Lithostratigraphy of the Mesoproterozoic Twakputs Gneiss

S. Doggart
Council for Geoscience, P.O. Box 775, Upington, 8800, South Africa
e-mail: sdoggart@geoscience.org.za

P.H. Macey
Council for Geoscience, P.O. Box 572, Bellville, 7535, South Africa
e-mail: pmacey@geoscience.org.za

D. Frei
Department of Earth Sciences, University of the Western Cape, Private Bag X17, Bellville 7535, South Africa
Central Analytical Facility, Stellenbosch University, Private Bag X1, Matieland 7602, South Africa
e-mail: dfrei@uwc.ac.za

Abstract

The Twakputs Gneiss is a garnetiferous, K-feldspar megacrystic, biotite granite-granodiorite orthogneiss. It represents a major unit in the Kakamas Domain of the Mesoproterozoic Namaqua-Natal Metamorphic Province extending about 250 km between Riemvasmaak in South Africa and Grünau in southern Namibia. The Twakputs Gneiss occurs as foliation-parallel, sheet-like bodies tightly infolded together with granulite-facies paragneisses into which it intrudes along with a variety of other pre-tectonic granite and leucogranite orthogneisses. These rocks were subsequently intruded by late-tectonic garnet-leucogranites, granites and charnockites.

The Twakputs Gneiss is a distinctive unit characterised by large ovoid to elongate megacrysts of twinned perthitic K-feldspar, set in a coarse-grained matrix of garnet, biotite, quartz and feldspar. It contains a penetrative foliation defined by the alignment of K-feldspars and streaks of biotite that developed during the main phase D_2 of the Namaqua Orogeny (~1.2 to 1.1 Ga). The foliation and an accompanying elongation lineation are more intensely developed along lithological contacts, especially at the margins of the mega-scale F_3 domes and basins that refold the regional fabrics.

U-Pb zircon dating of the Twakputs Gneiss has yielded concordia ages of between ~1192 and 1208 Ma. Whole-rock geochemistry shows consistent major, trace and REE elemental trends, and thus reflect chemical variability from a single fractionating magma. The Twakputs Gneiss has a granitic to granodiorite composition and is strongly peraluminous. The geochemistry and the ubiquitous presence of garnet and pelitic xenoliths indicate an S-type granite protolith.

The Twakputs Gneiss is the most voluminous and widespread member of the Eendoorn Suite which comprises seven textural variants of garnetiferous, K-feldspar-megacrystic granitoid orthogneiss of the same age.

Introduction

The Twakputs Gneiss is a garnetiferous, coarsely K-feldspar megacrystic biotite granite-granodiorite gneiss that occurs as voluminous sheet-like bodies between Riemvasmaak in South Africa and the Grünau-Ai-Ais basement inlier in southern Namibia (Figure 1; Moen, 2007; Moen and Toogood, 2007; Macey et al., 2015). The pre-tectonic orthogneiss intrudes high-T, low-P granulite-facies paragneisses in the Kakamas Domain (Figure 1; Macey et al., 2015) in the Mesoproterozoic Namaqua-Natal Metamorphic Province (NNMP, Cornell et al., 2006 and references therein). The Twakputs Gneiss was first mapped on the 2820 Upington geological sheet by Moen (1988) and is named after an abandoned settlement west of the hamlet of Riemvasmaak (Figure 1).

Type area

The Twakputs Gneiss occurs as a major rock unit in the lower Orange River region of the Northern Cape and in south-eastern Namibia. Good, accessible exposures of the Twakputs Gneiss can be viewed along the gravel road between the settlements of Riemvasmaak and Blouputs, north of the Orange River (Type Locality A; Figure 1) and in the Augrabies Falls National Park. Excellent fresh outcrops of the Twakputs Gneiss can also be viewed at a dimension stone quarry on *Vaalkoppies 80* (GPS: 28°46'26"S; 19°37'7"E; locality B – Figures 1 and 2). This notable exposure can be reached following the northwest-trending track from the main Onseepkans-Augrabies gravel road on *Upper Zwart Modder 78* (Figure 2).

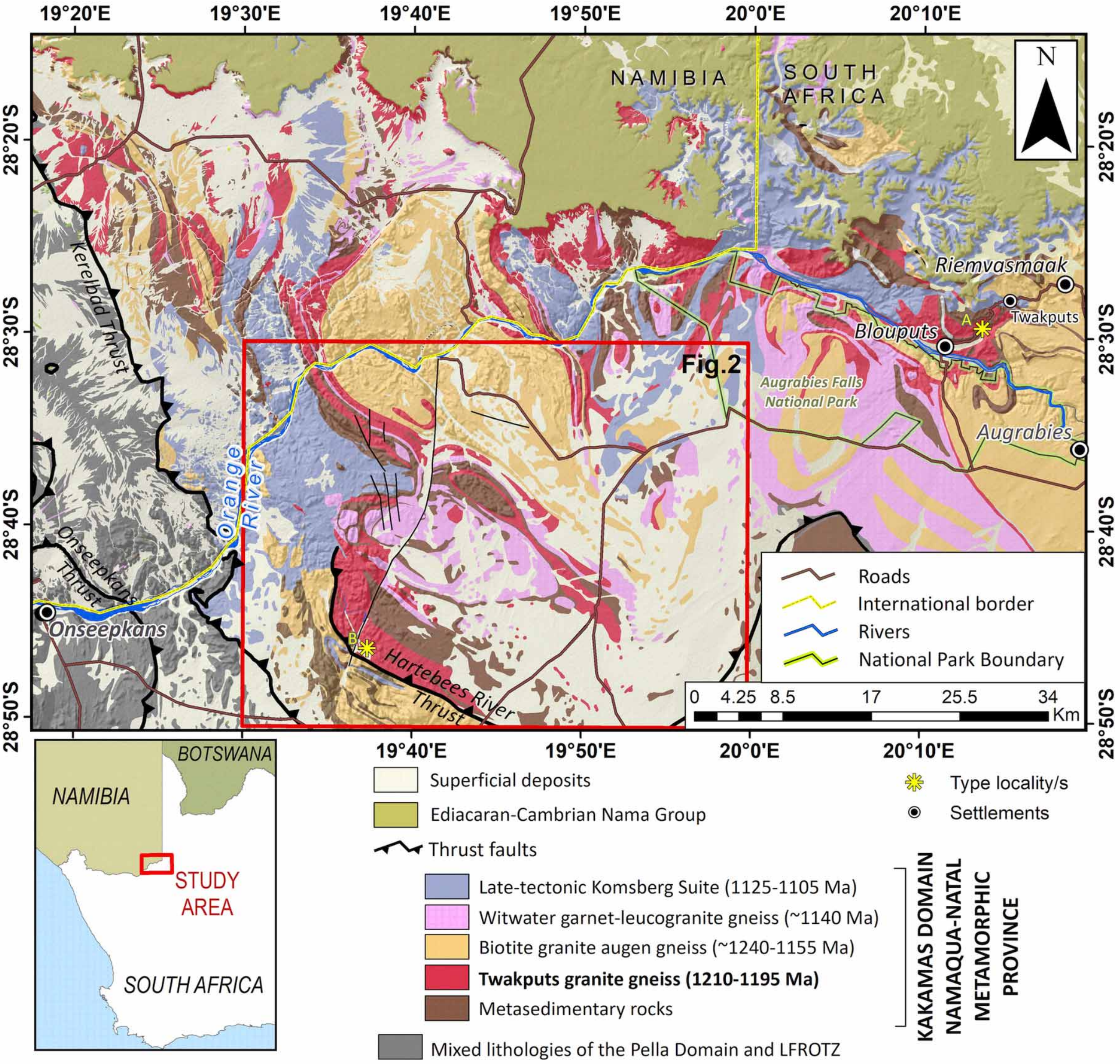

Figure 1. *Distribution of the Twakputs Gneiss. Compiled from geological maps by Moen (2007), Moen and Toogood (2007) and Macey et al. (2015).*

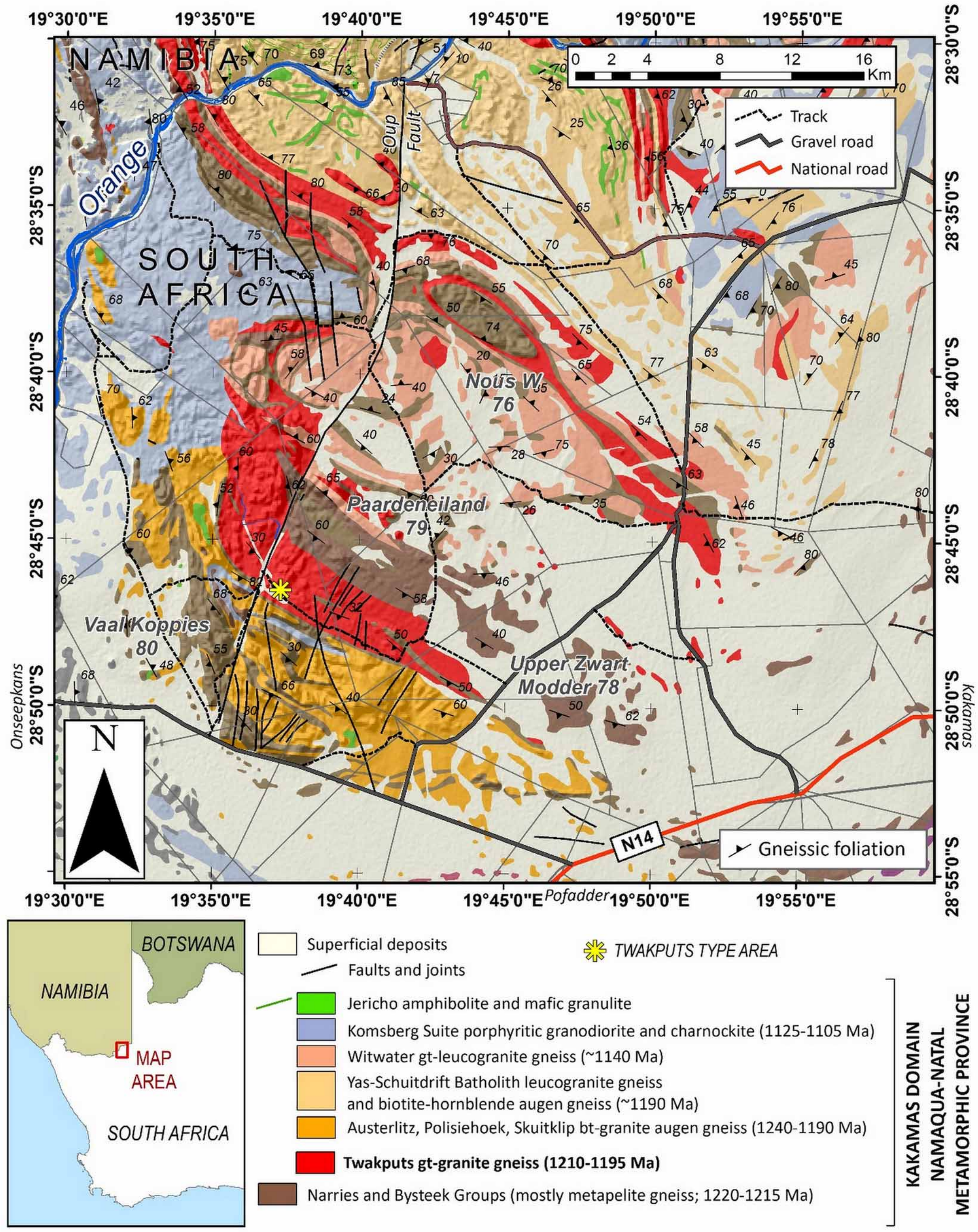

Figure 2. *Simplified map showing the geology of the western type area of the Twakputs Gneiss (locality B). Map and age data compiled from Moen (2007), Moen and Toogood (2007), Pettersson (2008), Bial et al. (2015), Colliston et al. (2015), Macey et al. (2015, 2018), Bailie et al. (2017), Groenewald and Macey (2020) and Abrahams and Macey (2020).*

Stratigraphic position and age

The garnetiferous and K-feldspar megacrystic granitic orthogneisses that are now included in the Twakputs Gneiss have a complex lithostratigraphic history of nomenclature and have been given various names by previous workers in the Northern Cape and adjacent regions of southeast Namibia. Toogood (1976) mapped vast areas of variably sheared "Beenbreek Megacrystic Granite" across much of southeast Namibia between 19 and 20° East, which he named after Beenbreek farm, and correlated the rocks with the Eendoorn Granite of Beukes (1973). Du Plessis, (1979, 1986) mapped the area along the South African side of the Orange River south of, and adjacent to, Toogood's map. He extended the Beenbreek Granite across the river but named it the "Eendoorn Granite" after Beukes (1973). Moen (2007) and Moen and Toogood (2007) further subdivided the "Eendoorn Granite" of Du Plessis into the Twakputs Gneiss in the east (in the Kakamas Domain) and the Beenbreek Gneiss in the west where it occurs within the Lower Fish River Onseepkans Thrust Zone (Macey et al., 2015, 2017).

The pre-tectonic Twakputs Gneiss intruded the granulite facies Narries metapelitic and semipelitic paragneisses (~1 220 Ma; Macey et al., 2015) and together, both were subsequently intruded by the Witwater Gneiss (garnet-quartz-feldspar leucogneiss; 1 142 ± 11 Ma; Moen and Toogood, 2007). The close spatial association of the Twakputs, Narries and Witwater Gneisses led Moen (1988, 2007) and Moen and Toogood (2007) to group them into the "Koelmanskop Metamorphic Suite". Whilst we confirm the spatial intimacy of the three units, age data indicate they are not cogenetic and hence the term Koelmanskop Metamorphic Suite has been abandoned (Macey et al., 2015; this study; SACS Mesoproterozoic Task Group, 2018). Instead, the Twakputs Gneiss is included as a lithodemic member of the Eendoorn Suite of Beukes (1973), as proposed by Toogood (1976) and Du Plessis (1979, 1986) on the basis of similarities in field appearance, field relationships, relative tectonic age, geochemical composition and geochronology. The Eendoorn Suite has been subdivided into six other lithodemes on the basis of variations in the size and shape of megacrysts, proportion of garnet, geographical distribution, tectono-lithological associations and historical subdivisions (Macey et al., 2015).

Two samples of the garnetiferous, K-feldspar-megacrystic Twakputs Gneiss were dated as part of this study (data tables provided as a supplementary appendix are archived in the South African Journal of Geology repository (https://doi.org/10.25131/sajg.124.0041.sup-mat)). Samples PM14041 (28°19'2"S; 19°45'35"E) and PM14048 (28°26'37"S; 19°50'46"E) were collected from southeast Namibia and contained single homogenous populations of small to moderately sized (80 to 200µm) concentrically zoned magmatic zircons with tabular to elongate habits and generally rounded edges. A few zircons have inherited cores. Twenty-seven spots were analysed on zircons from sample PM14041 of which three concordant inherited cores give $^{207}Pb/^{206}Pb$ ages of 1 863 ± 39, 1 444 ± 42 and 1 279 ± 46 Ma. Thirteen of the 21 analyses on the concentrically zoned igneous grains are >95% concordant from which a concordia age of 1 208 ± 7 Ma (Figure 3, MSWD = 0.10, probability = 1.0) was calculated and is considered as the crystallisation age of the porphyritic granite protolith. A best fit regression through all the data provides an upper intercept age of 1 213 ± 13 Ma. Sample PM14048 yielded an identical crystallisation concordia age of 1 208 ± 7 Ma (MSWD = 0.19, probability = 1.0) from 11 concordant analyses of 20 spots on igneous zircon and an upper intercept age of 1 212 ± 14 Ma (Figure 3). Three concordant inherited grains yield $^{207}Pb/^{206}Pb$ ages of 1831 ± 40, 1613 ± 41 and 1388 ± 50 Ma. The crystallisation ages reported here overlap with other published ages for the Eendoorn Suite of 1 192 ± 13 Ma, 1 197 ± 11 Ma and 1 205 ± 7 Ma (Nordin, 2009; Bial et al., 2015).

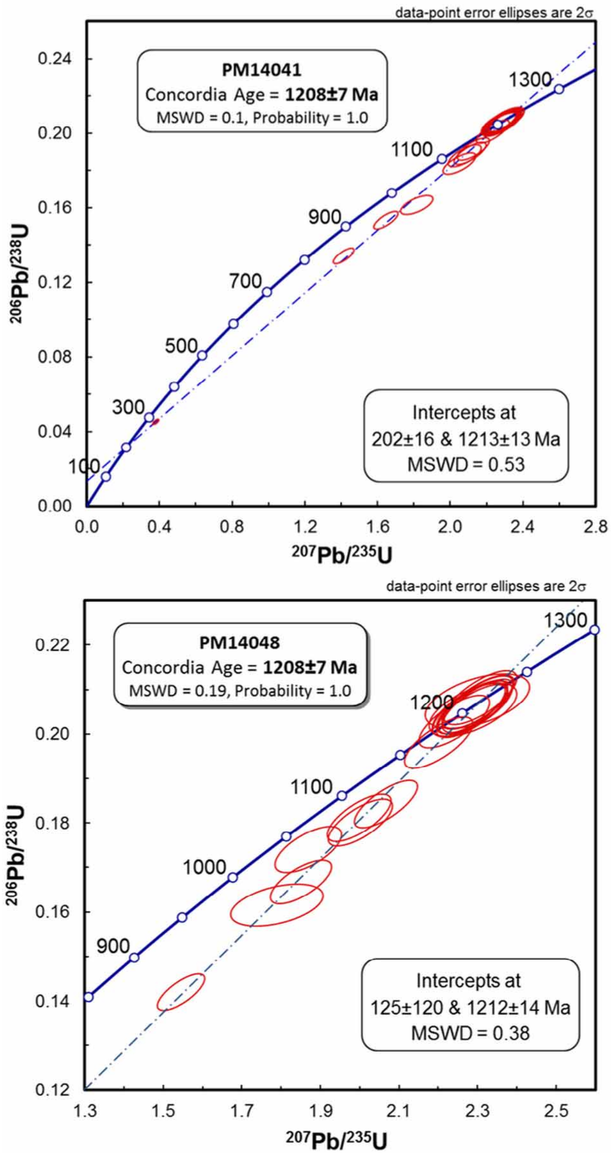

Figure 3. *Wetherill concordia diagrams showing LA-ICPMS zircon U-Pb data for two samples of Twakputs Granite Gneiss.*

Geological description

Basic concepts and unifying features

The Twakputs Gneiss is a leucocratic to mesocratic grey, strongly garnetiferous, biotite granitic gneiss with large, ovoid to elongate megacrysts of K-feldspar (Figure 4). Most often the megacrysts have dimensions in the order of 30 to 60mm x 10 to 25 mm (Figures 4a and b) but they can reach sizes in excess of 100 mm in places. The K-feldspar megacrysts are commonly recrystallised. Garnet always occurs as a minor phase but is more abundant close to contacts with metapelitic gneisses. (Figure 4c). The Twakputs Granite Gneiss weathers to medium-brown exfoliation pavements (Figures 5a and b), whereas the more strongly deformed and fissile examples have a "flaggy" style outcrop appearance.

Form and size of intrusions

The Twakputs Gneiss occurs as tabular sheets infolded with other pre-tectonic gneisses parallel to the regional Namaqua penetrative foliation (D_2 of Joubert,1986). The lateral and vertical thickness of sheets varies from thin bands, tightly interbanded with the paragneisses, to wider units up to ~5 km thick. Subsequent large-scale (up to several km) folding has reoriented the Twakputs Gneiss sheets into F_3 (Joubert, 1986) dome and basin-type structures with high strain fabrics developed along the margins.

Lithology

The Twakputs Gneiss is a garnet- and biotite-bearing megacrystic granite gneiss (see Figure4). The characteristic microcline megacrysts are commonly twinned and perthitic (~30-35%) and set in a coarse-grained (1 to 5mm) matrix of K-feldspar, plagioclase (~15 to 25%), quartz (~25 to 35%), oriented biotite with red-brown to pale yellow pleochroism (~15 to 30%) and anhedral garnet (up to 10%). The proportions of these major minerals varies across the outcrop area (Du Plessis, 1979; Moen and Toogood, 2007; this study). Much of the feldspar is altered, particularly the larger perthitic augen which are commonly surrounded by zones of finer-grained, recrystallised quartz and plagioclase. Garnet in many cases has an inclusion-free core surrounded by a rim with small inclusions of biotite and an opaque phase. Small sillimanite needles and, more rarely, elongate prismatic sillimanite are present in some sections, generally associated with biotite. Along the south-eastern border of Namibia, the Twakputs Gneiss is more garnet- and biotite-rich; leading to darker outcrop colours. In contrast, several outcrops along the escarpment below the Nama Group Plateau consist of more than 75% microcline megacrysts and represent a leucocratic facies of the Twakputs Gneiss.

Xenoliths

Xenoliths are common throughout the Twakputs Gneiss, especially at the contacts with the Narries Group metapelites. The variably-sized (metre to 100's of metres) xenolithic rafts are almost exclusively pelitic, semi-pelitic and psammitic paragneiss (Figure 5c). In places, the semi-concordant to concordant interfingering of the Narries Group and Twakputs is too fine to map at 1:50 000 scale, and in these cases, a mixed (informal) Twakputs-Narries unit was mapped by Macey et al. (2015).

Structure

The Twakputs Gneiss contains the regional penetrative Namaqua S_2 foliation and L_2 stretching lineation (nomenclature of Joubert,

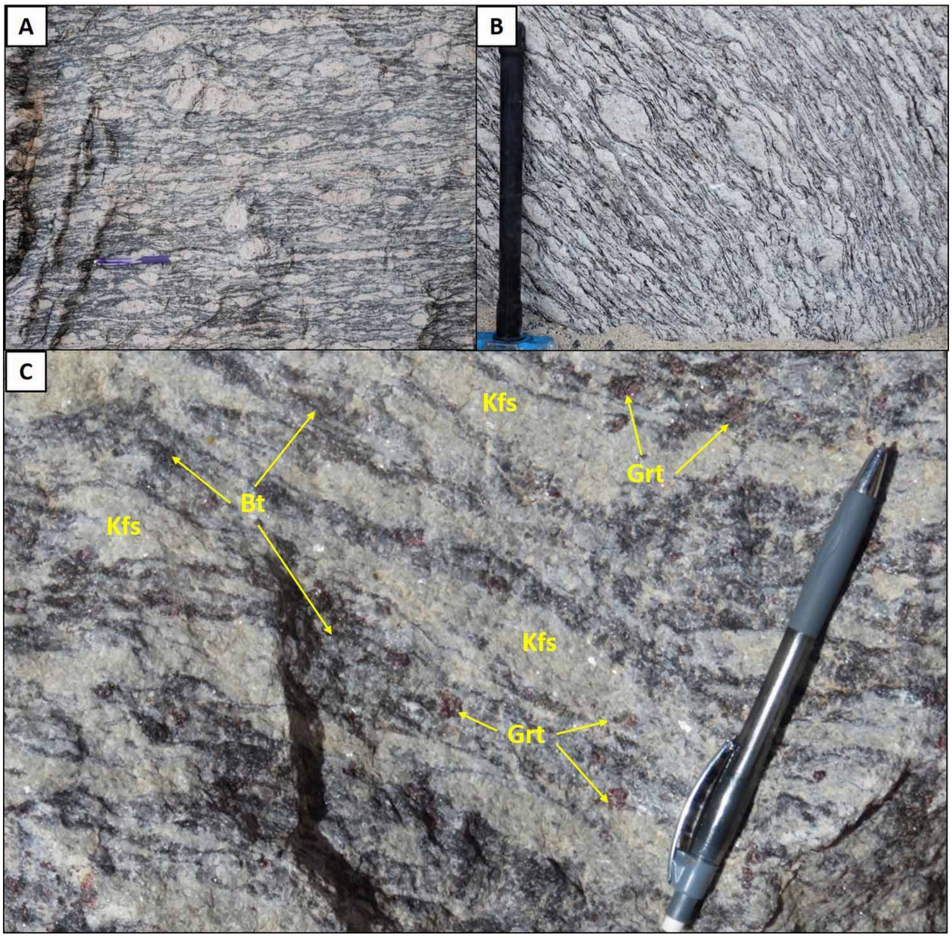

Figure 4. *(**a**) and (**b**) typical examples of the Twakputs Gneiss showing the stretched out ovoid feldspar megacrysts that define the strong penetrative ductile gneissic foliation (**c**) a close-up of the Twakputs Gneiss showing the disseminated garnet (Grt) grains found in association with biotite (Bt) streaks that separate the attenuated K-feldspar megacrysts.*

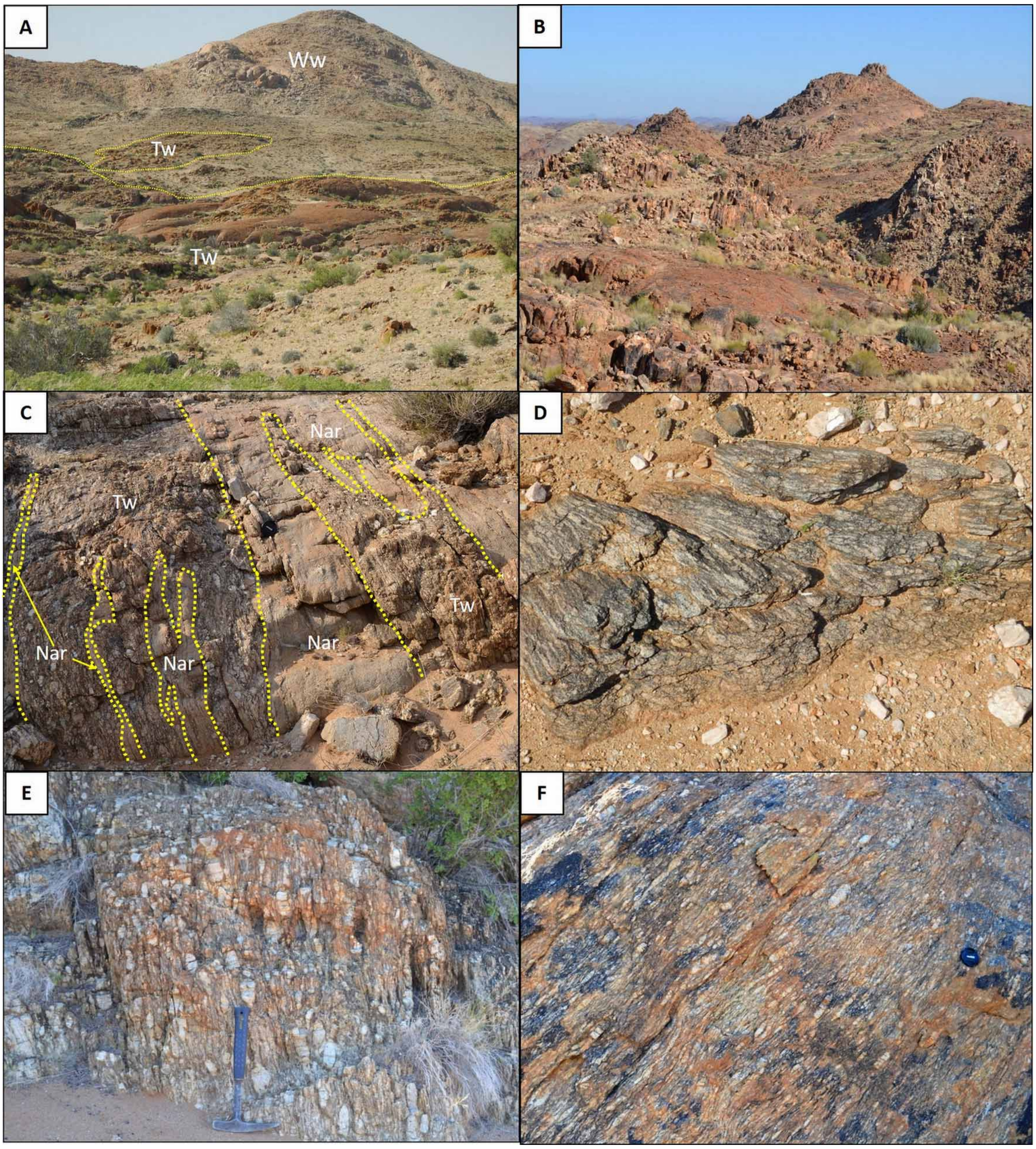

Figure 5. *(**a**) and (**b**) Typical pavement and boulder tor outcrop of the Twakputs Granite Gneiss. In photograph (a) notice the difference in colour between the resistant white ridges of Witwater Gneiss (Ww) in the background and the brown weathering Twakputs Gneiss (Tw, middle ground). (**c**) The Twakputs Gneiss with rafts of Narries Group metasedimentary gneiss (Nar). (**d**) strongly lineated Twakputs Granite Gneiss / L-tectonite. (**e**) brittle-ductile deformed Twakputs Granite Gneiss resulting in cataclastic textures; (**f**) ductile deformation resulting in mylonitic fabrics and asymmetric augen.*

1986) but the degree of strain varies across the unit. In most outcrops the gneissic foliation is defined by the alignment of euhedral to subhedral ovoid to elongated K-feldspar megacrysts and streaks of oriented biotite (Figure 5a). Higher strain is generally observed in areas where the Twakputs Gneiss is in contact with other major lithotectonic units and especially along the margins of large scale F_3 domes (e.g. where the Twakputs Gneiss and associated rock units are wrapped around the Yas-Schuitdrif Batholith; Figure 2). In these areas, the megacrysts occur as recrystallized aggregates with stretched out augen shapes (Figure 5b) and, where strongly lineated, form L-tectonites (Figure 5d and e). In some places strain is sufficiently high that mylonitic and cataclastic fabrics are developed (Figure 5e and f). The cataclastic deformation is characterised by large randomly oriented feldspar augen set in a finer-grained fragmentary matrix. These rocks may show evidence of secondary (hydrothermal?) leaching of the rock mass with little to no biotite present.

The Twakputs Granite Gneiss is occasionally cross-cut by northwest-trending discrete and relatively narrow shear zones possibly related to the late-Namaqua D_4 transcurrent shear deformation (similar to the Pofadder shear zone).

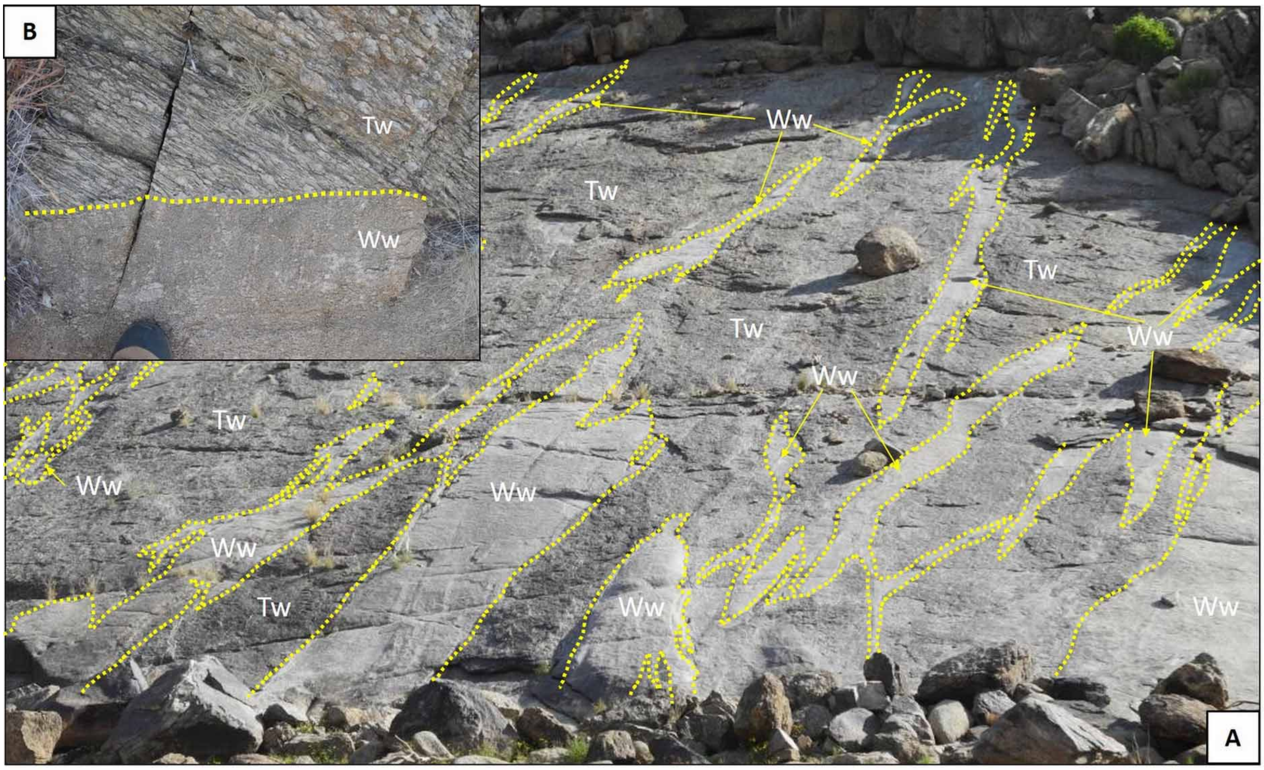

Figure 6. *(**a**) Irregular dykes of Witwater Gneiss (Ww) intruding the Twakputs Gneiss (Tw). (**b**) Foliation in the Twakputs Gneiss cross cut by younger dyke of Witwater Gneiss.*

Boundaries

The contacts of the Twakputs Gneiss with the deformed metasedimentary Narries Group vary from sharp to diffuse with lit-par-lit interleaving of the units which can make the mapping of the exact boundaries difficult.

The Twakputs Gneiss is often cross-cut by dykes of Witwater Gneiss (Figure 6), a garnet-quartz-feldspar leucogneiss considered to be dehydration melt veins that formed during the younger (~1.14 Ga) high grade metamorphism of the Narries Group and coeval metapelites (Moen and Toogood, 2007; Macey et al., 2015). The contacts with the Witwater Gneiss are sharp as are the contacts with the younger Komsberg Suite granites and charnockites (Macey et al., 2018; Abraham and Macey, 2020) that also locally intrude the Twakputs Gneiss.

Correlation

Based on similarities in appearance and radiometric age, Macey et al. (2015) correlated the Twakputs Gneiss with six other garnetiferous K-spar megacrystic biotite granite gneiss units (Beenbreek, Altdoorn, Bokkiesbank, Khais, Pioneer, Kinderzitt Gneisses) that occur in the Kakamas Domain and the underlying Lower Fish River-Onseepkans thrust zone. These gneisses have been grouped together as the Eendoorn Suite (Beukes, 1973; Macey et al., 2015).

Geochemistry and petrogenesis

The geochemistry of 12 samples of Twakputs Gneiss is presented together with 29 other samples of the Eendoorn Suite (Beukes, 1973; Du Plessis, 1979, 1986; Macey et al., 2015) in Figures 7 to 9 and Tables 1 and 2.

The Twakputs Gneiss is a felsic rock with a range in SiO_2 between 66 and 74 wt % (Table 1). It plots as sub-alkaline granite to granodiorite on the total alkali versus silica diagram (Figure 7a). Using calculated mesonormative mineral compositions, the Twakputs Gneiss samples classify as monzogranite on the Streckeisen (1974) Q-A-P diagram (Figure 7b). The Twakputs Gneiss is strongly peraluminous (mean alumina saturation index: 1.14 ± 0.07; Shand, 1943; Figure 7c) and has high K_2O/Na_2O reflecting the commonly garnetiferous, pelite-xenolith-rich nature of these granites and a likely S-type granite genesis during high grade metamorphism of the Narries metapelites at ~1200 Ma (Cornell and Pettersson 2007; Bial et al., 2016). The Twakputs Gneiss has high K_2O and plots in the high-K calc-alkaline and shoshonitic fields the K_2O against SiO_2 diagram (Figure 7d).

The Twakputs Gneiss and Eendoorn Suite display consistent major element trends on Harker diagrams (Figure 8). They show trends of decreasing Al_2O_3, MgO, CaO, FeO^{tot}, TiO_2, MnO, P_2O_5, Ba, Sr, Y, Hf, Th, Ta and the transition metals versus silica, but slight increases in K_2O and Rb, with increasing SiO_2 (Figures 8 and 9a). These trends suggest the progressive fractional crystallisation of plagioclase, amphibole, monazite, sphene and

Table 1. Whole rock major and trace element geochemistry of the Twakputs Gneiss and the Eendoorn Suite.

Major Elements	**Twakputs Gneiss (*n* = 12)**			**Eendoorn Suite (n = 29)**		
	Mean ± std.dev.	**Min**	**Max**	**Mean ± std.dev.**	**Min**	**Max**
SiO_2	69.83 ± 2.04	66.18	74.08	69.04 ± 3.12	63.01	73.37
TiO_2	0.57 ± 0.19	0.20	0.83	0.63 ± 0.29	0.28	1.31
Al_2O_3	14.61 ± 0.71	13.76	16.21	14.42 ± 0.79	12.91	16.26
FeO (t)	4.34 ± 1.31	1.63	5.89	3.63 ± 2.31	0.21	8.22
MnO	0.05 ± 0.02	0.01	0.09	0.06 ± 0.03	0.02	0.13
MgO	0.93 ± 0.37	0.12	1.41	0.83 ± 0.45	0.22	1.98
CaO	1.55 ± 0.37	0.70	2.10	2.11 ± 0.77	0.74	3.89
Na_2O	2.32 ± 0.28	1.76	2.82	2.64 ± 0.37	1.86	3.51
K_2O	4.64 ± 0.74	3.54	5.93	4.80 ± 1.21	1.85	7.29
P_2O_5	0.19 ± 0.06	0.09	0.34	0.19 ± 0.10	0.08	0.45
L.O.I.	0.53 ± 0.33	0.22	1.33	0.42 ± 0.24	0.09	1.19
Total	99.57 ± 0.48	98.32	100.34	99.57 ± 0.81	96.12	100.71
H_2O^-	0.16 ± 0.05	0.08	0.23	0.13 ± 0.06	0.04	0.25
ASI	1.26 ± 0.16	1.11	1.60	1.09 ± 0.11	0.90	1.32
$Al_2O3/(K_2O+Na_2O)$	1.68 ± 0.24	1.33	2.17	1.55 ± 0.26	1.15	2.49
K_2O+Na_2O	6.96 ± 0.89	5.63	8.54	7.44 ± 1.34	4.37	10.21

Trace Elements	**Twakputs Gneiss (n = 12)**			**Eendoorn Suite (n = 29)**		
	Mean ± std.dev.	**Min**	**Max**	**Mean ± std.dev.**	**Min**	**Max**
Li	40 ± 13	25	55	32 ± 14	16	58
Sc	9 ± 3.6	3.8	13	10 ± 6.9	0.7	26
V	60 ± 23	25	90	49 ± 28	10	110
Cr	31 ± 14	13	55	19 ± 16	4.7	60
Co	9.2 ± 3.1	4.4	13	7.5 ± 4.1	2.2	17
Ni	16 ± 6.7	6.4	27	13 ± 9.3	1.4	28
Cu	18 ± 5.0	8.0	25	13 ± 6.1	4.9	29
Zn	82 ± 27	45	122	71 ± 20	28	105
Ga	25 ± 9.5	18	48	29 ± 8.2	18	40
Rb	198 ± 61	69	278	172 ± 82	76	382
Sr	85 ± 26	47	138	113 ± 37	40	162
Y	32 ± 10	17	48	37 ± 20	14	75
Zr	152 ± 42	93	203	133 ± 67	39	232
Nb	13 ± 4.1	8.1	18	14 ± 4.6	6.3	21
Ba	544 ± 151	216	712	797 ± 396	140	1330
Hf	4.3 ± 1.1	2.7	5.6	3.9 ± 1.9	1.3	6.4
Ta	1.0 ± 0.5	0.4	1.7	0.9 ± 0.3	0.4	1.2
Pb	29 ± 4.2	24	37	30 ± 8.6	16	50
Th	20 ± 6.8	14	35	23 ± 12	6.8	47
U	2.6 ± 0.9	1.2	4.5	3.8 ± 5.7	0.6	22

zircon but limited fractional crystallisation of K-feldspar and biotite. The broadly coherent trends in mobile elements such as Rb, Sr and Ba indicate there has been little or no overall compositional change during metamorphism or weathering.

The Eendoorn Suite rocks show consistent saw-tooth trace element patterns on the MORB-normalised spider diagram (Figure 9a) and are generally enriched relative to the average Upper Continental Crust (UCC; except for Ta, Nb, Hf) and have negative P_2O_5 and TiO_2 anomalies. The seven samples analysed for rare earth elements show consistent patterns on the chondrite-normalised spider plot (Figure 9b) with high relative abundances (~10 to 200 times chondrite; sum of REE ~10 times average granite and UCC), moderate LREE enrichment (mean $(La/Yb)_N$ = 11.9 ± 3.0) and strong negative Eu anomalies (mean Eu_N/Eu^* = 0.57 ± 0.1).

The consistency in the trends in major, trace and rare earth element compositions of the various members of the Eendoorn Suite support their correlation as co-magmatic rocks.

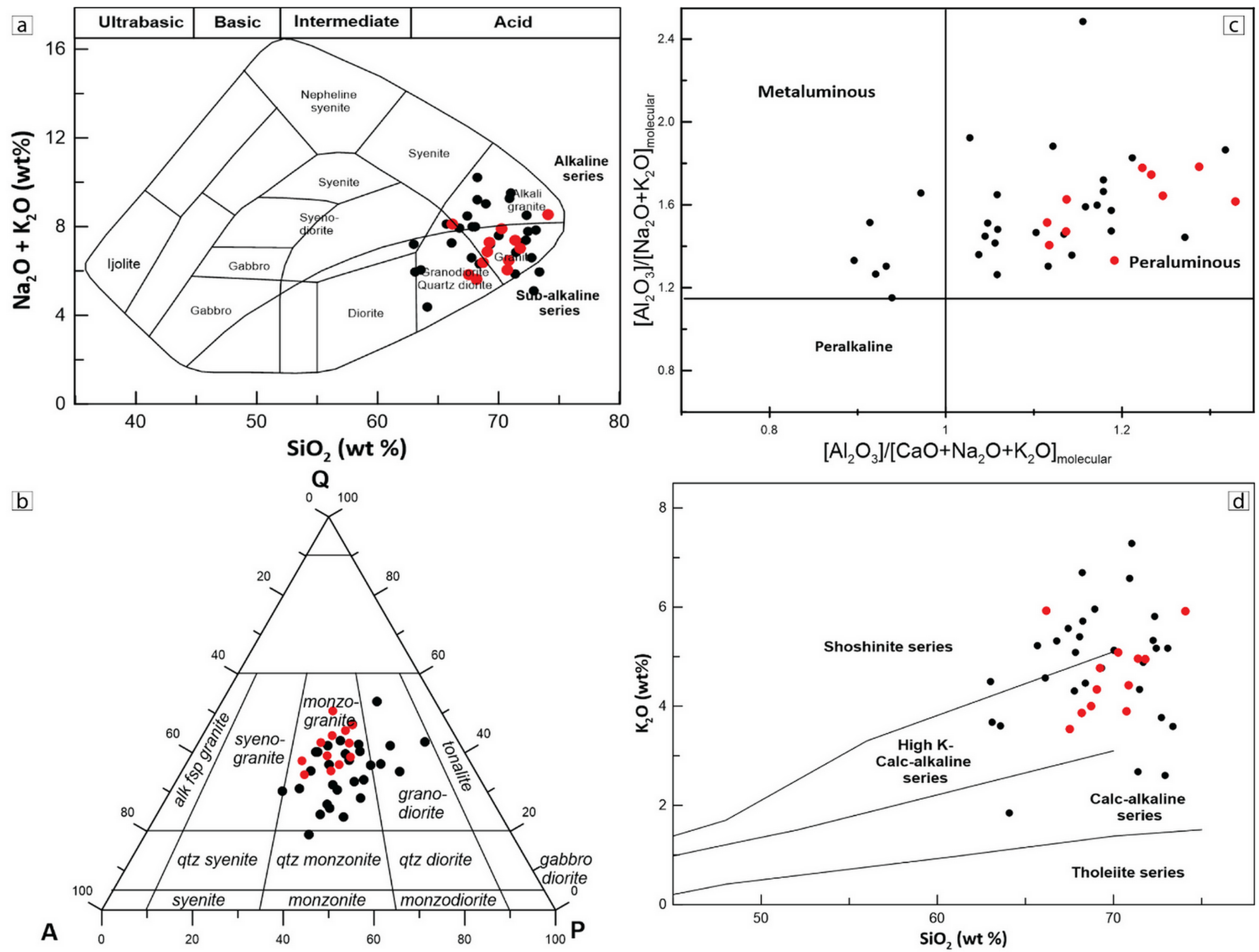

Figure 7. *The geochemical classification of the Twakputs Gneiss (red dots) and the Eendoorn Suite (black dots). Data after Beukes (1973), Du Plessis (1979, 1986) and Macey et al. (2015). (**a**) Total alkali versus silica plot (Cox et al., 1979), (**b**) QAP mesonormative mineralogy (Streckeisen, 1974). (**c**) alumina saturation index (Shand, 1943). (**d**) Le Maitre (1989) K_2O versus SiO_2.*

Table 2. Whole rock rare earth element geochemistry of the Twakputs Gneiss and the Eendoorn Suite.

Rare Earth Elements	Twakputs Gneiss (*n* = 7)			Eendoorn Suite (n = 14)		
	Mean ± std.dev.	Min	Max	Mean ± std.dev.	Min	Max
La	42.24 ± 9.42	28.35	53.16	60.58 ± 24.33	21.83	107.80
Ce	98.56 ± 21.69	66.49	121.60	130.83 ± 50.75	51.47	238.30
Pr	11.65 ± 2.53	7.93	14.44	15.05 ± 5.70	6.42	27.47
Nd	45.04 ± 9.76	30.70	55.94	58.33 ± 21.57	26.43	105.20
Sm	9.34 ± 1.72	6.99	11.59	11.39 ± 3.80	6.36	19.39
Eu	1.23 ± 0.29	0.71	1.66	1.54 ± 0.57	0.72	2.65
Tb	1.15 ± 0.20	0.86	1.42	1.29 ± 0.50	0.60	2.16
Gd	8.20 ± 1.36	6.54	10.31	9.36 ± 3.18	4.90	15.51
Dy	6.62 ± 1.63	4.12	9.10	7.44 ± 3.51	2.89	13.58
Ho	1.22 ± 0.35	0.66	1.74	1.41 ± 0.78	0.49	3.01
Er	3.37 ± 1.02	1.64	4.74	3.96 ± 2.42	1.36	9.44
Tm	0.46 ± 0.14	0.23	0.61	0.56 ± 0.36	0.17	1.45
Yb	2.87 ± 0.91	1.38	3.87	3.66 ± 2.40	1.02	9.82
Lu	0.42 ± 0.13	0.20	0.56	0.55 ± 0.37	0.15	1.55
ΣREE	232.37 ± 51.15	156.80	290.75	305.94 ± 120.23	124.81	557.34
$[Eu/Eu^*]_N$	0.43 ± 0.09	0.32	0.59	0.47 ± 0.12	0.22	0.63
$[La/Yb]_N$	10.92 ± 3.60	5.58	17.69	13.89 ± 7.11	7.54	32.70

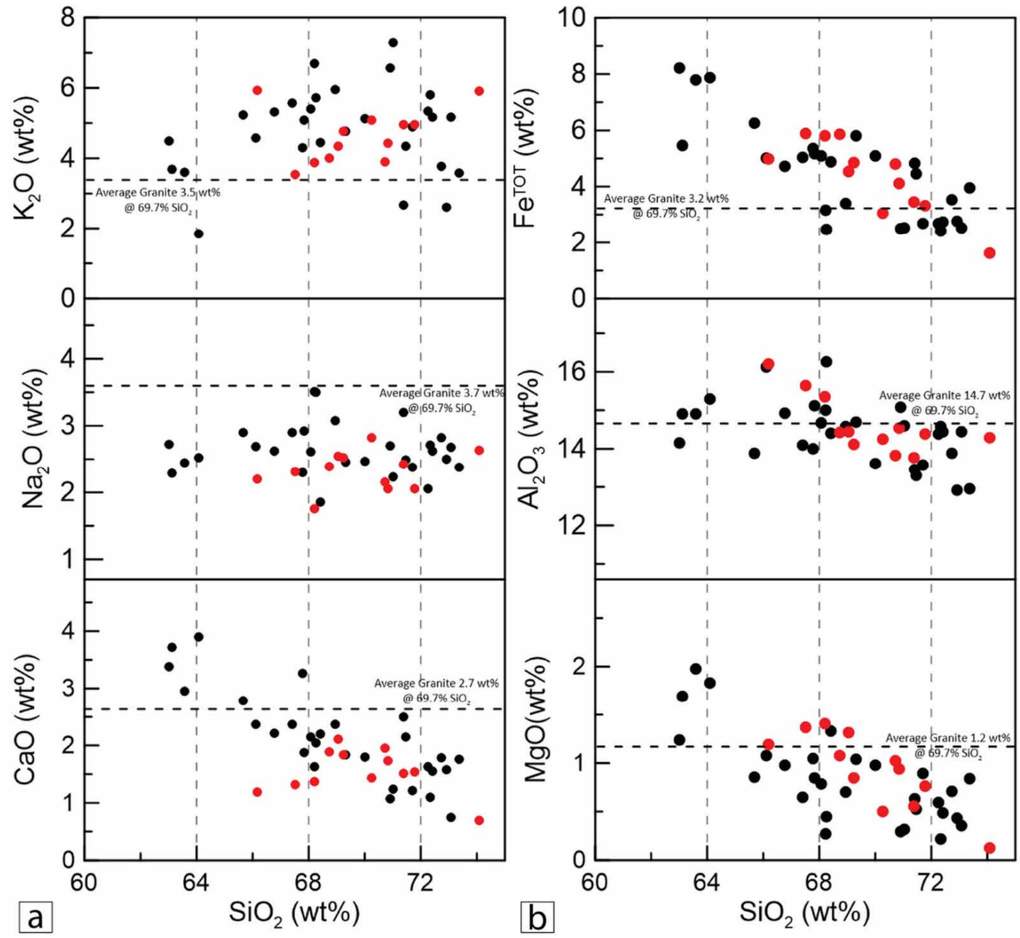

***Figure 8**. Harker bivariate major element diagram of the Twakputs Gneiss (red dots) and the Eendoorn Suite (black dots).*

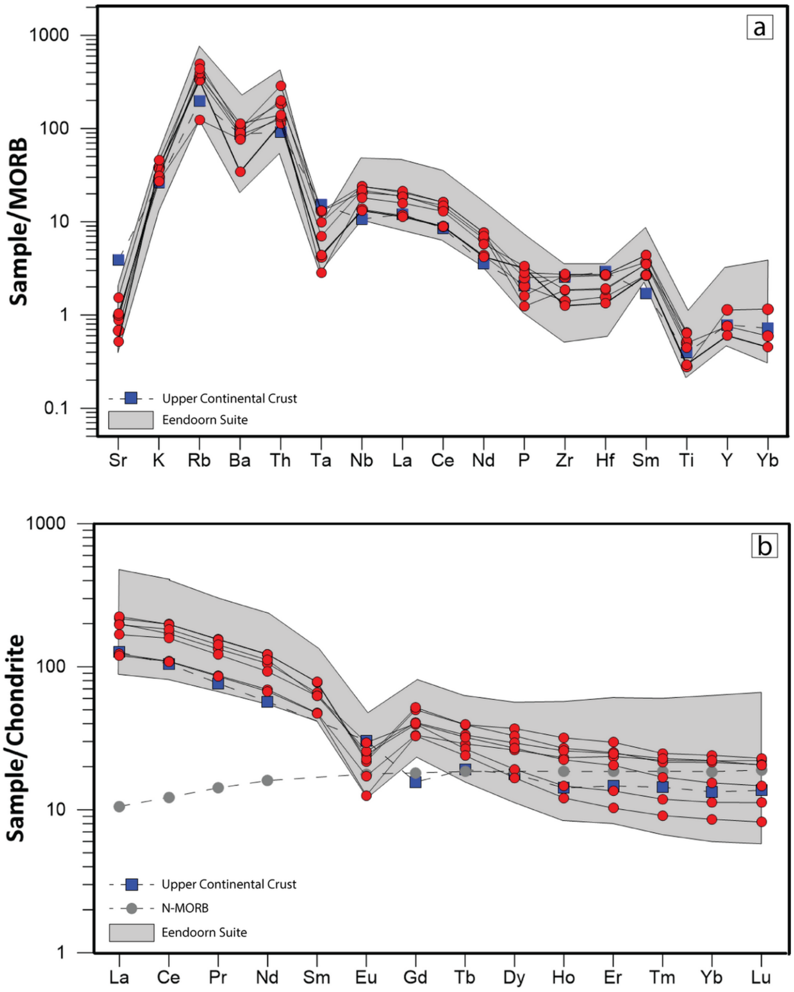

Figure 9. *(**a**) MORB-normalised (Sun and McDonough, 1989) trace element spider diagrams for the Eendoorn Suite (grey polygon) and Twakputs Gneiss (red dots) and (**b**) Chondrite-normalised (Nakamura, 1979) rare earth element patterns of the Eendoorn Suite and Twakputs Gneiss.*

Acknowledgements

This manuscript has benefitted from reviews by R. J. Thomas and D.H. Cornell.

References

Abraham, Y. and Macey, P.H., 2020. Ltihostratigraphy of the Mesoproterozoic Donkieboud Granodiorite (Komsberg Suite), South Africa and Namibia. South African Journal of Geology, 123, 421-430.

Beukes, G.J., 1973. 'n Geologiese ondersoek van die gebied suid van Warmbad, Suidwes-Afrika, met spesiale verwysing na die metamorf-magmatiese assosiasies van die Voorkambriese gesteentes. D.Sc. Thesis, University of the Orange Free State, Bloemfontein, 333p.

Bial, J., Büttner, S.H. and Frei, D., 2015. Formation and emplacement of two contrasting late- Mesoproterozoic magma types in the central Namaqua Metamorphic Complex (South Africa, Namibia): Evidence from geochemistry and geochronology, Lithos, 224-225, 272-294.

Bial, J., Büttner, S. and Appel, P., 2016. Timing and conditions of regional metamorphism and crustal shearing in the granulite facies basement of south Namibia: implications for the crustal evolution of the Namaqualand metamorphic basement in the Mesoproterozoic. J. Afr. Earth Sci. 123, 145-176.

Blignault, H.J., 1977. Structural-metamorphic imprint on part of the Namaqua mobile belt in South West Africa. Bulletin, Precambrian Research Unit, University of Cape Town, 23, 197p.

Cornell, D.H. and, Pettersson, Å., 2007. Ion probe zircon dating of metasediments from the Areachap and Kakamas Terranes, Namaqua-Natal Province and the stratigraphic integrity of the Areachap Group. S. Afr. J. Geol. 110, 575-584.

Cornell, D.H., Thomas, R.J., Moen, H.F.G., Reid, D.L., Moore, J.M. and Gibson, R.L., 2006. The Namaqua-Natal province. In: M.R. Johnson, C.R. Anhaeusser and R.J. Thomas (Editors), The Geology of South Africa (325-379). South Africa: Geological Society of South Africa and Council for Geoscience.

Cox, K.G., Bell, J.D. and Pankhurst, R.J., 1979. The Interpretation of Igneous Rocks. George, Allen and Unwin, London, 450p.

Du Plessis, G., 1979. 'n Metamorf-magmatiese studie van 'n deel van die Namakwalandse Metamorfe Kompleks langs die Oranjerivier Oos van Onseepkans. M.Sc. Thesis, University of the Orange Free State, Bloemfontein, 139p.

Du Plessis, G. 1986. 'n Petrochemiese ondersoek van die graniete van die Namakwalandse Metamorfe Kompleks langs die Oranjerivier Oos van Onseepkans. PhD. Thesis, University of the Orange Free State, Bloemfontein, 274p.

Groenewald, C.A. and Macey, P.H., 2020. Lithostratigraphy of the Mesoproterozoic Yas-Schuitdrift Batholith. South African Journal of Geology. 123, 431-440.

Le Maitre, R.W., 1989. A Classification of Igneous Rocks and Glossary of Terms. Recommendations of the IUGS Commission on the Systematics of Igneous Rocks. Oxford: Blackwell.

Macey, P.H., Abrahams, Y. and Miller, J.A., 2018. Lithostratigraphy of the Mesoproterozoic Stolzenfels Granite. South African Journal of Geology, 121, 217-226.

Macey, P.H., Minnaar, H.M., Miller, J.A., Lambert, C.W., Kisters, A.F.M., Diener, J.F.A., Thomas, R.J., Groenewald, C.A., Indongo, J.I., Angombe, M., Smith, H.P., Shifotoka, G., Le Roux, P. and Frei, D., 2015. The Precambrian geology of the Warmbad region, southern Namibia. An interim explanation to 1:50 000 geological map sheets of the 1:250 000 2818 Warmbad sheet. Geological Survey of Namibia and Council for Geoscience South Africa. 720pp, accompanied by twenty-four 1:50 000 geological maps.

Macey, P.H., Abrahams, Y. and Miller, J.A., 2018. Lithostratigraphy of the Mesoproterozoic Stolzenfels Enderbite (Komsberg Suite), South Africa and Namibia. South African Journal of Geology, 121, 217-226.

Moen, H.F.G., 2007. The geology of the Upington area: Explanation to sheet 2820 Upington (1:250 000), Geological Survey of South Africa/Council for Geoscience, 160p.

Moen H.F.G. and Toogood D.J., 2007. The geology of the Onseepkans area. Explanation of sheet 2818 Onseepkans, 1:250 000. Geological Survey of South Africa/Council for Geoscience, 101p.

Nordin, F., 2009. U-Pb dating, Lu-Hf isotopic analysis and geothermobarometry of rocks in the Grünau terrane and Richtersveld sub-province, Namaqua Sector, Southern Africa. Department of Earth Sciences, University of Gothenburg, Sweden.

Pearce, J.A., 1996. Sources and settings of granitic rocks. Episodes, 19, 120-125.

Pearce, J.A., Harris, N.B.W. and Tindle, A.G., 1984. Trace element discrimination diagrams for the tectonic interpretation of granitic rocks. Journal of Petrology, 25, 956-983.

Pettersson, Å., 2008. Mesoproterozoic crustal evolution in Southern Africa. PhD thesis, University of Gothenburg, Sweden. ISSN 1400-3813.

Streckeisen, A., 1974. Classification and nomenclature of plutonic rocks. Geologische Rundschau 63, 773-786.

Toogood, D.J., 1976. Structural and metamorphic evolution of a gneiss terrain in the Namaqua Belt near Onseepkans, South West Africa. Bulletin, Precambrian Research Unit, University of Cape Town, 19, 220p.

Editorial handling: R.J. Thomas.