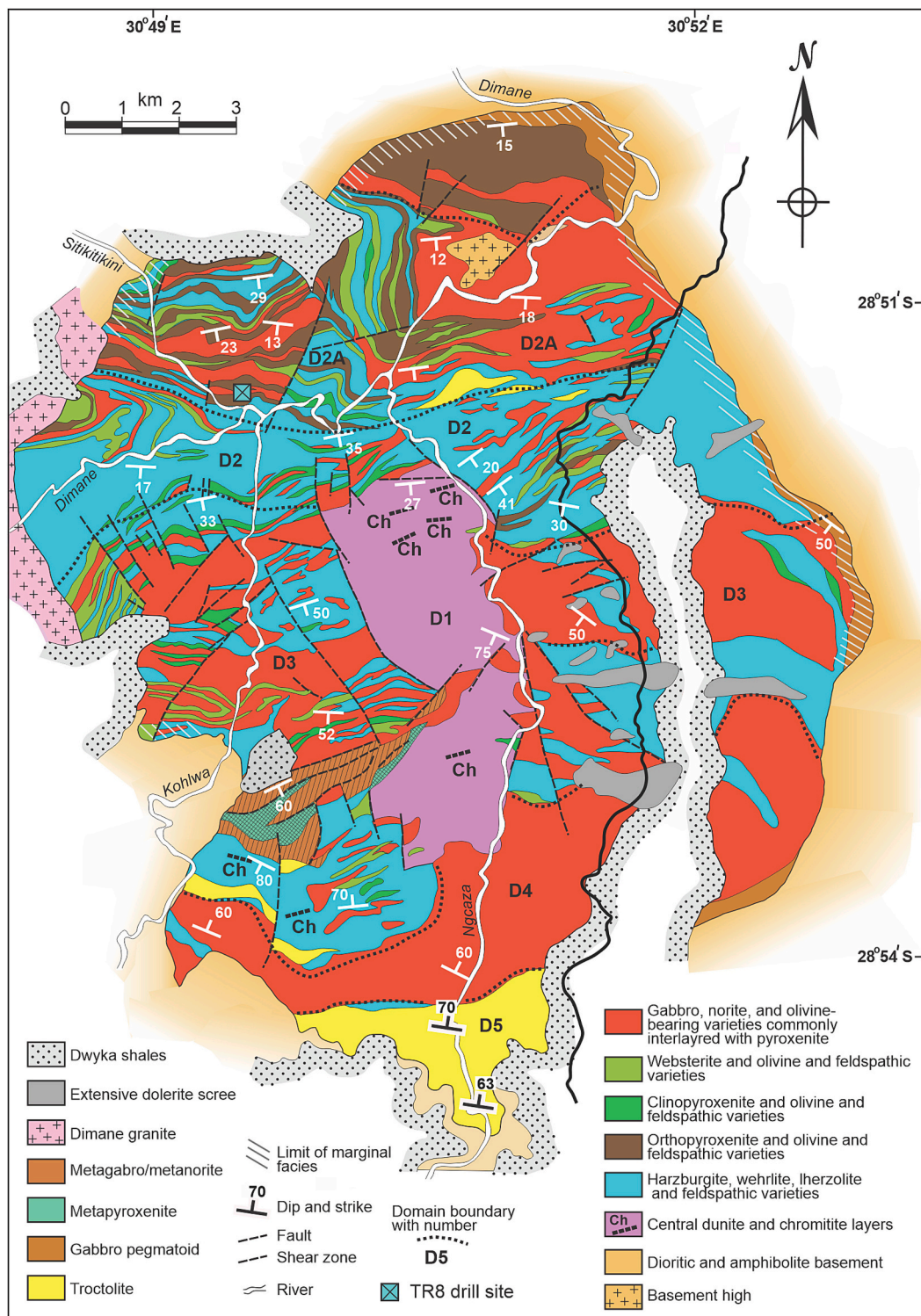


Fig. 2. Geological map of the Tugela Rand Complex. The map is a simplification because all units are intensely layered and except for the central dunite unit and the southern troctolites, all rock types are found in all areas but differing in their proportions. Areas shown as gabbros are made up of various olivine-bearing and olivine-free varieties and invariably layered with olivine clinopyroxenites. Areas with broad compositional and lithological conformity are identified as domains (D1–D5).

shearing and extension resulting in boudinage-like structures. Blocks of competent pyroxenite are contained within distorted ductile melagabbro and anorthosite (Fig. 5b). Some structural distortions are attributed to primary processes such as extreme density contrasts where anorthosite domes rise up into magnetitite (Fig. 5c).

5.2. Lithologies and rock interactions

The dominant rock-type is medium to coarse-grained gabbro grading into anorthositic gabbro and in some places into anorthosite. Plagioclase occurs as subhedral crystal laths or as clusters of anhedral crystals. Clinopyroxene interstitial to the plagioclase is the most common minor phase and is usually partly, and in some cases completely, altered to

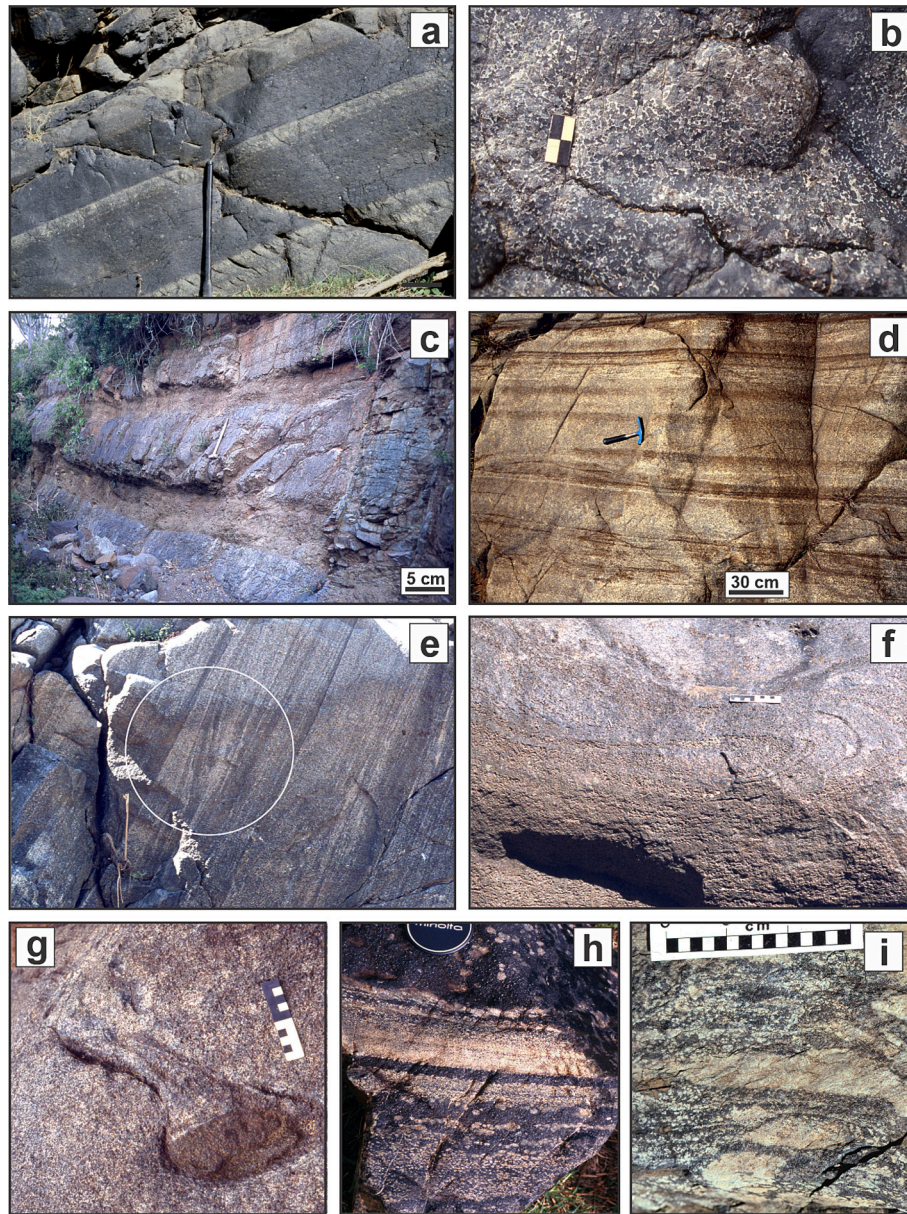


Fig. 3. Primary structures in the Tugela Rand intrusion. (a) Alternating layers of wehrlite and clinopyroxenite. (b) Coarse-grained plagioclase wehrlite. (c) Alternating layers of olivine orthopyroxenite and norite. (d) Alternating layers of pyroxenite and gabbbronorite. (e) Truncated cross-bedding in troctolite in the southern part of the complex. Circled. (f) Recumbent structure of gabbro layers due to slumping of the crystal mush. (g) Trail of the passage of a rounded block of consolidated orthopyroxenite sunk into a gabbroic crystal mush and then pivoted sideways (top left to lower right). The crystal mush below the fragment has been compacted. (h) Massive and inter-layered chromitite with dunite. (i) Thin chromitite layers draped over blocks of dunite.

hornblende together with epidote and magnetite. Bent plagioclase twin lamellae in almost all samples indicate pervasive stress during the early stages of emplacement. In the north and north west areas of the complex the main rock unit is finely-layered troctolite containing up to 20 % olivine.

Anorthosites (defined as containing >90 vol% plagioclase) are intimately related to the gabbros and sometimes form distinct units. The most striking texture of this rock group is the macro-sized plagioclase crystals exposed in the northern and north-western areas and particularly on the banks of the Tugela River where it cuts through the complex. At this locality individual crystals as big as 15 cm (Fig. 5d) are intergrown with interstices filled with clinopyroxene. In many cases the clinopyroxene is partly altered to amphibole and has a reaction contact with the plagioclase. Individual crystals of clinopyroxene can also be as large as 12 cm. Megacrystic anorthosite occurs in several areas in the

western parts of the complex and these bodies do not appear to be stratigraphically constrained with the layering. Veins of fine-grained anorthosite are observed to cut through macro-textured anorthosite indicating several generations of this rock type.

Pyroxenites range between those of dominantly orthopyroxene to dominantly clinopyroxene. They are generally coarse grained (2–5 mm) with plagioclase and magnetite interstitial to the pyroxene. Finer-grained pyroxenites occur as dykes cutting through the gabbros. Pyroxenitic units have intruded the coarse-grained anorthosites in the Tugela River and truncated the fabric of the anorthosites but also disrupted it resulting in the incorporation of large xenolithic fragments (Fig. 5e). The pyroxenite is highly foliated and largely altered to amphibolite. There is no evidence of chilled margins to these intrusions and their emplacement is considered to be synchronous with that of the complex overall.

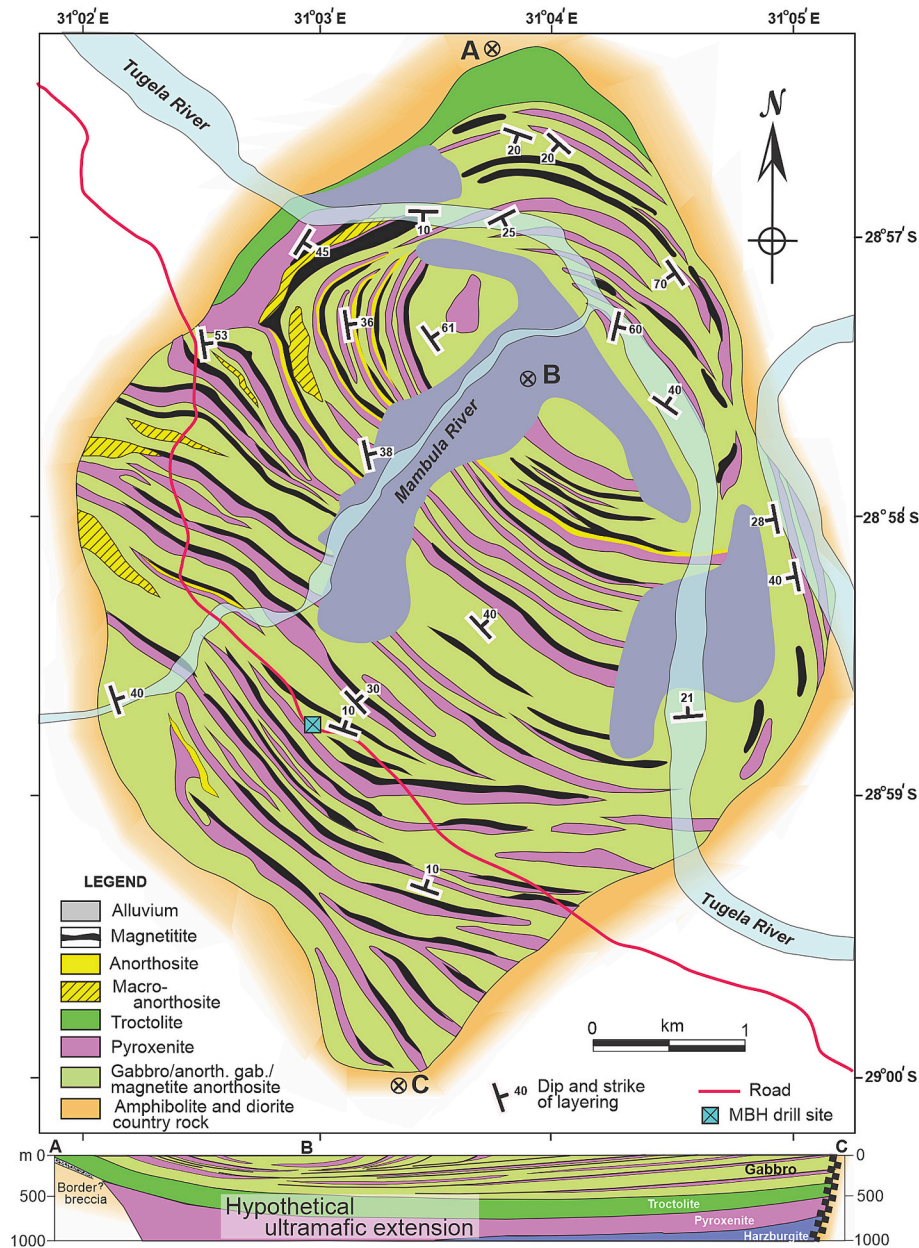


Fig. 4. Simplified geological map of the Mambula Complex and theorised cross-section. In most areas the magnetitite layers overlie anorthosite. In the south the anorthosite layers tend to be very thin and magnetitite appears to overlie pyroxenite. Hypothetical cross section along transect A-B-C. It is possible that a Tugela Rand-like sequence may occur at depth.

The magnetitite layers range in thickness from less than a metre to over 10 m. Although relatively massive (magnetite and ilmenite comprising more than 90 %) they contain abundant inclusions of pyroxene and plagioclase and commonly finely layered on scale of 1–5 cm with narrow anorthosite layers (Fig. 5f). In some cases, large blocks of included anorthosite, some as single plagioclase crystals, show strong reaction boundaries of amphibole and green spinel (pleonaste) (Fig. 5g). However, some magnetitite layers have been forcefully emplaced resulting in brecciation of the gabbro with both angular and rounded blocks present (Fig. 5h).

6. Emplacement Ages of the Tugela Rand and Mambula Complexes

Based on zircon chronology the age of the Mambula Complex was established at 1145 ± 6 Ma (Johnston et al., 2003; McCourt et al., 2006).

An approximate age of the Tugela Rand Complex of 1189 ± 13 Ma was given previously by Wilson (1990). Additional data and re-evaluation using IsoplotR (Vermeesch, 2018) for Sm-Nd isotopic data yields a combined mineral - whole rock isochron resulting in an age of 1164 ± 12 Ma (Fig. 6). The value of initial $^{143}\text{Nd}/^{144}\text{Nd}$ is 0.511339 ± 0.000040 and is tightly constrained by plagioclase separates with $^{147}\text{Sm}/^{144}\text{Nd}$ of less than 0.08. This age is essentially identical to that of the Mkondene diorite, which surrounds the complex with a zircon Concordia age of 1161 ± 9 Ma (McCourt et al., 2006). Therefore, the diorite and the Tugela Rand Complex are essentially coeval although the Tugela Rand Complex is clearly intrusive into the diorite. The value of $\epsilon^{143}\text{Nd}$ for the Tugela Rand data is +4 indicating a depleted mantle source. Four whole-rock samples from the Mambula Complex were analysed in this study and combining with three analyses from Ball (2013) give a limited data spread and a meaningless age of 974 ± 255 Ma with $^{143}\text{Nd}/^{144}\text{Nd}_i = 0.51147 \pm 0.00022$ constrained by a pure anorthosite with $^{147}\text{Sm}/^{144}\text{Nd}$

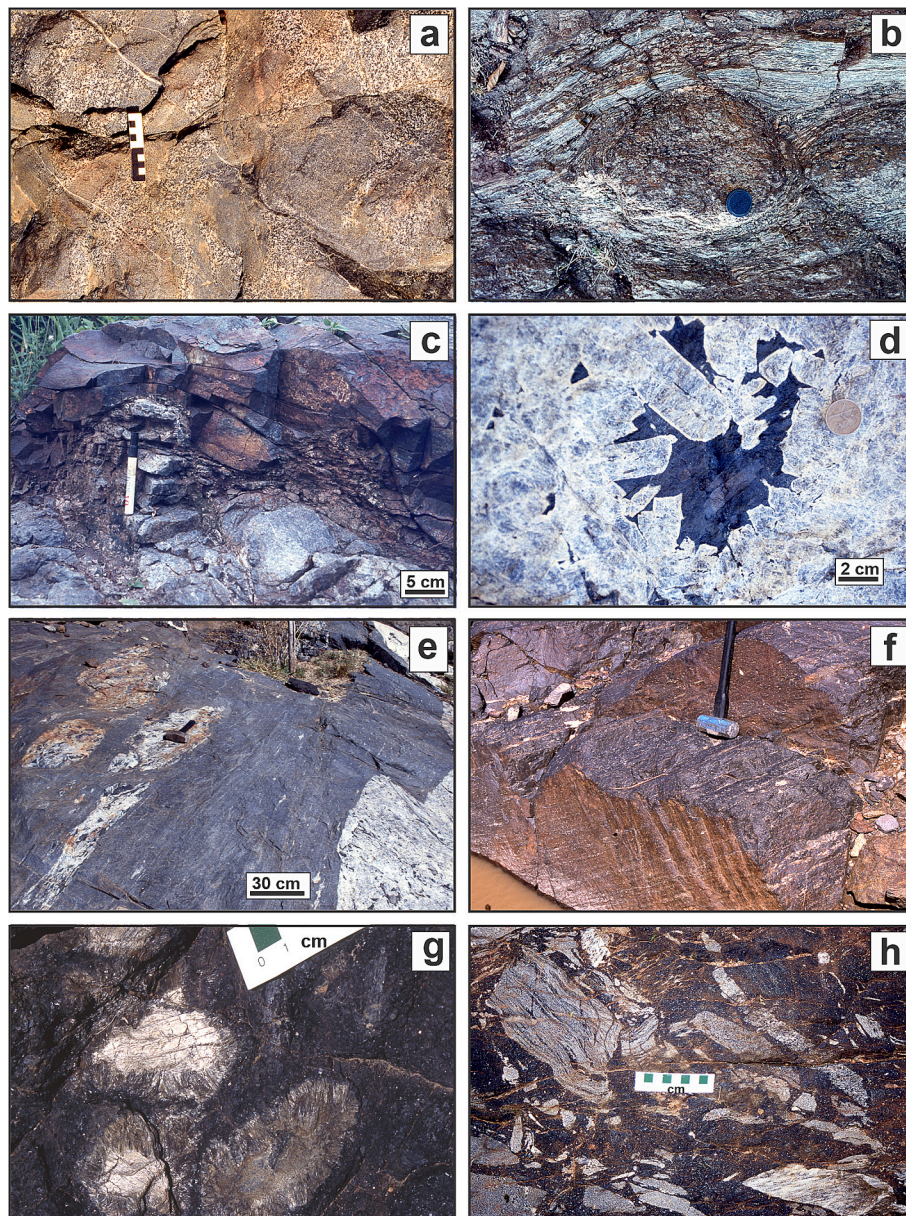


Fig. 5. Field relations in the Mambula Complex. (a) Fine-grained fragments of a mafic border zone incorporated within coarse-grained gabbro. (b) Rounded fragment of coarse-grained pyroxenite enclosed by more ductile anorthosite. (c) Dome of low density anorthosite impinging into the base of a massive magnetite layer. (d) Extremely coarse-grained plagioclase crystals with a mesostasis of pyroxene and amphibole. (e) Foliated and deformed amphibolite dyke intruding coarse-grained anorthosite. (f) Massive magnetite with silicate-rich layers made up of plagioclase, pyroxene and amphibole. (g) Rounded silicate inclusions within magnetite with reaction rim of amphibole between pyroxene and magnetite. (h) Angular and rounded fragments of gabbro contained within a magnetite layer at the eastern margin of the complex.

of less than 0.08. The Rb content of most samples from Tugela Rand is less than 1 ppm resulting in a very limited spread of Rb/Sr and yielding an age array of 1274 ± 282 Ma for Sr isotopes but giving a precise $(^{87}\text{Sr}/^{86}\text{Sr})_{\text{initial}}$ of 0.702866 ± 0.00002 .

7. Lithogeochemistry of the intrusions

7.1. Classification

The chemical compositions of the rocks are controlled by the dominant modal mineralogy because these are largely accumulates in the Tugela Rand Complex (except at the margins) with very low amounts of trapped melt. The range in rock-types is from dunite to anorthosite and a wide range of pyroxenites including olivine and

feldspathic varieties. Similarly, rock-types from the Mambula Complex range from pyroxenite to anorthosite and, apart from one unit of troctolite, olivine is absent. Layers of titanomagnetite characterize the Mambula Complex. In terms of Mg# the compositional range in Tugela Rand is limited at 0.80 to 0.87. Mambula rocks have a wider range of Mg# mainly influenced by varying amounts of magnetite, but magnetite-free samples throughout the complex have a limited range of Mg# from 0.70 to 0.77. Apart from the magnetitites most rock-types contain accessory magnetite.

7.2. Geochemistry of drill core sections

The complexity and scale of the layering is shown in Fig. 7 for drill core TR8 in the northwest part of the Tugela Rand Complex. The lower

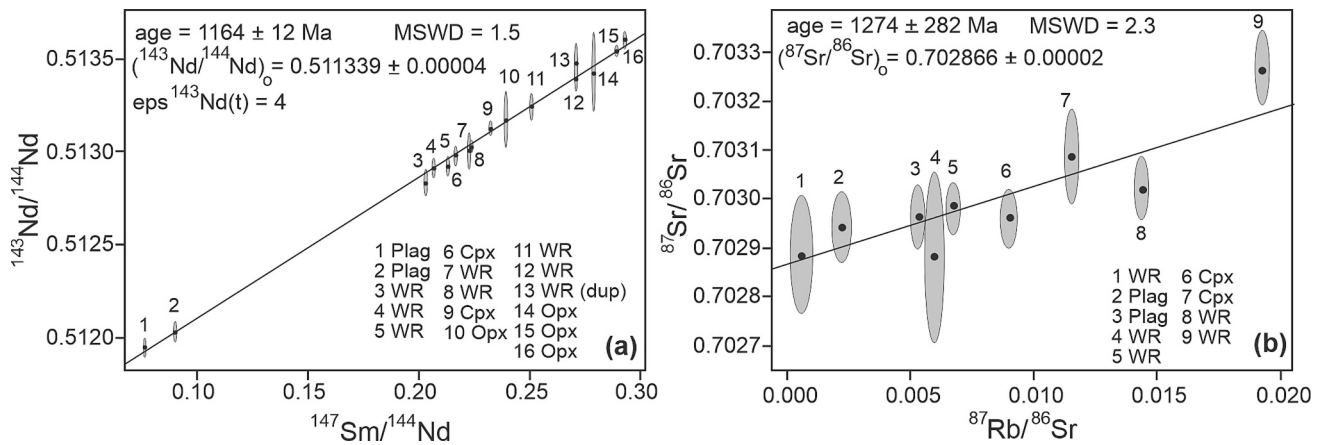


Fig. 6. Isochron diagrams utilizing whole rock and mineral separates for Tugela Rand constructed using IsoplotR. (a) Sm-Nd, and (b) Rb-Sr. Ages and initial values are shown in the diagrams. The low precision for the Rb-Sr age is attributed to the extremely low Rb/Sr range (0.001–0.03) due to very low Rb contents even in rocks where plagioclase is an intercumulus phase; this range compares with values of 0.1–0.3 for similar rock-types in the Lower Zone of the Bushveld Complex. Uncertainty is 95 % probability.

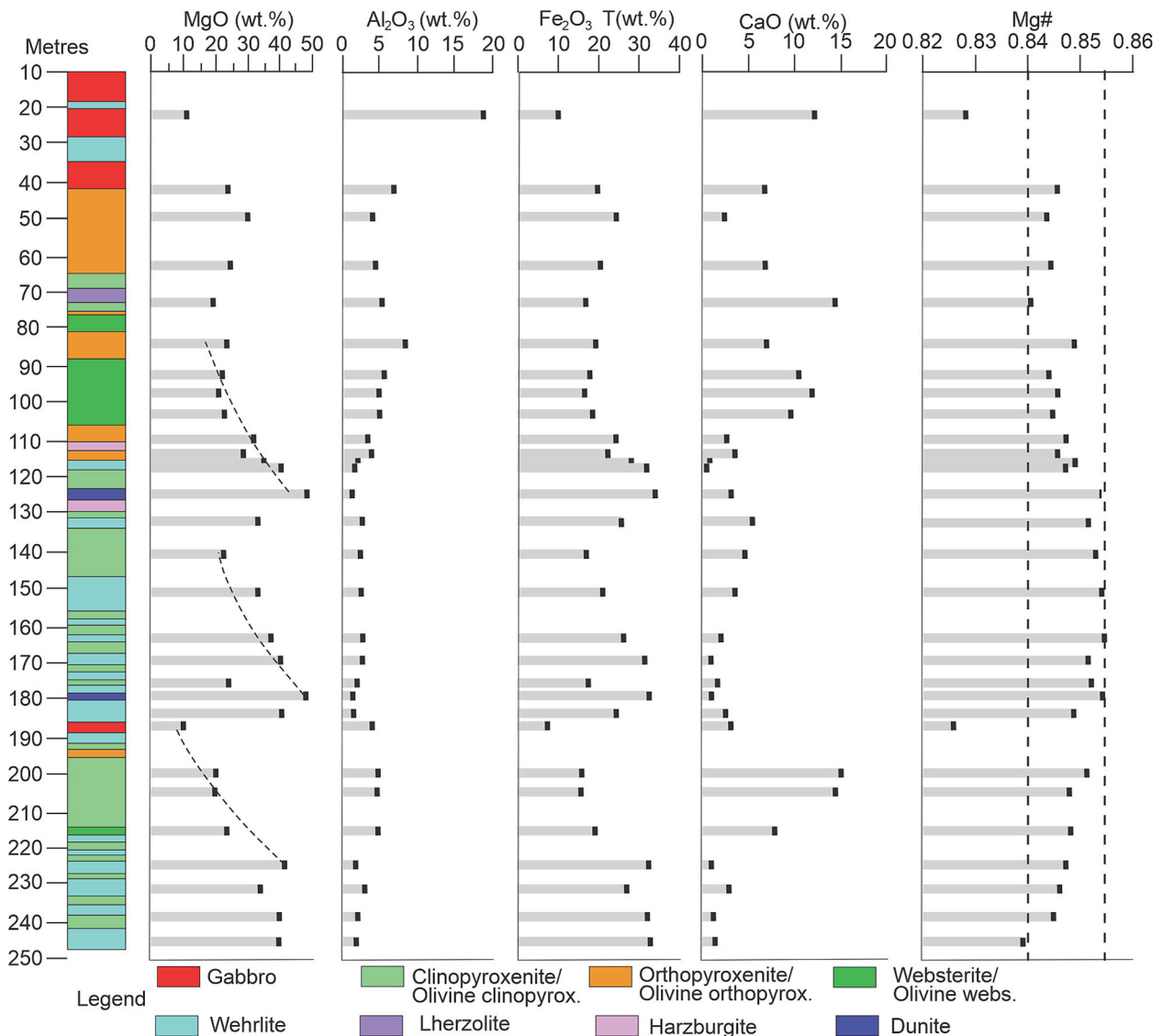


Fig. 7. Lithostratigraphy and compositional parameters for drill core TR8 in the northwest part of the Tugela Rand Complex. The lower section shows clinopyroxenite and wehrlite to predominate and the upper section is typified by orthopyroxenite and gabbros. No clear cyclic units are identified but a progression of compositions and rock types are seen in three intervals shown by dashed lines on the MgO column.

part of the section is made up of clinopyroxenites and wehrlites and the upper part of mainly orthopyroxenites, websterites and gabbros. Layering is on a scale of 2–30 m with layers <1 m thick excluded from the diagram. Clear cyclic units are not apparent but a progression of rock types is indicated by MgO seen in three intervals. The same progression is present for Al and Fe. Ca shows an oscillating variation most likely arising from the interplay between clino- and orthopyroxene. Mg# is remarkably constant with the entire range (excluding the gabbros) mostly between 0.84 and 0.86. The gabbros are more evolved.

In the Mambula Complex the chemical distribution is seen in a 372-m drill core section in the southern area (Fig. 8). Over 70 % of the section comprises gabbro and anorthosite. Similar to Tugela Rand clearly definable cyclic units are not identified. Two magnetitite layers are present in this section with complex layering involving gabbro, anorthosite and pyroxenite in the intermediate section. Aluminium distribution is controlled mainly by plagioclase and Ca by clinopyroxene (together with plagioclase). Titanium and Fe are controlled mainly by magnetitite, the latter resulting in very low Mg# but with the highest values entirely in the range of 0.6–0.7 in samples that contain minimal

magnetite.

7.3. Mineral compositions and regional subdivisions

In order to identify significant trends within the complexly layered sequence of Tugela Rand the mineral compositions and dominant distribution of rock types (based on field observations) are separated into geographically distinct domains (Fig. 9). Mineral compositions overlap in all domains but there is a clear progression in the compositional ranges from north to south, with the D1 dunite distinctly different. The overall ranges in composition are very limited with dunites and wehrlites having highest Mg#, pyroxenites intermediate and gabbroic rocks lowest Mg#. Marginal facies for each of the groups have lower Mg#. Details of the lithologies and sampling are less on the eastern side because of the rubble strewn steep topography. Sample localities are shown in the Supp. Data files.

Mineral composition Mg# for Mambula are more evolved compared with Tugela Rand and similarly show a restricted range (Fig. 9d) for specific rock-types. The widest range occurs within the more evolved

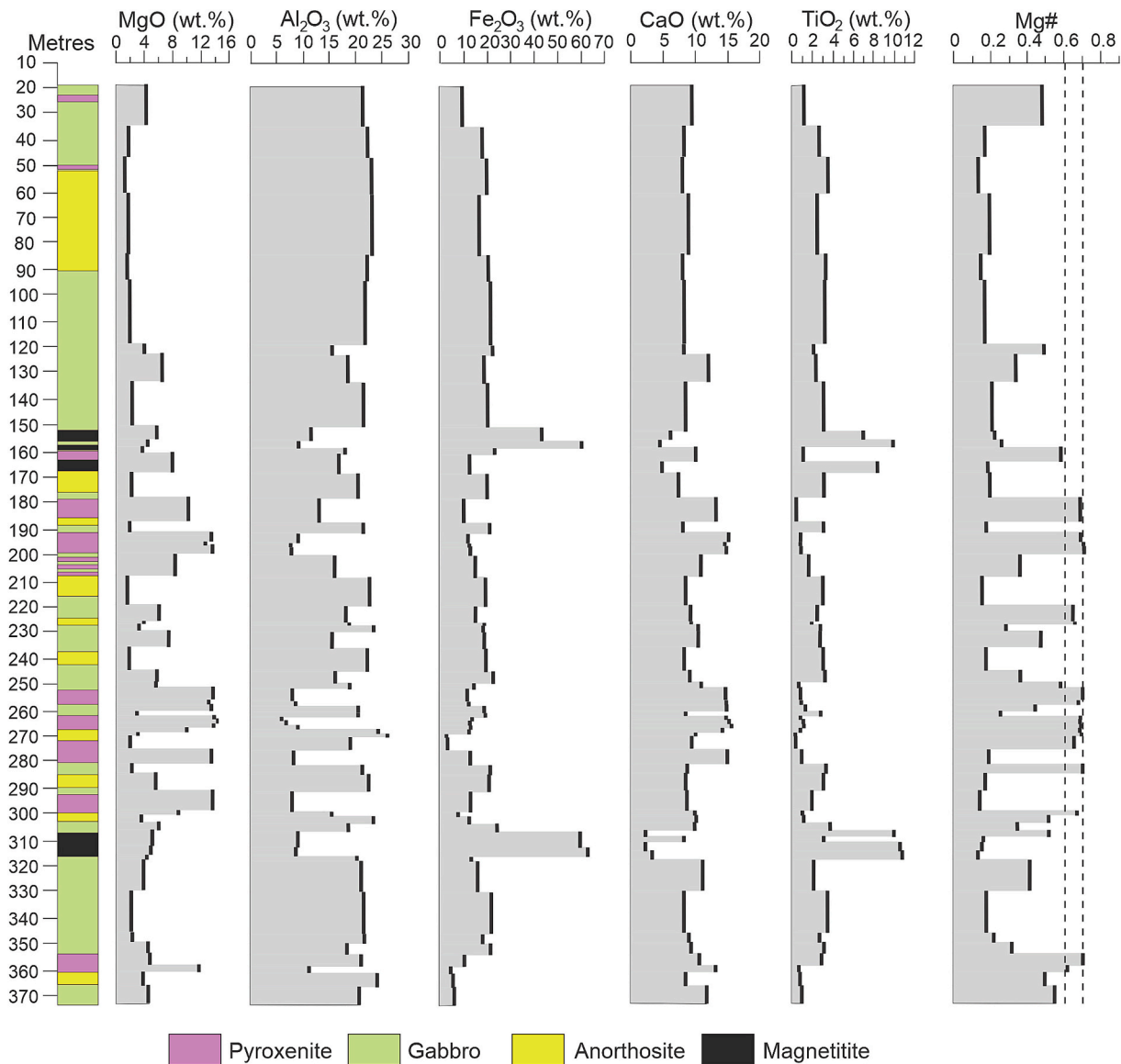


Fig. 8. Lithostratigraphy and compositional parameters for drill core MBH in the southern part of the Mambula Complex. No clear cyclic units are observed and intense small-scale layering is present in the middle section of the sequence between the magnetitite layers. Note that magnetitite overlies both anorthosite and pyroxenite in different sections of the core.

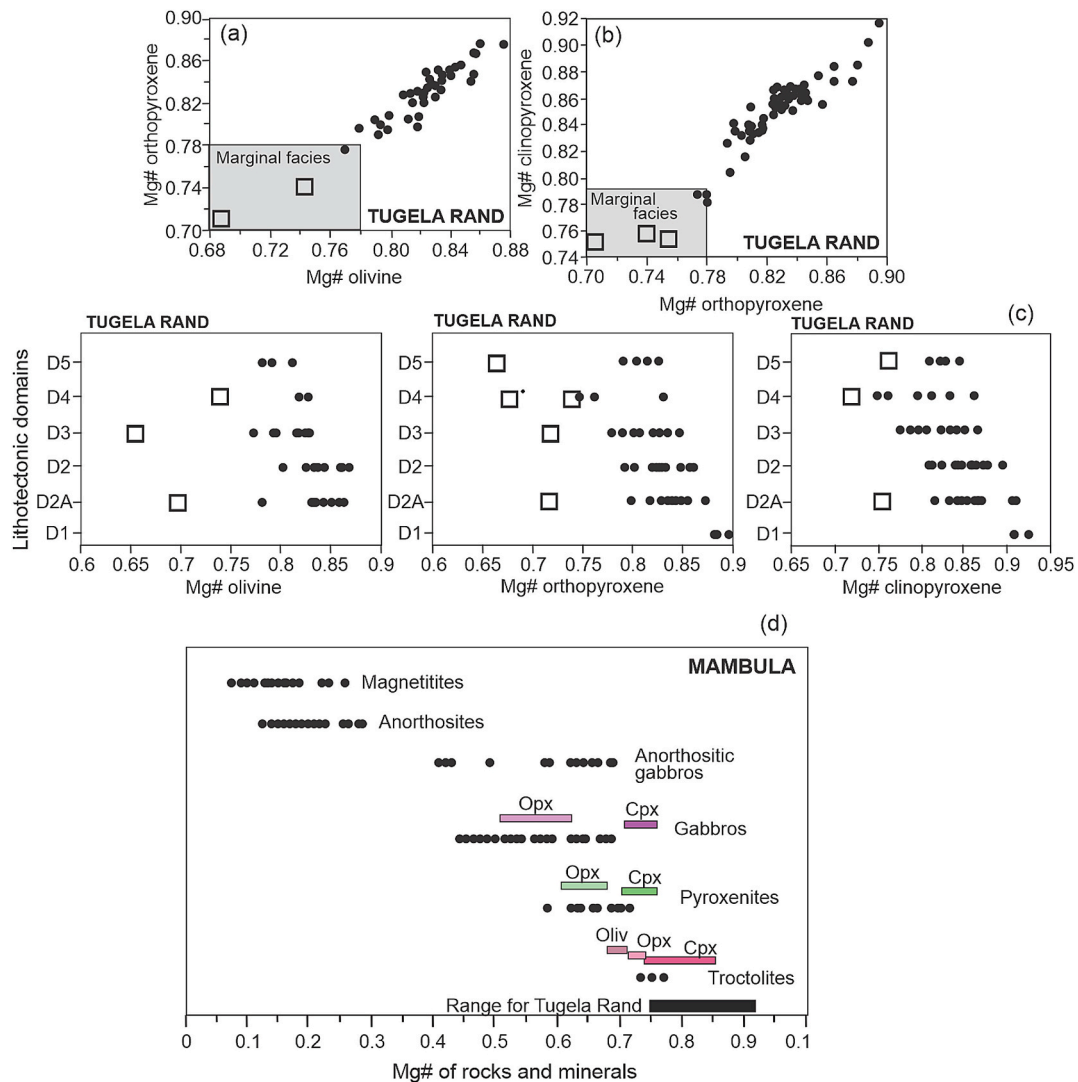


Fig. 9. Compositional ranges for ferromagnesium minerals for Tugela Rand and Mambula Complexes. (a) Mg# for coexisting olivine and orthopyroxene in Tugela Rand; (b) Mg# for coexisting orthopyroxene and clinopyroxene in Tugela Rand; (c) Domain compositional ranges for minerals in Tugela Rand (domain labels relate to Fig. 2). Open squares represent marginal facies; (d) Compositional ranges for minerals in the Mambula Complex (coloured bars) and whole rocks (solid dots). The range for Tugela Rand is shown but excludes marginal facies.

anorthosites (excluding the magnetites themselves) from the variable amounts of contained magnetite.

8. Geochemical trends

Both Mambula and Tugela Rand Complexes show strong interelement controls (Fig. 10) influenced by the modal proportions and compositions of the minerals. Compositions of Mambula rocks are strongly influenced by the presence of magnetite, even in small amounts. For Al vs Mg (Fig. 10a and b) the variations are co-linear with Tugela Rand data displaced to relatively higher MgO. In Mambula marked deviations in the trend are shown by the magnetites and the olivine gabbro/troctolite. The olivine gabbro of Mambula overlaps with the general trend for Tugela Rand. The sharp increase in Al occurs at 18 % MgO.

Mg# is strongly controlled by magnetite in Mambula for rock-types with <9 wt% MgO (Fig. 10c). The influence of magnetite on each rock-type produces distinct trends. The troctolite has the highest Mg# for Mambula and overlaps with the most evolved (lowest Mg#) rock-type of Tugela Rand (Fig. 10d). Tugela Rand data show a very limited range of Mg# over a wide range of MgO contents. The trend for Ca vs Mg

(Fig. 10e) shows a steady increase of Ca with decreasing Mg for Tugela Rand but decreasing from 18 % MgO as a result of clinopyroxene and plagioclase fractionation coinciding with the trends for magnetite-poor Mambula rocks.

TiO₂ is strongly correlated with Fe₂O₃ (total Fe) for Mambula (Fig. 10f) indicating the control of magnetite but also reflects the fractionation trend of silicates. A similar weak trend is seen for the higher Ti-bearing rocks of Tugela Rand which overlap with the olivine gabbros of Mambula. Whole rock V contents in Mambula correlate strongly with Fe₂O₃ indicating the role of magnetite (Fig. 10g) with calculated V content in magnetite having values of 6000–7500 ppm in the magnetites (Fig. 10h).

9. Textural relations and mineralogy

9.1. Gabbroic rocks

Gabbro and associated rock-types (olivine gabbro, gabbro-norite, anorthosite) are the dominant lithologies in both intrusions. Plagioclase is primarily the cumulus phase and is generally unzoned or poorly zoned but in many cases the crystals are bent with deformed twin sets. In some

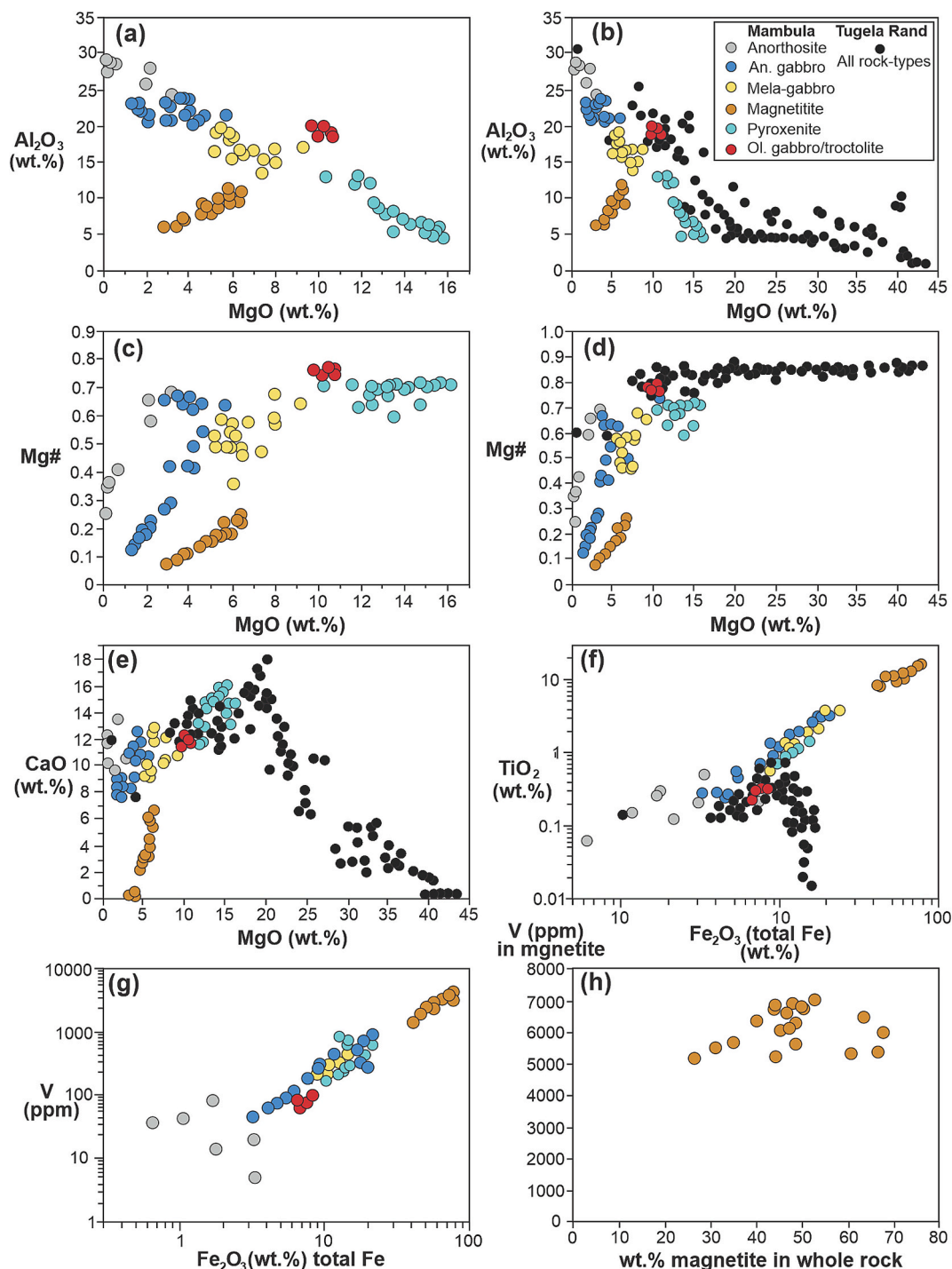


Fig. 10. Geochemical trends for Mambula and Tugela Rand Complexes. Data for Mambula are shown in relation to specific rock-types. Tugela Rand is shown for all data as a single symbol type (black dot). (a) Al_2O_3 vs MgO for Mambula; (b) As for (a) including Tugela Rand data; (c) MgO vs $\text{Mg\#}$ for Mambula; (d) As for (c) including Tugela Rand data; (e) CaO vs MgO for Mambula and Tugela Rand; (f) TiO_2 vs Fe_2O_3 (total Fe) for Mambula and Tugela Rand; (g) V vs Fe_2O_3 (total Fe) for Mambula; (h) Calculated V in magnetite for Mambula.

cases, the plagioclase is partly wrapped around mafic mineral assemblages, particularly where corona textures are developed. The compositional range of plagioclase in Tugela Rand is An58 to An75. Mambula plagioclases are more sodic overall with a compositional range of An46 to An67. Pure anorthosites occur in both complexes but are much more abundant in Mambula where in some cases the tabular crystals can reach macro dimensions of 15–20 cm across.

Corona textures formed by reaction between olivine and plagioclase in the olivine gabbros (Fig. 11a) and troctolite in both Tugela Rand and

Mambula are important petrogenetic indicators. Most commonly a rounded crystal of olivine is sequentially and outwardly surrounded by shells of micro crystals of orthopyroxene or clinopyroxene, then by a vermicular intergrowth of a Ti-rich Mg-rich pargasitic amphibole or clinopyroxene and a Cr-poor Fe-Mg spinel. There appears to be some relationship between the presence of the corona textures and hornblende developed elsewhere in the sample pointing to the role of water, a relationship observed in other similar occurrences (Torres-Rodriguez et al., 2021). Pleonaste spinel is present in the troctolites of Tugela Rand.

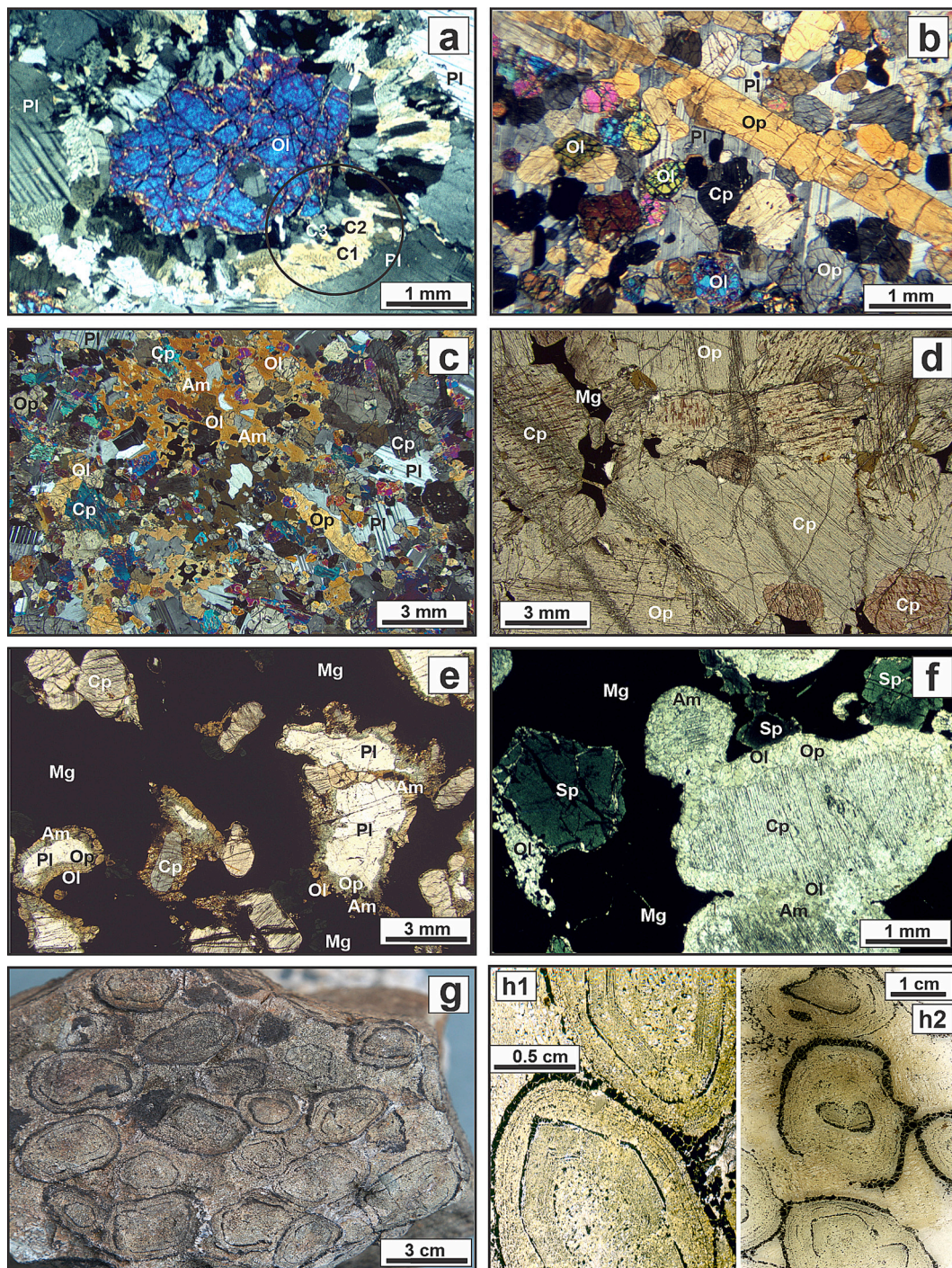


Fig. 11. Photomicrographs of rock textures and mineral associations of Tugela Rand (a-c; g-h) and Mambula (d-f). Abbreviations: Ol-olivine; Pl-plagioclase; Op-orthopyroxene; Am- amphibole; Mg- magnetite; Sp - spinel. (a) Corona texture (crossed polars) formed by reaction between olivine and plagioclase. Circled. The inner shell C3 is fibrous orthopyroxene growing perpendicular to the olivine contact; shell C2 is Ti-rich pargasite; C1 is an intergrowth of vermicular spinel and with pargasite amphibole. (b) Olivine-bearing feldspathic pyroxenite showing rounded olivine crystals with highly elongate crystals of orthopyroxene, clinopyroxene and plagioclase. Crossed polars. (c) Hornblende-bearing olivine feldspathic pyroxenite from the western marginal facies of Tugela Rand. Crossed polars. (d) Coarse-grained pyroxenite with interstitial magnetite. Reddish-brown exsolution in clinopyroxene is Ti-spinel. Plane light. (e) Inclusions within massive magnetite. Reaction shells between plagioclase and magnetite include pyroxene, amphibole and olivine. Plane light. (f) Reaction between magnetite and clinopyroxene and the formation of Fe-Mg spinel. Plane light. (g) Orbicular chromitite in the central dunite domain D1 of Tugela Rand. (h) Photomicrographs showing the internal structure of the orbicules. There are up to 30 fine-scale layers in each orbicule. In h1 the internal structure indicates the layers were built around a single olivine crystal. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

9.2. Pyroxenites

Clinopyroxenite is the next most abundant rock-type in both intrusions with clinopyroxene dominating over orthopyroxene. The compositional range is Mg# 0.76–0.88 in Tugela Rand and 0.70–0.78 in Mambula but in the latter case is extensively replaced by secondary amphibole. In Tugela Rand clinopyroxene crystals are sometimes rimmed by amphibole. In Mambula large clinopyroxene macrocrysts (>10 cm in diameter) are commonly surrounded by pure magnetite and enclosed within macro-scale anorthosite. Clinopyroxene in Mambula commonly has several sets of exsolution lamellae characterized by plates of a light brown Ti-rich (up to 41 % TiO₂) spinel (Fig. 11d).

Orthopyroxene is the dominant mafic mineral in the basal (northern) section of Tugela Rand, represented by orthopyroxenites and norites along with harzburgites, websterites and lherzolites (Fig. 11b). Orthopyroxene can occur in subordinate amounts throughout the complex with the compositional range Mg# 0.74–0.88. In Mambula, orthopyroxene is seldom contained within the gabbros. The compositional range is Mg# 0.62–0.70 in the pyroxenites. Close to the margins of Tugela Rand primary amphibole encloses rounded crystals of pyroxene and olivine (Fig. 11c) as a facies variation of the contiguous layer.

A unifying feature of the pyroxenes in both complexes is the relatively high Al₂O₃ contents. The average Al₂O₃ content in clinopyroxenes in Tugela Rand is 4.6 % and 3.1 % in orthopyroxenes. In the Mambula Complex clinopyroxene has an average of 5.2 % Al₂O₃ and 3.4 % in orthopyroxene.

9.3. Dunite and olivine dominated rock-types

Olivine is abundant in Tugela Rand and is present in most rock types although some gabbros and pyroxenites are devoid of olivine. It is the dominant silicate phase in the central dunite unit but is completely serpentinized. However, remnants of interstitial ortho- and clinopyroxene are preserved. The highest Mg# of the preserved olivine is 0.87 and occurs in wehrlites and lherzolites mainly in the northern part of the complex. The range of Mg# for olivine in each domain is highly restricted throughout the complex as 0.76–0.88. In marginal facies olivine has much lower Mg#. Overall, the most evolved olivines occur in the southern gabbro/troctolite zone. In the Mambula Complex the olivine compositional range is Mg# 0.68–0.72 in the coronas and is therefore slightly more evolved than the olivines in the corona-textured troctolites in Tugela Rand.

9.4. Magnetite

High abundances of magnetite and ilmenite do not occur in Tugela Rand but massive magnetite and magnetiferous gabbros and pyroxenites are a defining lithological feature in Mambula. However, the massive magnetites seldom contain more than 70 % magnetite with the remaining assemblage comprising ilmenite and silicates. The massive magnetites are of particular interest because of the range of textures and associated mineral phases first noted by du Toit (1918). Magnetite and ilmenite are intergrown in the magnetites as large irregular shaped grains but ilmenite occurs also as fine exsolution lamellae within the magnetite in two sets of different parallel arrays. Inclusions within the magnetite include large plagioclase and clinopyroxene crystals (Fig. 11e), in complex reaction relationships with amphibole, orthopyroxene and olivine. Discrete separate crystals of spinel of the pleonaste type ((Mg-Fe)Al₂O₄) are common (Fig. 11f). The enclaves of plagioclase are commonly enclosed within hornblende at the interface with the magnetite, and orthopyroxene is invariably mantled by olivine of Fo61.

9.5. Chromitites and spinel-bearing rock types in Tugela Rand and Mambula

Chromite is abundant as discrete layers in the dunite units in Tugela Rand and in subordinate amounts in wehrlites and lherzolites. In the southern part of the dunite unit in Tugela Rand (D1 in Fig. 9) the chromite occurs as clusters of orbicular structures as well as thin discontinuous layers. The orbicules have up to 30 concentric layers of small chromite crystals with an outer shell of larger chromite grains (Fig. 11g). In many cases a coarser-grained layer occurs within the orbicule (Fig. 11h) and, remarkably, each micro-layer has crystals of the same grain size but different to those in other layers in the same orbicule. Olivine (now completely serpentinized) occurred as micro-crystals between the chromite layers. In some cases, what appears to be olivine pseudomorphs, are at the centre of the structures (Fig. 11h), and the arrangement of the chromite crystals faithfully mimics this control.

Spinel in the Tugela Rand and Mambula Complexes have, overall, a wide range of compositions but fall into groups which are compositionally well constrained and clearly distinguishable (Fig. 12). The overall distribution defines the spinel miscibility gap (Fig. 12a) arising from the solvus between Cr-Al spinels and Fe³⁺-Cr spinels (Eales et al., 1988; Mattioli and Wood, 1988; Nell and Wood, 1989) and the reaction between Cr-bearing clinopyroxenes and chromite (Barnes and Roeder, 2001). The layered and podiform-type chromitites in Tugela Rand fall into the two categories with a preponderance of Cr and Al enriched types, although the crystals are invariably highly zoned and individual samples contain a wide range of compositions (Fig. 12b-c). High-Cr magnetite in Tugela Rand depicts a high-Cr and low-Cr series which may represent different solid-solutions defining limbs of slightly different solvi. Chromite in the orbicular type is dominantly, but not exclusively, of the high-Al type, and located in the southern area of the central dunite unit. The chromitites have a range of compositions encompassing both the Al-rich and Al-poor limbs of the miscibility gap. Spinel in the Mambula Complex are all Cr depleted comprising Al-rich types of the pleonaste-hercynite series and magnetite with <0.5 wt% Cr₂O₃ and < 2 wt% Al₂O₃. The fields of high-Cr and high-Al spinels are clearly defined with the intermediate sub-sets of interstitial chromite to straddle the gap between them (Fig. 11d). The low-Cr Mambula spinels and magnetite show almost a continuous range up to 25 % MgO. Magnetites have the highest Fe³⁺ component (Fig. 11e).

10. Discussion

10.1. Emplacement and solidification of the Tugela Rand and Mambula Complexes

The Tugela Rand Complex is slightly older than Mambula but both are located in adjacent thrust segments in the Natal belt and so could be genetically related even though they are geographically separate, thereby illustrating an evolutionary magmatic history for the belt. Little is known about the magma storage conditions in sub-arc environments (Nixon et al., 2024), particularly in the Precambrian.

Many features of these complexes are distinct and assist in interpreting their origin and emplacement. Both Tugela Rand and Mambula are intensely lithologically layered on scales of cm to metres indicating dynamic processes that include sedimentary-like processes such as slump structures (Fig. 3f), mineral density graded layers, cross-bedding (Fig. 3e), scouring and truncation of layers. Layers tend to be of limited lateral extent indicating transient and dynamic conditions within the magma chambers. Several of these structures give consistent and unequivocal evidence of way-up directions. The compositional range of minerals and whole rocks in each of these intrusions is more restricted compared to differentiated layered intrusions in general. Compacted sequences in Tugela Rand show progression of rock-types and compositions from peridotites through to pyroxenites with gabbro the predominant rock-type. In some cases, gabbro is observed to cap pyroxenite

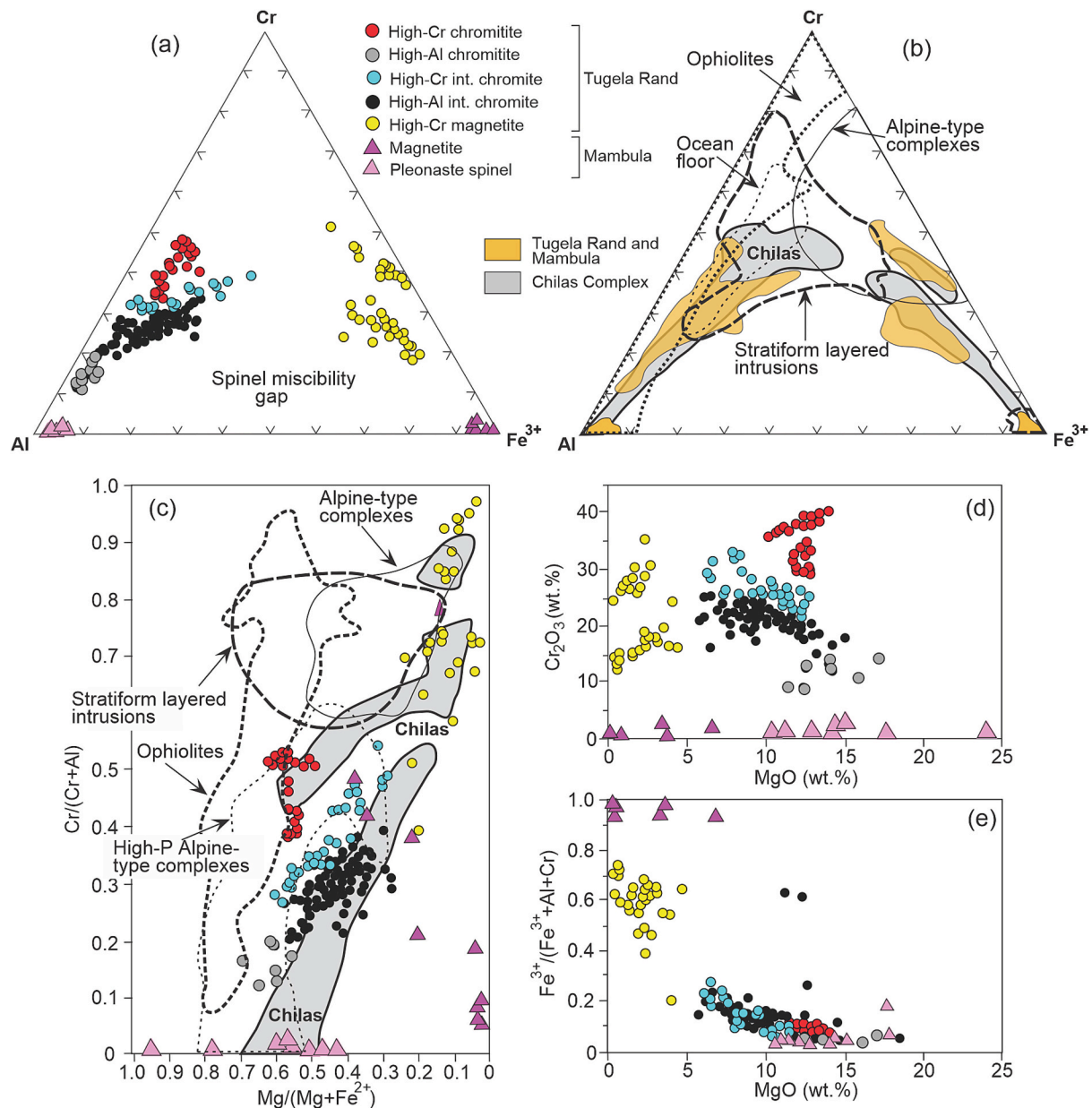


Fig. 12. Compositions of spinel mineral groups in Tugela Rand and Mambula. (a) Cr-Al-Fe³⁺ cation diagram showing the classification of chromite. The different groups relate to the textural environment and distinct compositional trends. A wide range of compositions may be observed within a single sample both as discrete crystals and as zoning within crystals. The high-Cr chromitites occur as massive layers in the northern part of the central dunite and the high-Al chromitites, which includes the orbicular varieties, are located in the southern part of the central dunite. The other groups relate to chromite interstitial with silicates. The high-Cr magnetites are strongly depleted in Al. Compositions for Mambula magnetite and pleonaste are shown. (b) Fields of spinel from (a) shown with typical compositions from other occurrences. The field for the Chilas Complex (data: Arif and Jan (2006)) is highlighted in grey. (c) Chromite compositions for C/(Cr + Al) vs Mg/(Mg + Fe²⁺). Symbols as for (a). Compositional fields for other occurrences are detailed. (d) and (e) spinel compositions in relation to MgO content. High-Al chromite has the highest MgO content. Pleonaste from Mambula shows a wide range in MgO.

layered sequences indicating local and restricted fractionation while at the same time primitive magma or crystal mushes were being emplaced. Thick sections of gabbro have relatively constant mineralogical compositions but are also invariably strongly layered involving olivine gabbro, olivine gabbro norite and gabbro norite. Crystallization and differentiation are interpreted to have been buffered by influx of primitive magma as the magma chamber evolved. In the compositional domains the most primitive rocks have similar compositions, but some have advanced to more evolved compositions indicating a greater proportion of more differentiated magma remaining in the chamber. Both Tugela Rand and Mambula were the products of dynamic magma chamber processes and most likely, through-flow systems characterized

by mass movement of crystal slurries. The lithological layers also show facies changes towards the margins, most noticeable in Tugela Rand. The marginal facies are characterized by the presence of primary magmatic amphibole and an increase in the abundance of orthopyroxene.

One of the characteristic features of Tugela Rand is the orbicular and podiform-like chromitite layers (Fig. 3i) in the central dunite domain D1. Podiform chromitites have been uniquely associated with the depleted mantle peridotite component of Phanerozoic ophiolites in many continental localities (González-Jiménez et al., 2014; Paktunc, 1990; Prichard and Lord, 1990; Uysal et al., 2005; Xu et al., 2011). However, there is little agreement on the origin of the rare orbicular

chromitite (Prichard et al., 2015). In the Troodos ophiolite, explanations have incorporated a combination of chemical and physical controls involving rolling of the chromite-olivine accretions under gravity (Greenbaum, 1977). Dunite-chromitite assemblages are recognized as a product of reaction between restitic harzburgite and mantle melts (or fluids, although contentious) flowing through and this is the predominant view since Zhou et al. (1994). Ophiolitic dunite and chromitites are increasingly believed to be of magmatic origin that form in channels and small chambers, which may also have been influenced by out-flow of melts and fluids from the mantle source (Arif and Jan, 2006; González-Jiménez et al., 2014; Liu et al., 2024; Su et al., 2023; Zhou et al., 2014). The central dunite is not contiguous with the surrounding layered rocks and is interpreted to have been up-faulted into its present position truncating the layered series or possibly thrust into its present position, or it represents a conduit for mantle-derived melts and fluids. Similar structures and rock associations are present in underplated sequences in magmatic island arcs (eg. such as occur in the supra-subduction Kohistan Arc Complex of Pakistan (Stirling et al., 2023)) and may represent a valid comparison.

The magma chamber of Tugela Rand was extremely heterogeneous and crystallization was most likely taking place simultaneously in different domains and at different structural levels. This is illustrated by several occurrences where the path created by movement of blocks of solid or semi-solid pyroxenite (Fig. 3g) within a less dense gabbro slurry, are still well preserved.

Many features similar to those described for Tugela Rand also occur in Mambula but overall the latter is much more evolved with abundant magnetites and Fe-rich pyroxenes, and also exhibits a greater degree of ductile deformation. Olivine gabbro and troctolite occur in the northern zone of that complex and are similar to those rock-types in domains D4 and D5 in Tugela Rand and exhibits symplectite reaction textures between olivine and plagioclase. It is therefore considered that both Tugela Rand and Mambula were supplied with magma derived from deep seated magma chambers of similar sources but with the magma chamber feeding Mambula significantly more evolved resulting in the crystallization of magnetite and ilmenite. Layers in Mambula appear to be more continuous than those in Tugela Rand but poor exposure in some areas results in uncertainty in the apparent continuity of individual rock units.

10.2. Mineralogical indicators

Divalent and trivalent cation substitutions of spinel involving several elements and the relative ratios of these elements renders the mineral group petrogenetically highly informative (Barnes et al., 1985). In addition, and together with olivine, chromite is the first phase to crystallize from mafic magmas but also has a wide range of crystallization temperatures (Sack and Ghiorso, 1991) and can therefore track the solidification history of melts from the liquidus stage to close to pre-solidus. In particular, podiform or nodular chromitites characterize subduction environments in which preserved components of the MOHO transition zone are obducted onto stable continental crust (Prichard et al., 2015; Rollinson and Adetunji, 2013; Zhou et al., 2014) and therefor reflect crust-mantle interaction. However, the origin of these chromitites is controversial and while earlier research considered them to have formed at Mid-Ocean Ridges, later views suggest a supra-subduction setting (Rollinson and Adetunji, 2013) with the most Cr-rich chromitites being the most primitive and likely to reflect primary melts. The highest Cr-chromitites in Tugela Rand have lower Cr/(Cr + Al) than many ophiolites (Liu et al., 2024; Rollinson and Adetunji, 2013) indicating a source other than pristine upper mantle.

Compositions of the spinels are strongly controlled by the initial parental magma and its evolutionary path but include the role of water and oxygen fugacity, with extensive re-equilibration taking place with trapped melt and other solid phases during cooling. This leads to various inter-related chemical trends with Cr-Al reflecting pressure control and Fe-Mg reflecting fractionation, but also moderated by crystal-chemical

effects (Barnes and Roeder, 2001), both superimposed on the control of the melt path.

Using combinations of the principal element components in spinel it is possible to assign specific patterns to different tectonic settings and controls by the primary melt. The generally sloping trends of increasing Cr/(Cr + Al) with decreasing Mg/(Mg + Fe²⁺) was attributed to equilibration between olivine and spinels (Irvine, 1967) but also the equilibrium relationship between spinels and Al-bearing pyroxenes at high pressures (Barnes and Roeder, 2001). However, the wide range of combinations of compositional controls with different pressures, temperatures and oxygen fugacities resulted in re-crystallization and re-equilibration so that primary liquidus compositions are rarely preserved and the interpretative consideration taken by Barnes and Roeder (2001) is adopted here, (see comparative fields in Fig. 12 b, c.) The origin of high-Al chromite, characteristic of this setting, remains enigmatic and has been extensively discussed in the literature (Bo et al., 2023; Rollinson and Adetunji, 2013; Zhou et al., 2014) with the conclusion that fluids played an important role. Primary pleonaste spinel is commonly found in ophiolites (Özkan and Çelik, 2018).

The Tugela Rand data fall into clearly defined compositional spaces and overlap for some part with spinel data from a variety of tectonic and environmental settings. The extent of the overlap shows very little conformity with data for stratiform layered intrusions and ophiolites. There is some overlap with ocean floor basalts (Fig. 12b) but the Tugela Rand data cover a much wider field. Cr-magnetites overlap with the general spinel field of Alpine complexes and high pressure Alpine complexes (Barnes and Roeder, 2001) and overlap with the high-Cr and high-Al chromitites. Such a compositional range has been attributed to hybridization of multiple magmas (Bédard and Hébert, 1998).

Corona formation between olivine and plagioclase, observed in both Tugela Rand and Mambula, occurs at moderate pressure with reaction taking place close to the solidus temperature of the cumulate phases and facilitated by the presence of evolved hydrous fluid during the final stages of crystallization (Torres-Rodriguez et al., 2021). Analogous systems indicate pressure appropriate to emplacement and crystallization of mafic magma at upper-amphibolite conditions and crustal depths of up to 25 km. As these textural forms are present in both intrusions it is deduced that emplacement and crystallization took place at deep crustal levels equivalent to these conditions.

Deep crustal conditions are also indicated by the relatively high Al contents in pyroxene which have been shown to be dependent on pressure (Colson and Gust, 1989; Thompson, 1974), although quantification is dependent on other minor components within the pyroxene structure (Bédard, 2014). The average content of Al in Tugela Rand and Mambula is 3.1–3.4 wt.% Al₂O₃ in orthopyroxene, and 4.6–5.2 wt.% Al₂O₃ in clinopyroxene, compared respectively with 1.49 wt.% Al₂O₃ in the Bushveld Complex, Lower Zone orthopyroxene and 2.8 wt.% Al₂O₃ in clinopyroxene (Wilson, 2015).

An important economic consideration is the V content of the magnetite of up to 8000 ppm V and comparable to that of the magnetites in the Bushveld Complex. Controls of the incorporation of V into magnetite are complex and include fO₂ (Reynolds, 1986) and the ratio of magnetite to melt (the R-factor). Magnetite and titanomagnetite may form as an immiscible liquid (Charlier and Grove, 2012) and some fragmental zones in Mambula may show evidence of this.

10.3. Marginal emplacement structures

Both complexes have a variety of boundary conditions with layering concordant and parallel to the country rocks in some places and in other areas strongly discordant indicating both passive and cross-cutting intrusive conditions. In the Tugela Rand Complex contacts with surrounding rocks are observed in the north, the NW and in the extreme south. Rounded xenolithic fragments of the Mkondene diorite are observed in the northern and eastern contacts indicative of the intrusive relationship. No chill margins are observed; instead the contact is a

gradational reactive boundary involving assimilation of enclosing rocks resulting in rock-types with an assemblage of iron-rich olivine, primary hornblende and pyroxenes. These boundary conditions, as facies variations of contiguous layers, extend up to 50 m from the contact with dioritic country rock and most likely represent assimilation of it. The eastern and western contacts are sharply transgressive to the layering and no contacts observable but the gabbro in these zones is coarse grained with relatively low Mg#.

In the Mambula Complex there is gradation from highly sheared amphibolite into contorted amphibolitic gabbro with no clear contact. Contacts in the north and east margins are marked by rounded fragments of fine-grained mafic gabbro enclosed within unstructured leuco-gabbro indicative of a chilled wall-facies that was subsequently fragmented by the dynamic intrusive process (see Fig. 5a). In other marginal occurrences partly rounded and stretched fragments of coherent feldspathic pyroxenite enclosed within ductile sheared anorthosite resulted from the interplay of magmatic dynamics and sub-solidus deformation (Fig. 5b).

10.4. Geochemical analogues of deep crustal intrusions

Interpreting the geochemical signature is key to understanding these complexes. While these rocks are cumulates, they may nevertheless reflect the relative distributions of the highly incompatible trace elements of the primary melt in remnants of trapped melt. The REE

distributions are controlled mainly by partitioning of these elements into the cumulate phases. On this basis distribution patterns of trace elements can offer distinctive insight into the origin of igneous intrusions associated with subduction processes. One of the best studied, and most extensive, igneous associations of this type is the late Cretaceous Kohistan Arc Complex (KAC) in NE Pakistan (Jagoutz et al., 2006; Jagoutz et al., 2007), comprising large mafic and ultramafic intrusions. It is not an ophiolite (Khan et al., 1989) but is regarded as a supra-subduction arc complex and has broad similarities with plutonic bodies of island arcs (Lutfi et al., 2023). It is suggested here to be a possible analogue of the Tugela Rand Complex and the Tugela Terrane. In particular, the Chilas Complex (Jagoutz et al., 2006; Lutfi et al., 2023; Stirling et al., 2023) of the KAC can be compared with Tugela Rand. The Chilas Complex developed during intra-arc extension by decompression melting resulting in the formation of relatively dry high pressure cumulates (Jagoutz et al., 2011) which subsequently interacted with crustal fluids. Common evidence of emplacement in a dynamic and evolving environment includes primary features such as mineral layering on a scale of cm to metres, commonly of limited lateral extent, slumping and syndepositional faulting, and contrasting intrusive relationship between mafic and ultramafic rocks resulting in truncation and thinning of layers (Jagoutz et al., 2006; Jagoutz et al., 2007; Khan et al., 1989; Treloar et al., 1996).

Deep crustal complexes such as the Chilas Complex, and the Tugela Rand intrusion as inferred, characteristically show no evidence of chilled margins or melt - enriched layers. Instead the ultramafic layers show

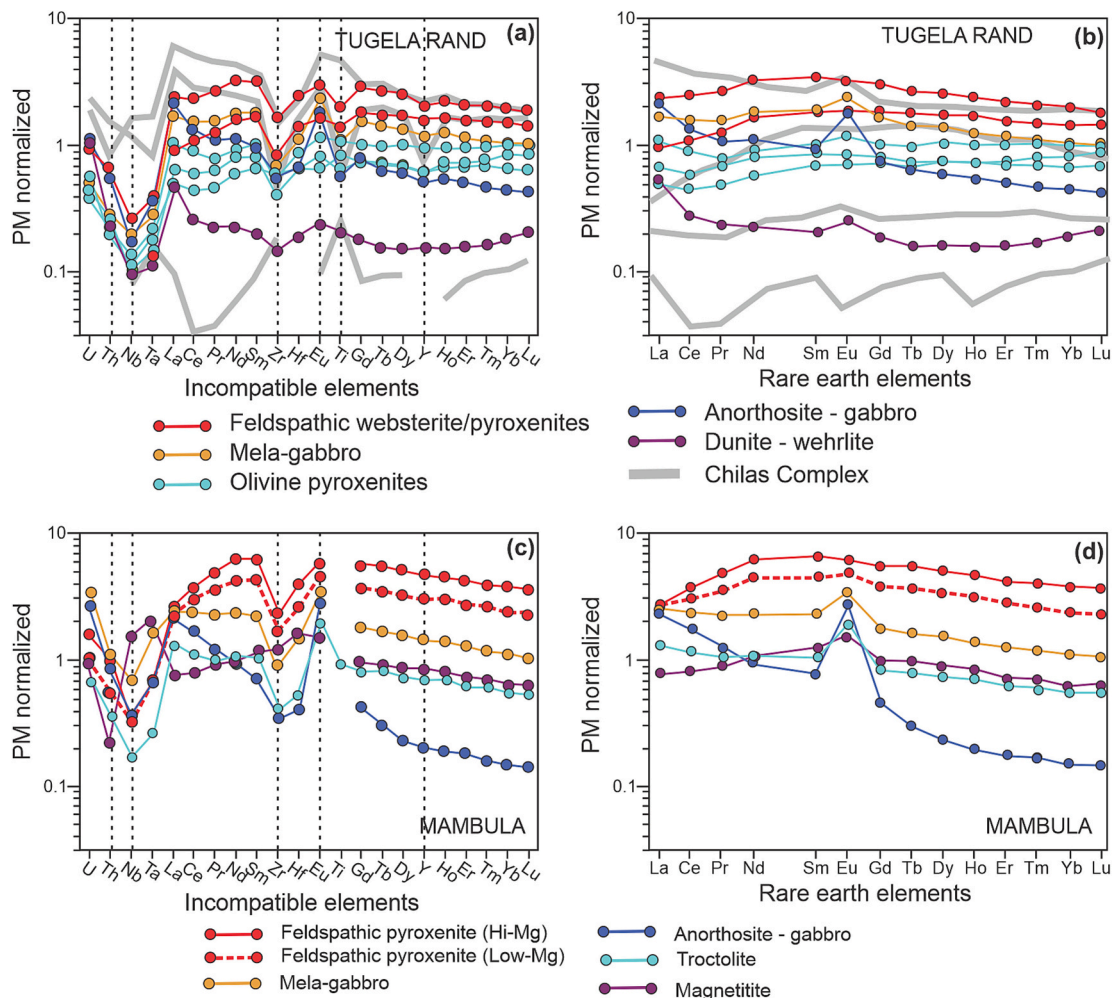


Fig. 13. Relative distribution of incompatible elements (a and c) and rare earth elements (b and d) normalized to primitive mantle (after McDonough and Sun (1995)) for Tugela Rand and Mambula as observed for specific rock-types. The range and distribution of trace elements for the Chilas Complex are shown for comparison. Nb and Ta are compatible with magnetite.

a disconnect with pyroxenite layers petering out against the gabbro units or being truncated against wall rocks. In the Chilas Complex this gave rise to an apparent subdivision based on the premise that the gabbros were derived as mantle diapirs and associated ultramafic bodies (Ultramafic-Mafic-Anorthosites abbreviated to UMA) formed from separate later pulses of mantle magma into the gabbro-norite (Khan et al., 1989). However, later studies (Burg et al., 1998) indicated that the UMA rocks developed prior (or synchronously) with the gabbroic rocks possibly as mantle conduits (Jagoutz et al., 2006). Compositional ranges are of limited extent (Jagoutz et al., 2007) indicative of continuous magma recharge.

The distributions of the incompatible elements in Tugela Rand and Mambula Complexes (Fig. 13) are related to the melt fraction remaining in the cumulus assemblages combined with solid phases present. In Tugela Rand, as expected, the olivine-rich rocks have the lowest concentrations of these elements, increasing through olivine pyroxenites, pyroxenites and websterites, and particularly the feldspathic varieties. The patterns normalized to Primitive Mantle are relatively flat with Nb and Ta markedly depleted relative to U, Th and La. Depleted elements are Zr, Hf and Ti to some degree. The patterns are similar to those of the ultramafic (UMA) suite of the Chilas Complex (Jagoutz et al., 2007) with particular similarity to the REE patterns of the clinopyroxenites, websterites and gabbros (Fig. 13a, b). Patterns for Mambula (Fig. 13c, d) have similar characteristics to Tugela Rand but overall have higher concentrations of incompatible elements reflecting the more evolved nature of the magma, and perhaps higher degrees of trapped melt.

This is further revealed in the REE patterns of the individual minerals from pyroxenites in the complexes. The patterns and concentrations of

REE in clinopyroxene, orthopyroxene and plagioclase (Fig. 14) are very similar to those observed in the Chilas Complex, although orthopyroxene in that complex has a steeper pattern. The cusp-shaped distribution for clinopyroxene is similar for both complexes and also for the Chilas Complex. The melt compositional patterns show an enrichment in LREE which is most likely derived from a crustal signature combined with fractionation of the parental magmas. Overall, the trace element concentrations in ortho- and clinopyroxene are higher in the Mambula samples. A primitive mantle pattern is not observed and all patterns are similar, therefore it is likely that the parental melt had already experienced some fractionation in deeper magma chambers and conduits. Pyroxenes in the Chilas complex show similar Al enrichment to those of Tugela Rand (Jagoutz et al., 2007).

Melt compositions may be interpolated from mineral compositions of REE (Fig. 14). However, these generally only broadly reflect liquidus compositions because of the influence of evolving trapped melt and later fluids that may have interacted with the rock and especially with trapped melt, together with uncertainties in partition coefficients. Ortho- and clinopyroxene indicate mantle-derived parental melt enriched in LREE. For Tugela Rand, concentrations are similar as deduced from ortho- and clinopyroxene. For Mambula the possible range of melt compositions as deduced from orthopyroxene is greater and most likely represents interaction with a variety of late stage melts and fluids.

Although the geochemical and petrological factors show characteristics of arc settings many of these are also observed in layered complexes in continental rift environments (such as the mafic intrusions of the Giles complex in Australia (Maier et al., 2023)) and distinction has to be made on the basis of the regional geological and tectonic settings.

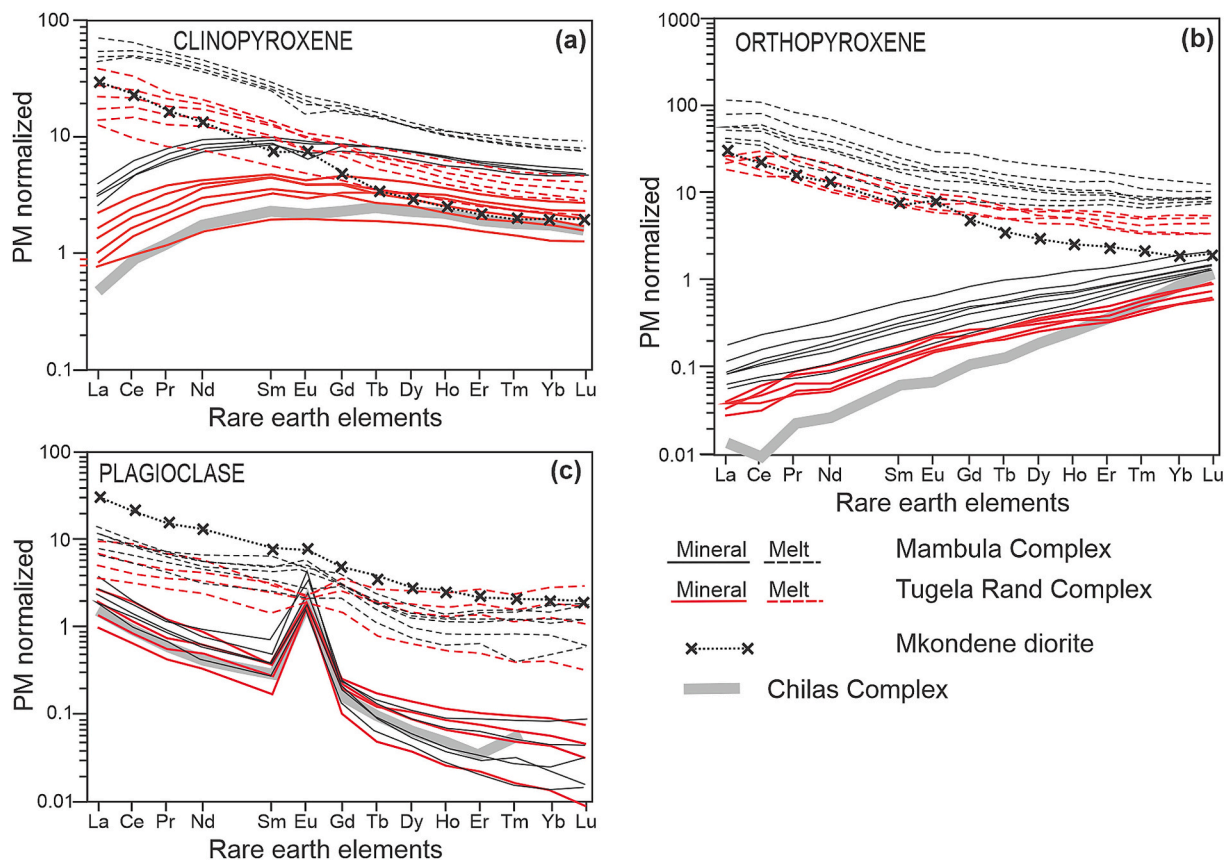


Fig. 14. Normalized rare earth distributions in individual minerals (a) clinopyroxene, (b) orthopyroxene, (c) plagioclase, for pyroxenites from Mambula and Tugela Rand Complexes. Shown for comparison are mineral compositions from the Chilas Complex. Melt compositions for rare earth elements are estimated using mineral-melt partition coefficients (Bédard, 2007; Bédard, 2014; Bédard, 2023; Johnson, 1998; McKenzie and O’Nions, 1991; Schnetzler and Philpotts, 1970). The melt compositions calculated can only be regarded as approximate because intrinsic parameters such as temperature, melt composition and pressure have not been taken into account.

11. Analogous terranes

In the South African context there are no other similar layered intrusions or equivalent terranes. A terrane which lithologically is remarkably similar to that of Tugela Rand is observed in the Cretaceous Chilas Complex (part of the Kohistan Island Arc) in the Himalayan north Pakistan. The Chilas Complex was emplaced in an active intra-arc rift environment (Schaltegger et al., 2002). It comprises ultramafic enclaves enclosed within gabbro-norite and diorite. The Chilas Complex is of immense size (300 km) (Treloar et al., 1996) and extends the entire width of the Kohistan-Karakoram Terrane and is thus much larger than the Tugela Terrane as presently exposed. However, this does not negate comparison of analogous deep crustal mafic complexes emplaced at high pressure and associated with compressional stages of an island arc system at the base of the volcanic succession (Fig. 15). Layered complexes in these settings can provide important information on the prevailing magmatic processes and magma transport.

The Mambula Complex was emplaced into amphibolite derived from basalt in the Mandleni thrust sheet. The most primitive rock-type (troctolite/olivine gabbro) is located towards the northern margin and therefore differs from Alaskan-type complexes where dunite occurs in the core (Himmelberg and Loney, 1995). The Tugela Rand and Mambula Complexes do not fall into the category of Alaskan-type complexes. Similar to deductions made for the Chilas Complex there is no evidence that the gabbroic rocks and ultramafic rocks formed from different magmas and it is most likely that liquidus conditions switched within narrow temperature intervals as crystal mushes at slightly different stages of fractionation intermingled. Similar pressure conditions for Tugela Rand and Mambula to the Chilas Complex are indicated by the olivine-plagioclase symplectic reactions and the Al content of the pyroxenes (Jagoutz et al., 2007), and also by the presence of pleonaste spinel.

Part of the Chilas suite is made up of exhumed lower arc crustal segments (Lutfi et al., 2023) with the latter possibly equivalent to the Mkondene diorite of the Tugela Terrane, preceded by the Kotongweni tonalite complex formed at 1207 ± 5 Ma with a characteristic arc signature of depleted HFSE (Arima et al., 2001; Zheng et al., 2020). The original extent of the Mkondene diorite is unknown and initially may have been much greater. Melting of oceanic crust in supra-subduction environments and in the upper mantle may have been an important contributor to the formation of juvenile continental crust (Gazel et al., 2015). The Kohistan volcanic arc represents such an environment (Jagoutz and Schmidt, 2012; Rolland et al., 2023). Parallels in lithologies, geochemistry and tectonic setting in the Tugela Terrane suggest that similar processes of juvenile crust formation were fully established by the Mesoproterozoic.

The Mandleni thrust slice hosting the Mambula Complex is dominantly amphibolitic containing abundant felsic units and a basal section of serpentinite with podiform-type chromitite layers. The general tectonic setting was similar for both intrusions. Differences may relate to the level of emplacement and the extent of fractionation of the parental magmas.

12. Conclusions

1. The Tugela Rand and Mambula layered complexes are important components of the Tugela Terrane in the eastern part of the Mesoproterozoic Natal metamorphic belt considered to have originated as a series of thrust segments of oceanic lithosphere accreted onto the southern margin of the Kaapvaal Craton. They are not ophiolites.
2. Layering styles and primary magmatic features indicate a dynamic emplacement setting with the two complexes representing different degrees of evolution of similar parental magma.

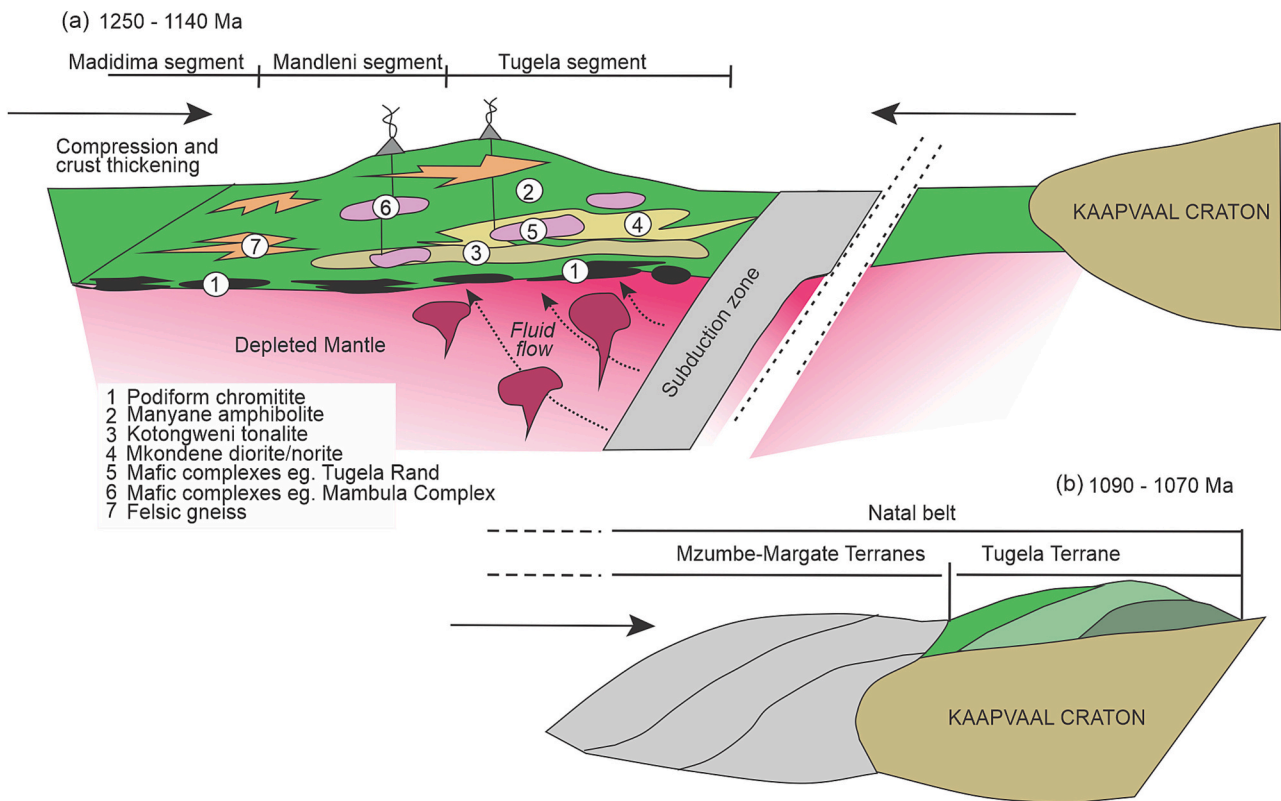


Fig. 15. Synoptic diagram of possible evolution of the Tugela Terrane. (a) Intra-oceanic arc showing the various types of lithological elements observed in the Tugela and Mandleni thrust segments. (b) Closure of the Tugela ocean basin by impact of the Mzumbi-Margate terranes with the Kaapvaal Craton and accretion of the Tugela Terrane (adapted from McCourt et al. (2006)).

3. The geochemistry and layering indicate repeated replenishment of the magma chambers, most likely as open systems.
4. Chromite occurs in several occurrences in the Tugela Terrane including podiform type and the rare orbicular chromitite is observed in Tugela Rand.
5. It is possible that an ultramafic sequence may underlie the more evolved succession in the Mambula Complex.
6. The Tugela Rand Complex has many features that are strikingly similar to the Cretaceous Kohistan arc complex of eastern Pakistan, and to the Chilas mafic complex in particular.
7. The inferred supra-subduction setting shows that generation of juvenile continental crust at intra-oceanic arcs, may have been fully operative by the Mesoproterozoic.

CRediT authorship contribution statement

Allan H. Wilson: Writing – review & editing, Writing – original draft, Visualization, Validation, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The author declares that there are no known competing financial or personal interests that could have influenced the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.lithos.2025.108052>.

Data availability

Analytical data and sample locality maps are available from the Wits data repository (<https://doi.org/10.71796/wits-figshare.28570223.v1>) and as Supplementary files to this article.

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