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Correlations between U, Th Content and Metamorphic Grade in the Western Namaqualand Belt, South Africa, with Implications for Radioactive Heating of the Crust

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The digital image of airborne radiometric data across South Africa reveals that the largest anomaly, $\geq$100 nGy/h, is caused by the granulite-facies rocks of the Namaquan metamorphic complex, whereas most of the country is <60 nGy/h. This observation is consistent with geochemical data that show that the ~1900 ± 100 Ma greenschist-facies Richtersveld Terrane near Namibia (max. U = 3·4 ppm; Th = 20·1 ppm) and the adjacent, 1100 ± 100 Ma, amphibolite-facies Aggeneys/Steinkopf Terranes (max. U ≈ 10 ppm; Th ≈ 52 ppm) are the least enriched in U, Th and K. In contrast, the lower-T granulite-facies Okiep Terrane near Springbok hosts more enriched granites (max. U ≈ 17 ppm; Th ≈ 66 ppm) and noritic intrusions (max. U = 14 ppm; Th = 83 ppm). The most enriched rocks are found in the 1030 Ma higher-T granulite-facies core of the Namaquan belt and include quartzo-feldspathic gneisses (max. U = 46 ppm; Th = 90 ppm) and charnockites (max. U = 52 ppm; Th = 400 ppm). Our findings contradict the notion that granulite-facies terrains are characteristically depleted in U and Th. In this study we modeled the heat production in the core of the Namaquan complex, where the granulites have had a very unusual metamorphic history, and show that ultra-high-T (~1000°C, P ~ 10 kbar) metamorphic conditions could have been achieved by radiogenic heating without invoking external heat sources. However, monazite-rich veins of charnockite and patches of granulites mark the passage of CO_2-dominated melts and fluids derived from fractionated noritic intrusions.

KEY WORDS: *charnockite; granulite; Namaqualand; thorium; uranium; radioactive heating; metamorphism*

INTRODUCTION

Geochemical and field investigations at Vaalputs, Namaqualand (Fig. 1), revealed a granitic to charnockitic basement unusually enriched in U and Th (Hart & Andreoli, 1985; Andreoli *et al.*, 1986; Andreoli & Hart, 1990). These works suggested that many of the U- and Th-rich rocks of Namaqualand could not be explained as the fractionated products of typical granites (Robb, 1986; Raith, 1995). Instead, these anomalous lithologies seemed to require more complex geochemical processes, including the increase of uranium, thorium and the Rare Earth Elements (REEs) during high-grade metamorphism (Andreoli *et al.*, 1992, 1994; Read *et al.*, 2002). These observations were confirmed by a gamma-ray exposure (total count) map of South Africa (Fig. 1),

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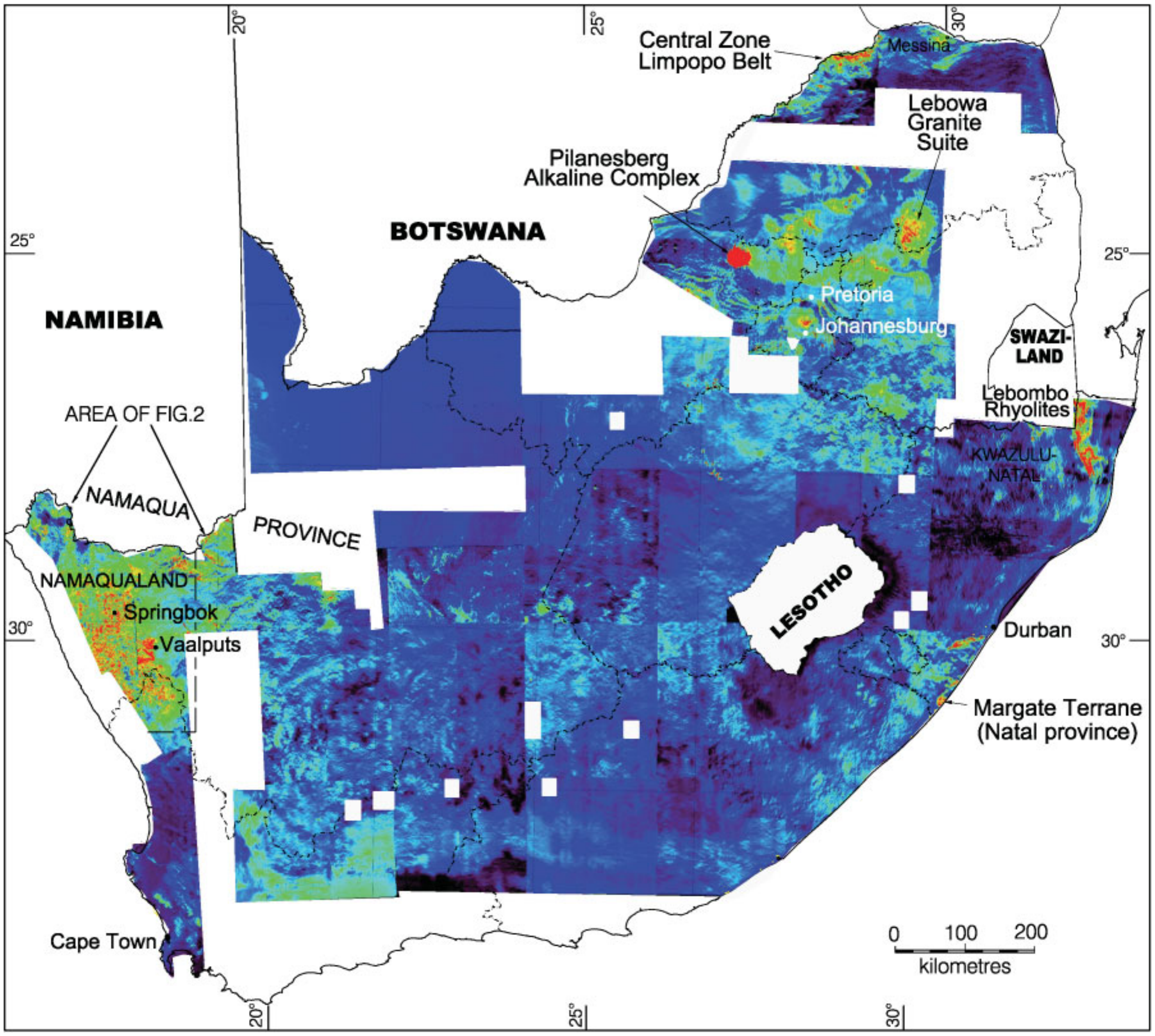

Fig. 1. Gamma-ray exposure rate (total count) map of South Africa semi-quantitatively expressed in nanoGray/hour (nGy/h). The map was produced by merging measurements taken over a time span of at least 30 years by means of different types of equipment and protocols. Despite limitations, such as the frequent discontinuities in the composite image and the absence of data over ~20% of the country, the resulting map demonstrates the heterogeneous character of the gamma-ray exposure rates from K, U and Th across South Africa. Blue to yellow green hues relate to exposure rates ≤60 nGy/h. The orange to red hues define areas, such as Namaqualand, in the ~2000–1000 Ma western sector of the Namaqua Province, with exposure rates ≥100 nGy/h. Other anomalies include (1) the ~1250 Ma Pilanesberg alkaline complex (U max. 141 ppm, Th max. 950 ppm; Lourie, 1986); (2) the ~2060 Ma Lebowa granite suite (U max. 30 ppm, Th max. 70 ppm; Walraven *et al.*, 1985); (3) the ~1030 Ma granulite-facies Margate Terrane, in the Natal sector of the Namaqua-Natal Belt (K_20 5·27 wt %, U 4·1 ppm, Th 32·9 ppm; Saunders, 1995); (4) the ~2600 Ma granulite-facies Central Zone of the Limpopo Belt (U max. ~90 ppm, Th max. ~500 ppm; Andreoli *et al.*, 2003) and (5) the ~180 Ma Lebombo rhyolite suite, Northern Kwa Zulu/Natal (U max. 3·95 ppm, Th max. ≤ 17·4 ppm; Betton *et al.*, 1984).

where Namaqualand defines a major radiometric anomaly with exposure rates ≥100 nGy/h, double the typical terrestrial values (≤60 nGy/h; UNSCEAR, 2000, p. 90). This study provides an account of the petrology, geochemistry and metamorphism of the rocks causing these anomalies, focusing on a very prominent anomaly near Vaalputs (Fig. 2). We also demonstrate that the most radioactive rocks include granitic orthogneisses, granulites and charnockites that experienced high- to ultrahigh-T metamorphism at ~1030 Ma (Mouri *et al.*, 2003; Raith *et al.*, 2003). Heat produced during radioactive decay in these rocks was largely responsible for their metamorphic conditions, especially where granulite and charnockite formation was promoted by the circulation of U–Th–REE-rich H_2O-deficient fluids and melts. We also report on a previously unrecognized suture represented by the Buffels River shear zone, separating older crust of the Okiep Terrane near Springbok from the younger higher-grade Vaalputs Terrane in the south.

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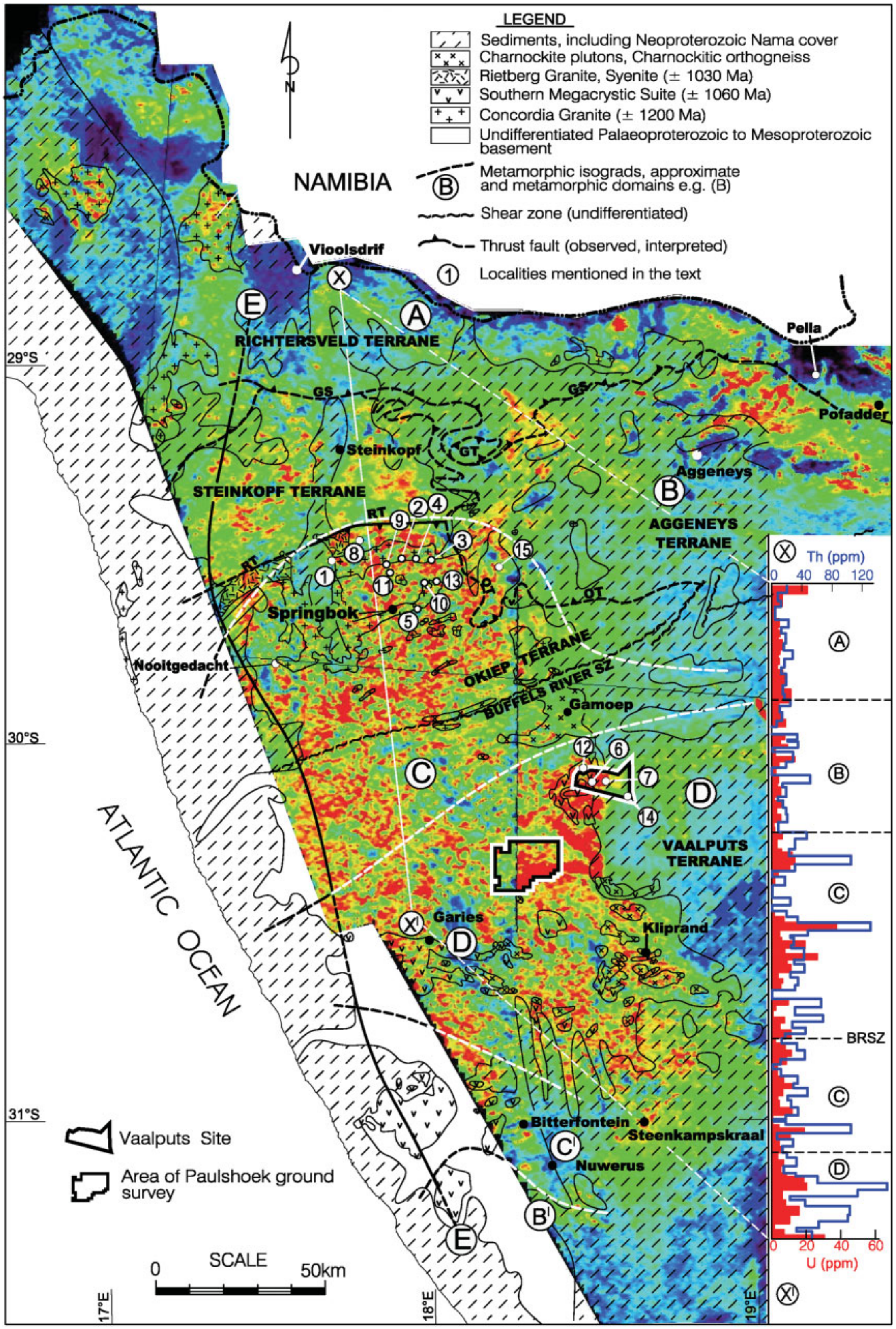

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GEOLOGICAL SETTING OF THE NAMAQUALAND γ ANOMALY

Current literature describes the western sector of the Namaquan metamorphic complex as the amalgamation of four fault/suture-bound crustal blocks yielding ages in the ~2000 to ~1000 Ma range (Fig. 2; Jacobs *et al.*, 1993; Thomas *et al.*, 1994; Praekelt *et al.*, 1997; Colliston & Schoch, 2003). These blocks are known as the Richtersveld, Steinkopf, Aggeneys and Okiep Terranes, with the latter extending south to Nuwerus and Steenkampskraal. The precise number and definition of these terranes is still debated, in part because the Steinkopf, Aggeneys and Okiep Terranes have also been considered as members of a much larger Mesoproterozoic Bushmanland Terrane (Frimmel, 2004). From N to S, the Richtersveld Terrane represents juvenile ~1900 ± 100 Ma crust comprising calc-alkaline, mainly andesitic lavas and younger intrusions. These rocks are suggestive of a mature island arc/back-arc environment above a northerly dipping subduction zone (Reid & Barton, 1983; Reid *et al.*, 1987*a*; Moore, 1989). In terms of metamorphism, the Richtersveld Terrane is in greenschist- to lower amphibolite-facies (Zone A, Fig. 2) and has largely escaped the ~1200 to ~800 Ma Namaquan Orogeny (Thomas *et al.*, 1994; Clifford *et al.*, 2004). To the south, the Steinkopf and Aggeneys Terranes are both largely in upper amphibolite-facies (Zone B, Fig. 2) and have significant granitic components coeval to the Richtersveld Terrane (~1900 ± 100 Ma; Reid *et al.*, 1997*a*). The same terranes also comprise orthogneisses and supracrustal sequences with ages of ~1700 to ~1300 Ma (Reid *et al.*, 1987*b*, 1997*a*, 1997*b*). In contrast, there are no rocks older than 1250 Ma in the Okiep (also spelled O'okiep) Terrane where most orthogneisses, granites and mafic intrusions yield emplacement ages of 1195 ± 15 Ma or 1040 ± 20 Ma (Thomas *et al.*, 1994; Clifford *et al.*, 1995, 2004; Robb *et al.*, 1999; Raith *et al.*, 2003). With the exception of some metasediments, quartzofeldspathic granulites and rocks of intermediate to mafic composition, ~80% of the crust exposed in the Okiep Terrane consists of granite gneisses and post-tectonic granites that are locally pyroxene-bearing (Jackson, 1979; Reid & Barton, 1983; Joubert, 1986; Reid *et al.*, 1987*b*; Moore, 1989; Moore *et al.*, 1990; Keyser, 1997). Among the latter intrusions, the most important lithologies are represented by the commonly plug-like bodies of the anorthositic to noritic Koperberg Suite, whose emplacement coincided with the so-called Klondikean Episode (1030 ± 10 Ma) of the Namaquan Orogeny, characterized by ductile D_3 folding and low-T granulite-facies metamorphism (Clifford *et al.*, 2004). The metamorphic patterns of the Okiep Terrane are complex but essentially represented by four E–W trending belts with either tectonic or gradational contacts and designated, from north to south, as Domains C, D, C′ and B′ in Fig. 2. Domains C and C′ are in the lower-T granulite-facies, whereas the core Domain D is in the upper-T granulite-facies. Finally, Domain B′ is situated at the southern edge of the metamorphic complex and is represented by gneisses and metapelites in upper amphibolite-facies (Waters & Whales, 1984; Waters, 1989).

It has been proposed that during the Neoproterozoic, between ~1000 and ~800 Ma, the metamorphic complex experienced isobaric cooling and by 570 Ma was eroded close to the current level of exposure, before burial beneath the sediments of the Vanrhynsdorp Group (southernmost subsidiary basin of the Nama basin; Waters, 1989; Gresse, 1995; Robb *et al.*, 1999). Closer to the Atlantic Ocean, the Namaquan gneisses and granulites and their Neoproterozoic cover were subsequently overprinted by the Pan-African orogenic cycle, between 545 ± 2 Ma and 507 ± 6 Ma (the staurolite zone west of the line marked E, Fig. 2; Moore & Reid, 1989; Frimmel, 2000).

SOURCES OF NATURAL RADIATION

Radiometric surveys and scintillometer-assisted field traverses were conducted over a number of radiometric highs situated near Springbok, Vaalputs and Steenkampskraal (Fig. 2). These areas are underlain by granulite-facies ortho- and paragneisses, often with above-average contents of U and Th (Albat, 1984; Robb, 1986; Andreoli *et al.*, 1986, 1994; Moore, 1989; Thomas *et al.*, 1996; Raith *et al.*, 2003). For the purpose of this paper the term 'above-average' will be applied to lithologies whose U and Th contents exceed the average values in the upper continental crust (U = 2·5 ppm; Th = 10·3 ppm; Wedepohl, 1995). Petrographic

Fig. 2. Gamma-ray exposure rate map of Namaqualand (total count; see details below and in Fig. 1) in relation to the main lithological and tectonic-units of the area. Isograds separate the metamorphic facies zones of the Namaqua belt: A, greenschist-facies; B and B′, amphibolite-facies; C and C′, low-T granulite-facies; D, high-T granulite-facies; E, eastern limit of the staurolite zone and Pan-African overprint (Waters & Whales, 1984; Moore & Reid, 1989; Waters, 1989). GT: Groothoek thrust; RT: Ratelpoort (Skelmfontein) thrust; OT: Oranjefontein thrust; Buffels River SZ: Buffels River shear zone (modified after Visser, 1995; Praekelt *et al.*, 1997; Colliston & Schoch, 2003). Inset to the right: N–S geochemical profile from Namibian border (X) to Garies (X′; after Muller & Smit, 1983). Numbers indicate localities mentioned in the text. For further explanations see the legend and text. The image was produced by merging data collected over several years using different types of equipment and protocols and should be regarded as semi-quantitative. The N–S lines at 18°15′E and 19°E represent the boundaries between survey blocks Springbok, Gamoep and Pofadder. Note that the termination of the radiometric anomaly at 18°15′E in the Paulshoek survey area was confirmed by a ground radiometric survey (Fig. 5; Thompson, 1988).

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characteristics, field relations and stratigraphic position were used to subdivide the anomalous rocks into four major groupings: (1) granite gneisses and granites, (2) charnockites, (3) the norite-anorthosite kindred and (4) granulites of supracrustal and undetermined origin.

Granite gneisses and granites

Foliated granites, granitic orthogneisses and late- to post-tectonic granites are extensively represented in all the metamorphic zones of Fig. 2, including the high-T granulite-facies Domain D. With the exception of the ~1033 Ma Rietberg Granite, most of these rocks have emplacement ages ranging from ~1200 Ma to ~1060 Ma, therefore predating metamorphism at ~1030 Ma (Thomas *et al.*, 1996; Ashwal *et al.*, 1997; Robb *et al.*, 1999; Clifford *et al.*, 2004). In view of this, most of the less deformed Namaquan age granitoids found in the Terranes of Fig. 2 represent relics whose fabrics have escaped obliteration during granulite-facies metamorphism (Andreoli *et al.*, 1986; Raith & Harley, 1998; Raith *et al.*, 2003; Frimmel, 2004). As presented in Table 1, the Okiep Terrane hosts granulite-facies granitic plutons with the highest concentrations of heat-producing elements (K, U and Th) when compared with other acid intrusions in the lower-grade Steinkopf, Aggeneys and Richtersveld Terranes (Figs. 2 and 3a). Foremost among these intrusions of the Okiep Terrane are the Rietberg and Kweekfontein granites, and the variably foliated Concordia, Bloukop and Jakkalshoek granite gneisses (Columns 1–3, 7 and 8 respectively, Table 1). In the northern Okiep Terrane, close to the margins of the Concordia granite (named after the village at Loc. 4, Fig. 2), there are also numerous late-stage smaller intrusions of U-rich leucogranite that may constitute potential resources of uranium (Nooitgedacht, Fig. 2; Column 2, Table 1; Jacob *et al.*, 1986; Robb, 1986). Further intrusions of highly radioactive granite were also reported near Garies (profile X–X′, Figs. 2 and 4; Jack, 1980). Detailed accounts of the petrology and mineralogy of these rocks with a view to their complex U phases are available for several areas, especially those near Springbok, Steenkampskraal and Bitterfontein (Robb & Schoch, 1985; Robb, 1986; Robb *et al.*, 1986; Andreoli *et al.*, 1994; Raith, 1995; Thomas *et al.*, 1996). Less enriched, but still with concentrations above upper crustal averages are the regionally extensive, Nababeep augen gneiss (Column 4, Table 1; Robb *et al.*, 1999) and the foliated granites, frequently megacrystic, found at Vaalputs and Steenkampskraal (Columns 5 and 6, Table 1, Fig. 3a; Andreoli *et al.*, 1986; Ashwal *et al.*, 1997; Knoper *et al.*, 2001). The granitic rocks of the Okiep Terrane, with the exception of the Bloukop granite (Column 7, Table 1), are enriched in Th relative to U compared with average upper continental crust (e.g. Th/U ≅ 4·2, Column 18, Table 1 and Fig. 3a). Our own observations indicate that the elevated contents of U and Th in the granitic rocks described above are hosted mainly by zircon and less commonly by monazite. In a detailed description of the accessory phases of the Concordia granite (Column 3, Table 1), Raith (1995) mentions primary (Ce-rich) monazite, zircon (including U- and Th-rich varieties) and secondary (Ce-) allanite. The zircons of this high-U granite are largely metamict and euhedral with high-U and low-U cores mantled by high-U rims (Clifford *et al.*, 2004). Similarly, the Kweekfontein granite (Column 2, Table 1) includes zircons with homogeneous, euhedral, high-U and low-U cores mantled by high-U rims (Clifford *et al.*, 2004). In the same rock type, quantitative fission track micro-mapping showed that U is hosted by both primary and secondary phases (Robb & Schoch, 1985). Primary phases include biotite, magnetite, zircon, allanite and monazite-like (Ca, LREE-) silico-phosphates such as cheralite and britholite. The secondary minerals include chlorite, epidote and sphene-like products.

As mentioned previously, the granitic rocks in the amphibolite-facies Aggeneys and Steinkopf Terranes tend to have lower U and Th contents. In particular, plutonic rocks with anomalous U and Th in the Aggeneys Terrane are represented by the ~1185 ± 15 Ma Achab orthogneiss and, in lesser measure, by the ~1180 ± 20 Ma Aroams and related gneisses (Columns 9–12, Table 1 and Fig. 3a; Reid *et al.*, 1997*a*; Bailie & Reid, 2004). Our data show that the Achab gneiss, and to a lesser extent the Aroams gneiss, are enriched in Th (range: 26–52 ppm) and have higher Th/U ratios (range: 5–7·5) when compared with the average upper crust (Columns 9–12 and A, Table 1 and Fig. 3a).

The Steinkopf Terrane shows weaker radiometric anomalies, consistent with the low-U content of this crustal segment (Columns 13–15, Table 1 and Figs. 3a and 4). These granitic rocks are also U-depleted relative to K, as suggested by the K/U ratios (>1·7E+4), which are higher than world averages (1·15E+4; Column 18, Table 1). In contrast, the Th content of the same granites (17–47 ppm) exceeds average upper crust values (~10·3 ppm) and is closer to that of the Aggeneys Terrane. In particular, the Th-rich Wyepoort intrusion (Column 14, Table 1 and Fig. 3a) may be correlated with the Concordia granite in the Okiep Terrane on the basis of geochemical affinities (Reid & Barton, 1983). Similarly, less-enriched gneisses with 23 ppm Th may be compared to the regionally extensive Nababeep augen gneisses of the Okiep Terrane (Columns 13 and 4, Table 1 and Fig. 3a; Barton, 1983; Reid & Barton, 1983; Joubert, 1986; Robb *et al.*, 1999). Data for the ~1800 Ma Gladkop orthogneisses (Column 15, Table 1; Robb *et al.*, 1999) show that apart from U, for which there are no reliable data, these rocks are mildly enriched in Th (~17 ppm)

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Table 1: K_2O, U, Th values of selected granites and granitic orthogneisses, western Namaquan metamorphic complex

Terrane	Okiep								Aggeneys				Steinkopf			Rich[1]	Namaquan complex	AUC
Column	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
K_2O %	5·7	5·77	5·83	5·88	5·36		5·01	4·89				5·2	3·9	5·7	4·19	4·45	3·9	3·45
		[0·43][2]	[1·21]	[1·30]	[0·87]							[0·3]	[0·4]	[0·2]	[0·8]	[0·6]	[0·2]	
Rb ppm	299	258	311	255			407	302	251	249	368	274	184	302	166	197	182	110
	[39]	[31·6]	[65]	[75]			[56]	[43]				[37]		[67]			[17]	
U ppm	4	155·2	16·7	3·3	7·18	4·48	26	15	3·85	4·58	9·97	5·2	1·5	<2	<2	3·43	5·5	2·5
		[117]	[13·1]	[2·2]	[5·6]	[2·41]			(2·1–8)[3]	(2·8–5·7)		[3·6]	[3·4]			[1·8]	[1·4]	
Th ppm	45	86·1	65·6	34·7	49·13	35·6	57	77·3	28·79	32·67	51·6	26·3	23	47	16·9	20·1	29	10·3
		[78]	[38·5]	[17]	[29·5]	[25·5]			(26–32)	(27–51)		[9·3]	[11]	[12]	[6]	[6]	[4]	
Nd ppm	137	60·8	55·98	50·7	53·94	33·48			47·8	37·3	48	45·8	440	49	44	39		25·9
	[88]	[31]	[30·9]	[11·42]	[25·7]	[20·9]			[1·2]	(29–46)	(45–50)	[8·2]	[2]	[15]				
K/Rb	158	186	157	191			102	135				157	169	156·7	210	188	178	260
K/UE4	1·18	0·03	0·29	1·48	0·62		0·16	0·27				0·83	2·15	>2·3	>1·7	1·08	0·59	1·15
Th/U	11·4	0·55	3·93	10·51	6·84	7·95	2·19	5·15	7·48	7·13	5·17	5·06	15·33	>23·5	>8·5	5·86	5·27	4·12

[1]Richtersveld terrane; [2][*n*]: standard deviation; [3](*n*): range. U, Th and Nd data in Columns 5, 6 and 9 were measured by Instrumental Neutron Activation Analysis (INAA; Erasmus *et al.*, 1977). K and Rb contents were determined by X-ray fluorescence (XRF). Column 1: Rietberg granite (Fig. 2; Reid & Barton, 1983; Robb, 1986); Column 2: leucogranite, Kweekfontein Suite (Nooitgedacht, Fig. 2; Robb & Schoch, 1985; Robb, 1986); Column 3: Concordia granite, Spektakel Suite (Nababeep Flat Mine, Hoogkraal East and Homeep East: Loc. 1–3: Fig. 2; Jones, 1987); Column 4: Nababeep augen gneiss, Little Namaqualand Suite (Carolusberg West, Loc. 5, Fig. 2; Jones, 1987); Column 5: pink and megacrystic, in places charnockitic, Stofkloof granite (Vaalputs: Loc. 6 and surroundings, Fig. 2; average of 34 samples from groups 1 to 4 [Gamoep, WFK, WAB, KAT samples excluded]; Hart & Andreoli, 1985; Andreoli *et al.*, 1986); Column 6: gray, medium to coarse grained granite gneiss (average of samples HLD1/663·5, -664·9, -777·1, -785·9, -831·7 (Loc. 7, Fig. 2); column 7: Bloukop granite (Bitterfontein, Fig. 2; Thomas *et al.*, 1996); Column 8: Jakkalshoek granite (Bitterfontein, Fig. 2; Thomas *et al.*, 1996); Column 9: megacrystic Achab gneiss (Aggeneys area, Fig. 2; Reid *et al.*, 1997*a*: NF samples); Column 10: banded Achab gneiss (Aggeneys area, Fig. 2; Reid *et al.*, 1997*a*: NF samples); Column 11: banded, migmatitic Achab orthogneiss (Aggeneys area, Fig. 2; Reid *et al.*, 1997*a*: GHA samples); Column 12: Aroams granitic orthogneiss (Aggeneys area, Fig. 2; Reid & Barton, 1983; Reid *et al.*, 1997*a*); Column 13: Konkyp augen gneiss (Steinkopf area, Fig. 2; Reid & Barton, 1983); Column 14: Wyepoort granite (Steinkopf area; Reid & Barton, 1983); Column 15: Gladkop suite (average of Steinkopf grey gneiss and Brandewynsbank grey gneiss; Steinkopf area , Reid & Barton, 1983); Column 16: Vioolsdrif Suite (Vioolsdrif area, Fig. 2; Reid & Barton, 1983); Column 17: average composition of Namaquan crust (Holland & Marais, 1983); Column 18: Average upper continental crust (Wedepohl, 1995).

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relative to upper crust values (Th = 10·3 ppm; Column 18, Table 1 and Fig. 3a). Finally, the ~1700 Ma tonalite and granite in the Richtersveld Terrane (Column 16, Table 1 and Fig. 2) are also enriched in K_2O (~4·5%), U (~3·4 ppm) and Th (20·1 ppm) and have a higher Th/U ratio (~5·9) compared with the average upper continental crust (Column 18, Table 1 and Fig. 3a). In summary, the data presented in Table 1 and in Fig. 3a are consistent with the airborne spectrometric and geochemical profiles (X–X′, Figs. 2 and 4; Muller & Smit, 1983) as all show a regional increase in radioactive elements from a low in Zone A to a maximum in Zone D.

Charnockites

Orthopyroxene-bearing rocks of igneous origin and granitic composition, by definition called charnockites (Streckeisen, 1976), have widespread distribution in the Okiep Terrane, especially in the Garies–Kliprand area south of the Buffels River shear zone (Fig. 2; Joubert, 1971; Jackson, 1979; Albat, 1983; Thomas *et al.*, 1996). The following three groups of charnockitic rocks were distinguished as described below.

Charnockite veins, dykes and megabreccia

The charnockite veins are a few centimeters wide and a few meters in length. They are slightly wavy, discontinuous and tend to occur in swarms. At their type locality (no. 13; Fig. 2), the veins develop along incipient and steeply dipping zones of warped older D_2 foliation (Raith & Harley, 1998) in the Nababeep augen gneiss host. As such, these warped zones are compatible with the ~1030 Ma D_3 deformation in the area (Raith & Harley, 1998; Robb *et al.*, 1999). The overall appearance of these orthopyroxene-bearing veins (dark green with oily luster) is reminiscent of the charnockite veins described at Kabbaldurga, southern India (Janardhan *et al.*, 1979; Friend, 1985; Newton, 1992). The Th- and U-enriched nature of the individual veins may be detected by using a spectrometer (e.g. Koperberg West: Loc. 5, Fig. 2; Saunders *et al.*, 1995), and narrowly spaced clusters/swarms of veins may produce radiometric anomalies recognizable even in airborne surveys (e.g. Steenkampskraal; Fig. 2; M. Knoper, personal communication). Under the microscope, the charnockite veins seem to display igneous-looking textures as many samples contain subhedral plagioclase, perthitic K-feldspar and chloritized orthopyroxene. Also conspicuous are nodular myrmeckitic intergrowths of quartz + plagioclase. Biotite and hornblende in most cases appear to be texturally secondary as they replace orthopyroxene. Accessories comprise zoned, euhedral zircon, apatite, opaque grains and occasional crystals (~0·7 mm across) of a yellow and metamict mineral phase surrounded by expansion cracks. Some allanite grains were also observed as inclusions in the center of subhedral plagioclase. When compared with their gneissic/granitic host rocks (Table 2) the charnockite veins tend to be markedly enriched in Th and the LREE, and more moderately in U, Zr, Nb, Ta, Y, Rb, K, and Cr. U, Th and the LREE show an increase even in texturally unmodified host gneiss, up to 18 cm from the veins (Columns 1–5, Table 2 and Fig. 3b), and inter-element ratios tend to display erratic variations.

The charnockite dykes differ from the veins in terms of lateral continuity, thickness and the large (up to ~8 cm long) size of the euhedral orthopyroxene. The radioactivity appears to be heterogeneously distributed, and at Kliphoogte (Loc. 9, Fig. 2) it varies from three times background, where the dyke is 2 m thick, to background values where its thickness has decreased to ~5 cm, over a distance of 200 m. The charnockite dykes have pegmatoid characteristics and are frequently developed in country rocks close to their contacts with the Koperberg Suite (Loc. 3, 5 and 9, also at Kliprand and Steenkampskraal, Fig. 2; Boshoff, 1951; Mostert, 1964; Andreoli *et al.*, 1994; Saunders *et al.*, 1995; Read *et al.*, 2002). The matrix of the dykes contains common accessory monazite, responsible for the measured radioactivity, while the groundmass in places consists of graphic intergrowths of quartz and alkali feldspar ± plagioclase. The analytical data reveal that Th, the LREE, and in lesser measure $\Sigma[CaO + MgO + FeO + Fe_2O_3]$ and Sr may be highly enriched in the dykes when compared with their host Concordia granite. However, the latter has higher K, Na, U, Rb and Zr content than the charnockite dyke (Columns 8–10, Table 2; Fig. 3b).

The megabreccia charnockite is similar to the previous rock type and constitutes, in intimate association with leucogranite, the matrix between blocks of structurally disrupted country rocks in small stocks that are minor though characteristic constituents of the Springbok area (Kisters, 1993; Gibson *et al.*, 1996). These bodies, also found near Steinkopf and Vaalputs (Table 4), tend to occur close to D_3 cusp-shaped anticlines known as steep structures, which are another distinctive feature of the Springbok area (Gibson *et al.*, 1996; Watkeys, 1996). Typically, the charnockite and the leucogranite grade into each other (Kisters, 1993). In rare cases, the megabreccia matrix is represented by other rock types, such as glimmerite, leucotonalite and enderbite, a dark bluish green rock with a vitreous luster that consists of quartz, plagioclase and minor orthopyroxene (Table 4; Streckeisen, 1976). The distribution of radioactive minerals in the megabreccia charnockite is poorly known.

Foliated charnockites

Foliated greenish-brown, orthopyroxene-bearing granulites of granitic composition are common in the domain

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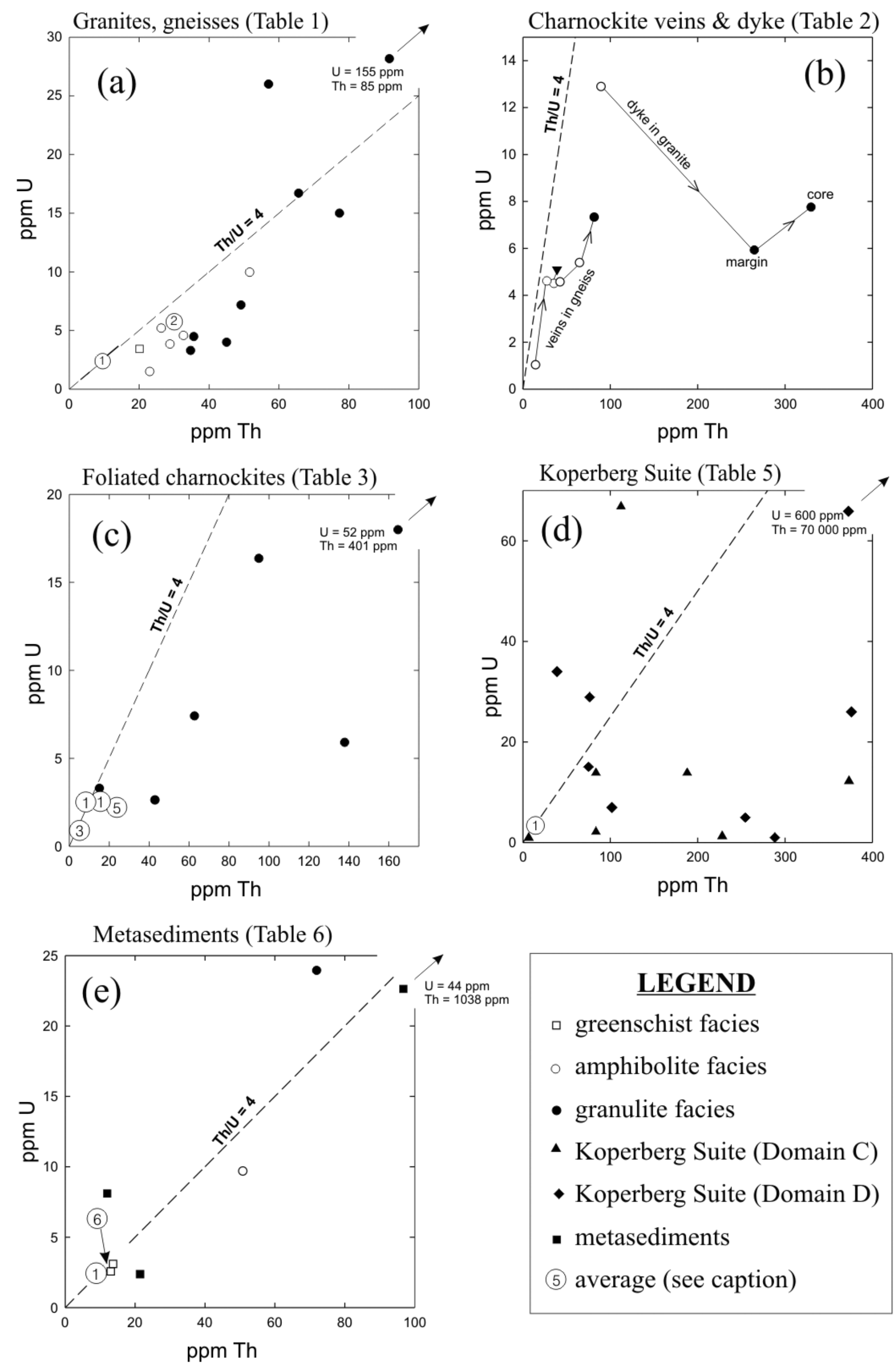

Fig. 3. (a–e). U–Th distributions in the principal rock suite of Domains A–D in of the western Namaquan metamorphic complex (Fig. 2). See Legend for the explanation of symbols, and Tables 1–3, 5 and 6 for sources of data). Plot for Table 6 includes pink quartz-feldspathic granulites of uncertain origin. Numbers in circles represent average compositions of: 1, average upper continental crust (Column 18, Table 1); 2, Namaquan crust (Column 17, Table 1); 3, lower continental crust (Column A, Table 3); 4, Archaean charnockites, Northern Marginal Zone, Limpopo Belt, Zimbabwe (Column C, Table 3); 5, Archaean granulites, Jequié, Bahia, Brazil (Column D, Table 3); and 6, North American Shale Composite (Column A, Table 6).

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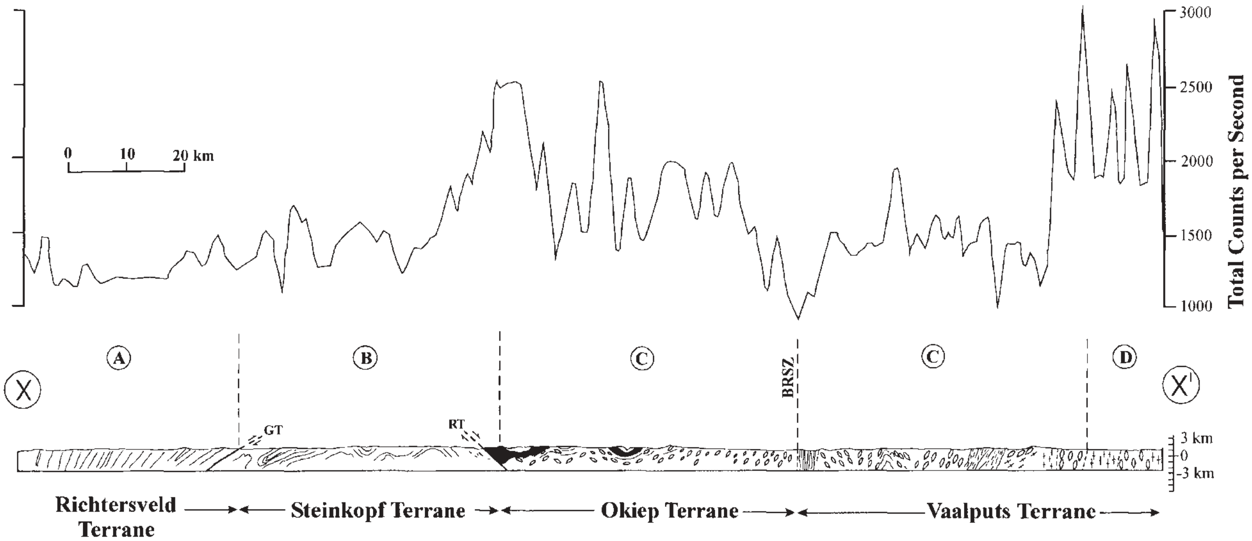

Fig. 4. Schematic geological cross section along the profile X–X′ of the inset in Fig. 2. Symbols indicate A, B, C and D, metamorphic domains as in Fig. 2; GT, Groothoek thrust; RT, Ratelpoort thrust; filled regions, Rietberg and Concordia granites; lenses, undifferentiated augen gneiss; crosses, Southern Megacrystic Suite; structural form lines, undifferentiated gneiss. Range of dips: Richtersveld Terrane, 30°–78°; Steinkopf Terrane, 30°–86°; Okiep Terrane, 5°–45°; Vaalputs Terrane, 20°–90° (modified after Blignault *et al.*, 1983; Marais *et al.*, 2001; and C. De Beer, personal communication). Radiometric profile, expressed as total count rate per second, was recorded at 100 m above ground level (after Muller & Smit, 1983).

of highest metamorphic grade and especially in the area between Paulshoek and Vaalputs, recognizable in Fig. 2 by the most prominent radiometric anomaly. A site easily accessible for the study of these rocks is located at the southwest boundary of the Vaalputs property (5 km SW of Loc. 6, Fig. 2), close to the edge of a $>150\,km^2$ sheet of the 1056 ± 10 Ma megacrystic Stofkloof granite (Andreoli *et al.*, 1986; Andreoli, 1996; Ashwal *et al.*, 1997). Mapping at this locality has identified a crescent-shaped exposure of Stofkloof granite gneiss, at least $6{\cdot}5\,km^2$ in area, that is more intensely sheared and whose colour grades inward from pink (lower gamma-ray counts; Column 5, Table 1) to greenish brown (higher gamma-ray counts; Column 3, Table 3) over a distance of ~500 m (Andreoli *et al.*, 1986). The highest radiometric reading (max. K, 4·5 wt %; eU, 13 ppm; eTh, 160 ppm) was measured at the core of this anomaly, next to the historical Stofkloof farmhouse, on a $\sim20\,m^2$ dyke-like exposure of massive charnockite with conspicuous megacrystic orthopyroxene. A detailed, three-dimensional view of the granite gneiss–charnockitic orthogneiss relationships was also gained from stratigraphic boreholes drilled to depths of up to 1000 m on the eastern side of the Vaalputs property. In particular, alternating bands ~50 cm to >1 m wide of light pinkish (less foliated) and dark green (more foliated, charnockitic) Stofkloof granite gneiss are common in boreholes HLD-1 and -3 from Vaalputs (Loc. 7 and 14, Fig. 2; Columns 5 and 6, Table 1, and Columns 1 and 3, Table 3; Fig. 3c; Andreoli, 1996). The elevated concentrations of U and Th in these charnockitic rocks are typically hosted by monazite, zircon and, in places, by a yellow and highly metamict mineral resembling allanite (sample NAM 524: Column 6, Table 3).

In general, the granite to charnockite transition in the area of the Vaalputs–Paulshoek anomaly is geochemically complex because in some places U, Th and the LREE remain unchanged, whereas in others they increase sharply from granite to charnockite (cf. Columns 5 and 6, Table 1 vs Columns 1–4, Table 3; Fig. 3c). The most spectacular increase was observed ~10 km N of Paulshoek, where a granulite-facies metamorphic overprint on augen gneisses is accompanied by a ~10-fold increase in U, Th (Figs 3c and 5; cf. Columns 5 vs 6, Table 3). A significant yet less striking increase in the LREE contrasts a decrease in Rb and in the K/U, Th/U and Rb/Sr ratios. The Th/U ratio of the foliated charnockites is variable, and in only a few samples does it approach the value of the average lower continental crust (Column A, Table 3). A large group of enriched samples, however, has a Th/U ratio that exceeds by a factor of 3, the value for average lower crust (Columns 2 and A, Table 3). The unusual geochemical characteristics of the high-Th charnockitic granulites are further emphasized by their inter-element ratios. In particular, their very low K/Rb and K/U, coupled with high Rb/Sr ratios (≤209, <0·7 E+4, and 3·3–4·96, respectively), indicate that these rocks are enriched in U (Th) and Rb relative to K when compared with average continental crust (Columns A–D, Table 3 and

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Table 2: Analyses of charnockite veins and host rocks

Column	1	2	3	4	5			6	7	8	9	10
Comment	Host	18 cm to vein	8 cm to vein	5 cm to vein	Vein	Min.	Max.	Host	Vein	Host	Dyke margin	Dyke core
SiO_2[1]	68·24			72·24	73·22			73·16	71·52	72·45	74·58	71·34
TiO_2	0·71			0·49	0·37			0·2	0·28	0·17	0·04	0·03
Al_2O_3	14·08			13·03	12·02			13·53	13·9	13·47	13·30	13·58
Fe_2O_3	1·55			0·61	0·47			0·82	1·21	0·72	0·07	0·2
FeO	2·05			2·1	2·54			1·03	0·87	0·9	1·65	2·06
MnO	0·04			0·05	0·07			0·02	0·03	0·04	0·4	0·06
MgO	1·13			0·42	0·32			0·25	0·5	0·18	0·35	0·77
CaO	2·12			1·72	1·6			0·98	1·69	1·24	1·91	2·56
Na_2O	2·03			2·08	1·91			2·48	3·03	2·92	2·4	2·81
K_2O	3·44	3·30	4·44	6·34	5·81	4·85	6·3	6·68	5·12	6·5	5·6	2·94
P_2O_5	0·25			0·15	0·13			0·11	0·14	0·08	.13	0·13
Total	97·14			99·23	97·5			99·26	98·29	98·67	100·43	97·12
Rb[2]	130			367	344			262	169	344	198	137
Sr	368			78	77			124	147	82	156	160
Y	34			57	45			25	41	56	23	27
U	1·04	4·59	4·6	5·36	7·36	5·9	9·36	4·4	5·1	12·9	5·79	7·88
Th	14·35	41·35	28·09	66	83·5	76·6	95·51	32·6	39	89·35	264	365
Zr	143	3331·9	259·9	176	255	175	303		127	133	36	26
Nb	11			21	15			6	13	14	2	6
Ta	1·12	2·23	1·56	2·08	2·15	1·37	3·75	0·53	0·82	0·93	0·31	0·39
La	51·87	77·05	70·28	87·44	77·95	63.	94	54·46	197·52	74·56	234·5	288
Ce	Nd	140·59	164·48	235·07	184·4	147·7	230·5	120·11	472·3	211·4	776	990
Nd	52·21	102·34	66·65	64·98	57·93	42·5	73·6	80·55	197·18	60·7	204	257
Sm	7·83	19·26	13·17	14·53	10·91	8·7	13·7	10·07	32·82	15·0	31	39
Eu	2·39	1·66	1·94	1·46	1·78	1·4	2·3	1·05	2·05	1·84	1·85	1·94
Tb	1·1	3·5	2·24	2·26	1·64	1·2	2·1	1·29	3·27	2·45	2·39	3·0
Yb	2·08	9·43	5·79	5·98	5·24	4·4	6·6	1·32	4·8	7·06	2·42	3·6
Lu	0·17	0·84	0·67	0·75	1·03	0·7	1·3	0·63	0·70	1·59	0·68	1·12
Cr	12·5	21·5	24	14·25	32·2	15·6	54	9·6	20	15	16·3	15·8
K/Rb	177	103	127	143	140·2			212	251	157	235	178
Rb/Sr	0·35			4·7	4·5			2·11	1·15	4·2	1·27	0·86
K/U E+4	2·21	0·6	0·8	0·98	0·67	0·5	0·9	1·09	0·84	0·41	0·56	0·31
Th/U	14	9	6·1	12·3	11·3	8·7	14	7·65	23·25	6·9	43·6	42·2

[1]Major oxides as wt %; [2]trace elements in ppm Analyses of REE, U, Th (and K) by INAA (see Table 1); other elements/oxides are by XRF. Columns 1: Nababeep gneiss, host to charnockite veins, sampled several m from veins (sample OCC 72 h; Hoits mine area, Loc. 13, Fig. 2; total includes 1·5 wt % H_2O and CO_2); Columns 2, 3 and 4: Nababeep gneiss sampled at 18 cm, 8 cm and 5 cm from vein, respectively (samples OOC 72/3, 72/2 and NAM 226 h; *ibid*); Column 5: average of four samples from adjacent charnockite veins (OCC72/1, OCC 72/C, NAM 226 v and NAM 577; *ibid*); Column 6: granite gneiss host, Steenkampskraal (Fig. 2; average of samples NAM 30, -31, 327 T); Column 7: average of two charnockite veins (average of samples NAM42, -327x; *ibid*, Fig. 2). Column 8: Concordia granite, host to charnockite dyke (sample OCC 4; Kliphoogte, Loc. 9, Fig. 2); Column 9: contact zone of pegmatitic to megacrystic charnockite dyke (Col. 8; average of samples OCC1, -1N, -1X); Column 10: pegmatitic core of charnockite dyke (see Columns 8 and 9; total includes 0·64 wt % $H_2O + CO_2$; average of samples OCC PEG, -5; Column 1).

Fig. 3c). This type of strong enrichment of incompatible trace elements relative to incompatible major elements is reminiscent of processes of extreme magmatic differentiation.

Charnockite plutons

Charnockitic plutons of irregular shape and size (up to $\sim$400 km^2) are important constituents of Zone D, and display a variable radiometric response (Fig. 2). The

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Table 3: K_2O, U, Th values of selected charnockites, high-T granulite Domain D

Column	1			2				3		4	5	6	7	A	B	C	D
N[1]	4	Min.	Max.	16	SD	Min.	Max.	5	SD	1	1	1	1				
K_2O %	5·66	5·5	5·8					6·07	0·5		6·14	5·98	5·09	1·58	3·45	2·43	5·07
Rb	400	320	480					296·8	55·9		311	238	177	41	110		183
Sr	88	75	101					90	13		51	48	264	352	316		
U	7·41	3·95	14·03	5·91	3·16	2·25	15·5	16·36	8·7	3·33	2·8	51·2	0·79	0·93	2·5	2·57	2·3
Th	62·67	25·6	82·5	137·87	137·52	23·3	555	94·89	10·4	15·1	42·45	400·5	4·96	6·6	10·5	13·84	23
Nd	54·93	40·7	63·3					64·59	7·9		84·17	333·5	68·86	28·1	25·9		148
K/Rb	117							170			164	209	239	320·5	260·45		230
Rb/Sr	4·5							3·3			6·1	4·96	0·67	0·116	0·348		
K/UE4	0·63							0·29			1·8	0·1	5·35	1·41	1·15	0·78	1·83
Th/U	8·46			23·3				5·48		4·53	15·1	7·82	6·28	7·1	4·12	5·3	10

[1]*N*: Number of analyses for each average; SD, standard deviation. All elements (apart from K_2O) as ppm; U, Th and Nd data in Columns 1–6 were measured by INAA (see Table 1). K, Rb and Sr contents were determined by XRF. Column 1: Foliated charnockite, charnockitic orthogneiss (average of samples HLD1-131·8, -477·7, -638, -785·9; Vaalputs site, Loc. 7, Fig. 2); Column 2: foliated charnockite and charnockitic granite gneiss, undifferentiated and reddened in places (average of samples HLD-3/34, -98, -99, 109, -185, -186, -187, -207, -208, -268, -269a, -269b, -275, -278, -279, -280; Vaalputs site, loc. 14, Fig. 2); Column 3: foliated charnockitic gneiss and granulite, undifferentiated (average of samples NAM 16; VAL 206a, -119, -160 and -163c; western side of Vaalputs Site, west–southwest of Loc. 6, Fig. 2); Column 4: charnockitic gneiss (NAM 1621; Paulshoek, Fig. 5); Column 5: 'Nababeep-type' Mesklip augen gneiss, in places charnockitic (NAM 523; Paulshoek, Fig. 5); Column 6: charnockitic granulite (NAM 524; Paulshoek, Fig. 5); Column 7: megacrystic Kliprand charnockite (NAM 28, Kliprand, Fig. 2); Column A: average lower continental crust (Wedepohl, 1995); Column B: average upper continental crust (Wedephol, 1995; Column C: average of Archaean charnockites and enderbites, Northern Marginal Zone-Limpopo Belt, Zimbabwe (Kramers *et al.*, 2001); Column D: average of Archaean granulites, Jequié, Bahia, Brazil (Sighinolfi *et al.*, 1981; Iyer *et al.*, 1984).

best known of these plutons, dated at 1063 ± 18 Ma, is exposed in a small quarry ~2 km southeast of Kliprand, where it appears undeformed, almost black in colour and megacrystic (Fig. 2; Albat, 1984; Frimmel, 2004; and Frimmel, personal communication, 2004). A sample from this locality has the lowest U and Th values among all the analyzed granites and charnockites (Column 7, Table 3), even though Fig. 2 reveals several small radiometric anomalies within the same pluton. The U and Th data are close to the averages for the lower continental crust (Columns 7 and A, Table 3). Instead, the K/Rb and Rb/Sr ratios demonstrate that Rb is enriched relative to K and Sr when compared with the average of lower and upper crust rocks, as observed in most other granite gneisses and charnockites listed in Tables 1–3.

Norite–Anorthosite kindred

A distinctive feature of the Springbok area is a swarm of ~1700 irregular and discontinuous dykes, plugs and sheets of generally mafic to ultramafic igneous rocks attributed to the ~1030 Ma (syn-D_3) Koperberg Suite. These rocks, locally mined for copper, crystallized under low-*T* granulite-facies conditions (Table 4; Clifford *et al.*, 1995, 2004; Gibson *et al.*, 1996; Robb *et al.*, 1999). Other swarms of Koperberg Suite bodies intrude the Vaalputs, Kliprand and Steenkampskraal areas (Fig. 2 and Table 4). Anorthosite, leuconorite, diorite, norite and hypersthenite represent the more common lithologies of this suite, which displays some affinities to massif-type anorthosite (Conradie & Schoch, 1988; Clifford *et al.*, 2005). The emplacement style of the Koperberg Suite is peculiar, as it exploited the dilatant sites caused by strain incompatibilities during the formation of D_3 steep structures, during peak granulite facies conditions (Table 4; Gibson *et al.*, 1996; Watkeys, 1996). Despite the fact that their bulk chemistry is typically mafic (biotite norite) to intermediate (diorite), the rocks of the Koperberg Suite may host significant amounts of U and Th (Table 5 and Fig. 3d). This is consistent with the observation that the $^{238}U/^{204}Pb$ (μ_2) values for typical mafic to intermediate rocks of the Koperberg Suite are in the 9·98–10·20 range, higher than the corresponding values (8·7–9·8) in anorthosite and related rocks from Norway and Canada (Clifford *et al.*, 1995). The fact that these U/Pb values are only slightly high, whereas the actual U concentrations are more than an order of magnitude above normal, indicates that the rocks are enriched in Pb as well as in U. REE, Th and U enrichments are also associated with the more differentiated/contaminated (?) members of the Koperberg suite, such as glimmerite and leucocratic

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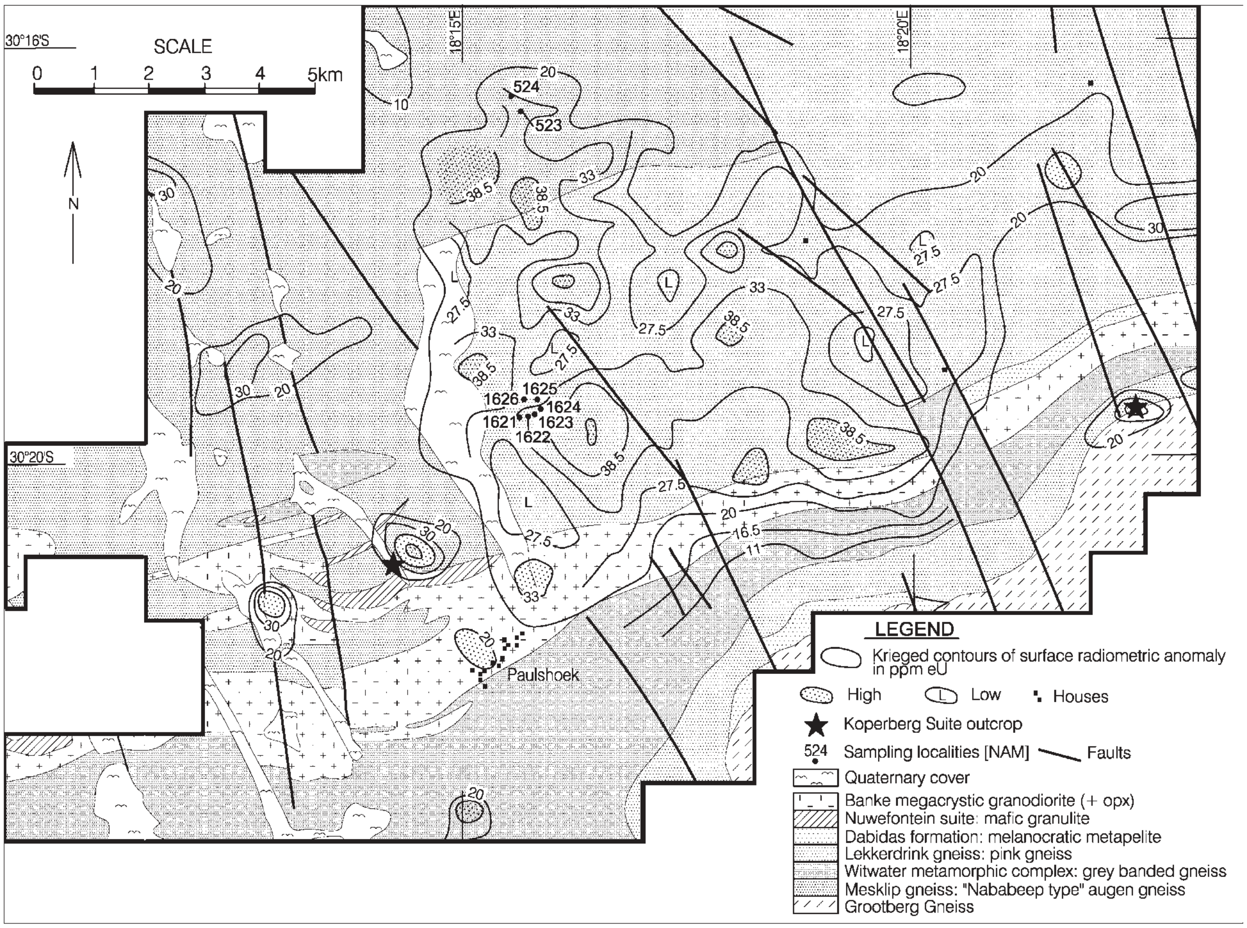

Fig. 5. Geological map of the Paulshoek area (Fig. 2; after Macey *et al*., 2006). Contours define the Paulshoek radiometric anomaly and represent ground-based spectrometric data (as eU or 'equivalent' U) processed by the geostatistical method of 'kriging' (Thompson, 1988). Sampling points referred to in the text are indicated. Additional symbols are explained in the legend.

tonalite (Table 4; Columns 8 and 9, Table 5; Andreoli *et al*., 1994; Read *et al*., 2002). Hyper-enrichment in U, Th, REE, Zr and F distinguishes the Koperberg Suite in the Steenkampskraal mine area, where $\sim 5 \times 10^4$ metric tons of monazite (chalcopyrite) concentrate with 0·7% F were extracted from a $\sim$400 m $\times$ $\sim$10 m dyke comprising leuconorite, enderbite, charnockite and leucocratic tonalite (Fig. 2 and Table 4; Andreoli *et al*., 1994; Read *et al*., 2002).

Detailed studies have indicated that in the Koperberg Suite the radioactivity is largely carried by monazite, zircon (max. U, 9729 ppm; max. Th, 1821 ppm), allanite, titanite and apatite (Andreoli *et al*., 1994; Clifford *et al*., 1995; Robb *et al*., 1999; Read *et al*., 2002). Geochemical oddities of the Koperberg Suite include a positive correlation between Cu mineralization and radioactive element anomalies (Andreoli *et al*., 1994; Saunders *et al*., 1995), enrichment in ^{18}O, Rb, F, Cl, negative ε_{Nd} values (Tables 4 and 5; Conradie & Schoch, 1988; Boer *et al*., 1993) and, near Springbok, a notable S deficiency (Boer *et al*., 1994).

Supracrustal granulites and rocks of undetermined origin

Dismembered relics of highly metamorphosed sedimentary and volcanic rocks are widespread within the metamorphic complex. Although these rock suites were not investigated in the same detail as the preceding igneous rocks and granitoids, some Th and/or U values are listed for completeness in Table 6 (Fig. 3e). These data demonstrate that even the supracrustal rocks may be enriched in U and/or Th relative to the average upper crust (Fig. 3e). Some of the highest values are encountered among calc-silicate granulites and iron formations (Columns 1, 2 and 7, Table 6), but these anomalous rocks are rare and unlikely to contribute to the regional patterns given in Fig. 2 (Moore, 1989; Moore & McStay, 1990). Instead, the metapelites in the

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Table 4: Occurrences and selected geochemical and isotopic data for Koperberg Suite rocks of the norite-anorthosite kindred

Distribution	Associated structures	Ore metals	Main lithologies	Age (Ma)	ε_{Nd} at 1030 Ma	T_{CHUR} (Ma)	T_{DM} (Ma)[1]	References/comments
Steinkopf Terrane								
Besondermaid	Hosted by megabreccia and shear zones	Cu, REE, U	Glimmerite	—	—	—	—	M. Andreoli, unpublished data
Okiep Terrane								
Springbok	Steep structures, Megabreccia	Cu	Anorthosite, leuconorite, norite, hypersthenite, diorite, tonalite, glimmerite	~1030 ± 10	Samples with Nd <60 ppm: −8·879 [0·95] Samples with Nd > 60 ppm −9·142 [1·351]	1719 ± 163 1823 ± 97	2018 ± 182 2148 ± 124	Clifford *et al.* (1995, 2004); Robb *et al.* (1999)
Vaalputs Terrane[2]								
Vaalputs	Steep structures, rare megabreccia	Fe, Ti, Zn	Anorthosite, leuconorite, norite, hypersthenite, diorite, tonalite, leucotonalite	1041·5 +2·5/−2·1 1018·7 ± 1·6	—	1058 1102	—	Andreoli *et al.* (1994); Ashwal *et al.* (1997)
Steenkampskraal	Steep structures	REE, Th, Cu	Leuconorite, anorthosite, diorite, tonalite, apatite hypersthenite	~1030 Ma	Quartz diorite: −1·79 (> −2·43 to < −1·05) Leucotonalite: −1·3 (> −2·4 to < −0·2) Monazite ore: −1·38 Charnockite: −0·165	1079 1160 1138 1048	1631 1644 1576 1617	Previously known as Roodewal Suite (Andreoli *et al.*, 1994; Knoper *et al.*, 2001; Read *et al.*, 2002)
Pauls se Vley	Contacts not exposed		U- and Th-enriched leuconorite	—	—	—	—	29° 50′′S−19° 19′E
Kliprand	Steep monoclinal fold	Ni, Cu	Diorite, norite, anorthosite, tonalite	—	—	—	—	Andreoli & Moore (1991); Hamman *et al.* (1996)
Garies	Cross-cutting dykes	REE, Th	Diorite, monazite−magnetite rock	—	—	—	—	M. Andreoli (unpublished data); J. Moore (personal communication)

[1]De Paolo *et al.* (1991).
[2]See the Discussion section for Vaalputs Terrane.

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Table 5: K_2O, U, Th and selected trace elements in selected intrusions of the Koperberg Suite

Locality	Springbok						Vaalputs		Steenkampskraal		Kliprand		
Column	1	2	3	4	5	6	7	8	9	10	11	12	13
Lithology	Biotite norite	Diorite	Monzo-diorite	Leucodiorite	Anorthosite	Magnetite rock	Diorite	Tonalite	Tonalite	Quartz anorthosite	Leucodiorite	Diorite	Diorite
K_2O %	3·56	2·68	3·6 (2·9–4·1)	2·58	0·98	0·1	5·4	1·14 (1·1–1·2)	2·56		5·12	3·29	2·77
ppm													
Rb	274	214	452	140	51		300		129	367	179	258	173
Sr	646	665		723	505	11			114	96	851	311	2211
U	14	14	12·29 (11·6–13·1)	1·4	2·2	67	28·86	6·9 (3–12)	34	26	1	5	15
Th	83	188	373 (303–439)	228	83	112	76·32	100·9 (69–156)	39	376	288	255	75
Zr	2530	1828	556	572	149	5212	200		104	633	20	4	717
Nd	1233	956	276	514	100·4	532	49·48	115 (66–200)			328	358	257
K/Rb	108	104	66	153	160		149		165		237·3	106·1	132·65
Rb/Sr	0·42	0·32		0·19	0·1				1·13	3·82	0·21	0·83	0·08
K/U E4	0·21	0·16	0·24	1·53	0·37	0·001	0·15	0·13	0·06		4·25	0·55	0·16
Th/U	5·93	13·43	30·3	163	37·7	1·67	2·64	14·25	1·14	55	288	33·2	5

Parentheses: see Table 1 for explanations. Determination of U, Th and Nd data in Columns 1–8 by INAA (see Table 1) and K, Rb, Sr, Zr contents by XRF. Columns 1: biotite norite with 1·5 wt % Cu (NAM 160; Bulletrap Prospect, Loc. 8, Fig. 2); Column 2: diorite with 0·6 wt % Cu (NAM 152; *ibid*); Column 3: biotite ± garnet monzodiorite (average of NAM 556, -557A, -557B; Kliphoogte, Loc. 9, Fig. 2); Column 4: leucodiorite with 0·18 wt % Cu (average of NAM 95, and -150; Bloustasie prospect, Loc. 10, Fig. 2); Column 5: anorthosite (NAM 99; *ibid*); Column 6: magnetite rock with 0·52 wt % Zr (sample NAM 86, Klondike prospect, Loc. 11, Fig. 2); Column 7: biotite diorite (VAL 209, Garing R. E., Vaalputs, Loc. 12, Fig. 2); Column 8: tonalite (average of NAM-464, -465, -466, -819; *ibid*); Column 9: sulphides-bearing tonalite with 0·7 wt % Cu, 0·4 wt % Zn and 1229 ppm Ta (NAM 1683, Steenkampskraal, Fig. 2; analyst: Dr W. Bernotat, Univ. Munster); Column 10: sulphides-bearing quartz anorthosite with 1·9 wt % Cu, 1 wt % Zn and 391 ppm Ta (NAM 1319A; *ibid*; analyst: Dr W. Bernotat, Univ. Munster); Column 11: leucodiorite (HKF05-06, Hondekloof, Kliprand, Fig. 2; Hamman *et al*., 1996); Column 12: diorite (HKF03-16, *ibid*; Hamman *et al*., 1996); Column 13: diorite with 5604 ppm Ba (HKF26-19, *ibid*, Hamman *et al*., 1996).

Okiep and Aggeneys Terranes and the volcanic rocks (porphyries) of the Richtersveld Terrane have wider distribution but are only moderately enriched in Th (and U) relative to shale and the average upper crust (Columns 6, 10 and 11, and A and B, Table 6; Fig. 3e). The U content and the K/U ratio of a metapelite from Vaalputs are close to the values of an average shale (Columns 4 and A, Table 6; Fig. 3e).

The origin of the quartzo-feldspathic pink gneisses, which are very common in the western metamorphic complex, is highly controversial, and this lithological "sack name" probably includes components of supracrustal (e.g. acid volcanics and/or arkosic sediments), intrusive and anatectic origins (Reid *et al*., 1997*a*; Macey *et al*., 2006). Consequently, the status of the pink U-rich (up to 46 ppm) quartzo-feldspathic Lekkerdrink gneiss in the area of Fig. 5 is also uncertain (Column 8, Table 6; Figs. 2, 3e and 5; Macey *et al*., 2006). Conversely, the pink gneisses of the lower grade Aggeneys Terrane (zone B, Fig. 2) are also less enriched in U and Th than those from the area shown in Fig. 5 (Columns 8 and 9, Table 6, and Fig. 3e). Even so, the pink gneisses of zone B are still highly enriched in K, U and Th (and in Th, U relative to K) when compared with the average upper continental crust (Columns 9 and B, Table 6). The main geochemical characteristic of these rocks, which helps to distinguish them from the majority of the granites listed in Table 1, is their low Th/U ratio (~3).

DISCUSSION

The K, U and Th values for rocks of the metamorphic complex are sufficient to explain the elevated airborne radiometric anomalies displayed in Fig. 2, especially those in the highest metamorphic grade zone D. We also note that U and Th are largely hosted by primary

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Table 6: K_2O, U, Th values of selected supracrustal suites and quartzo-feldspathic granulites of uncertain origin

Column	1	2	3	4	5	6	7	8	9	10	11	A	B
K_2O %	0·07	0·3	0·11	2·46	3·56 [1·30][1]	3·91 [1·44]	1·34 [2·5]		5·8	4·2 [0·61]	3·36 [1·5]	3·8	3·54
ppm													
U			8	2·35			43·7 [62·7]	24 (9–46)[2]	9·7 [4·9]	3·1 [0·4]	2·57 [1·85]	2·66	2·5
Th	61	118	12·5	21·54	18 [4]	17 [6]	1038 [1800]	72 (53–90)	50·8 [13]	13·7 [1·3]	13·03 [7·87]	12·3	10·3
Nd	1935	1871	271	48·77	38 [10]	27 [11]	48·77	48·77	27·9 [21·9]		32·9 [11·71]	27·4	26
K/U			0·01	0·87					0·49	1·11	1·08	1·19	1·15
Th/U			1·56	9·17			23·7	3	5·24	4·42	5·07	4·62	4·12

[1][*n*], [2](*n*): see Table 1. Data in Column 4: U, Th and Nd measured by INAA (Table 1) K_2O content was determined by XRF. Columns 1 and 2: allanite-bearing calc-silicate rocks with 2000 ppm REE oxides (Springbok; Loc. 15, Fig. 2; Moore & McStay, 1990); Column 3: calc-silicate rocks with La + Ce + Nd = 880 ppm (WW-6, WW-14, Paulshoek area, Fig. 5; Moore, 1989); Column 4: cordierite-spinel-sillimanite (metapelite) granulite of the Garies subgroup (NAM 817; Vaalputs site, Loc. 6, Fig. 2); Column 5: average of metapelitic rocks south of the Buffels River shear zone (Fig. 2; Moore, 1989, p. 151); Column 6: average of metapelitic rocks north of the Buffels River shear zone (Moore, 1989, p. 151); Column 7: average of iron formations: La + Ce + Nd = 5597 ppm, Cu max 2·1 wt %, Zn 0·19 wt % (samples SK-3, ER-3, ER-4; ROF-9, GA-BIF; Moore, 1989); Column 8: pink, quartzo-feldspathic and pre-tectonic Lekkerdrink gneiss (average of samples NAM 1622 to −1626; Paulshoek; Fig. 5); Column 9: pink quartzo−feldspathic gneiss (Hoogoor Suite, Aggeneys area, Fig. 2; Reid *et al.*, 1997*a*; K_2O is average of 46 analyses of related leucogneiss (Moore, 1989); Column 10: quartz-feldspar porphyry (Orange River Group, southern Namibia, Fig. 2; Jones, 1987); Column 11: calc-alkaline, andesite-dominated metavolcanics (Orange River Group; southern Namibia, Fig. 2; Reid *et al.*, 1987*a*). Column A: North American Shale Composite (Gromet *et al.*, 1984). Column B: average upper continental crust (Wedepohl, 1995).

igneous or high-grade metamorphic minerals, mainly zircon and monazite. This observation implies that their presence is not related to secondary, i.e. hydrothermal/low grade metamorphic processes, but rather to the emplacement history of their igneous host rocks or to metamorphic processes in the granulite-facies (Andreoli *et al.*, 1994). These observations are clearly inconsistent with the commonly held views that the granulites are generally depleted in heat-producing elements, especially uranium (Taylor & McLennan, 1985; Rollinson, 1993). Instead, Namaqualand displays the almost paradoxical phenomenon in which increases in metamorphism and the distribution of charnockites rich in U and Th are connected.

Terranes, crustal growth and radioactivity

Studies in the western metamorphic complex have shown that the lower grade terranes consist wholly (Richtersveld Terrane), or partly (Steinkopf Terranes), of a ∼1700–2000 Ma juvenile volcanic and plutonic crust that probably accumulated in a mature island arc (Reid, 1979; Reid & Barton, 1983; Moore, 1989; Thomas *et al.*, 1994). Some of the oldest rocks could also represent amalgamated fragments of a juvenile, ∼2000 Ma continent (Moore, 1989). The elevated High Field Strength Element (HFSE) and Large Ion Lithophile Element (LILE) contents of these older rocks were tentatively considered by Reid *et al.* (1987*a*, 1987*b*) to reflect magmas derived from source regions (e.g. the mantle wedge) modified by subduction zone metasomatism. However, the Steinkopf and Aggeneys Terranes differ from the largely pristine ∼2000–1700 Ma Richtersveld Terrane in that they were extensively intruded by granite and migmatized at ∼1100 ± 100 Ma. In addition, they host several stratigraphic sequences comprising metapelites, quartzite, calc-silicates and metavolcanics, which near Aggeneys yield ages of ∼1700 to ∼1300 Ma (Reid *et al.*, 1997*a*, 1997*b*). Reid *et al.* (1987*a*, 1987*b*, 1997*a*, 1997*b*) and Raith & Meisel (2001) considered the modest enrichment in U and Th of these mafic metavolcanics (amphibolites) to be primary, and compared the latter to continental (tholeiitic) basalts or arc magmas with a subduction-related fertile source component.

The *Okiep Terrane* north of the Buffels River shear zone (Figs 2 and 4) consists predominantly of syntectonic to post-tectonic granites intruded in a ∼30 Myr interval, between ∼1200 and ∼1170 Ma (Clifford *et al.*, 1995, 2004; Robb *et al.*, 1999). Of these, the 1192 ± 9 Ma syntectonic Nababeep augen gneiss is the least enriched in U and Th, whereas the late-syntectonic and massive to poorly foliated 1206 ± 16 Ma Concordia granite that intrudes the Nababeep gneiss is U-enriched and fractionated in the LILE (Raith, 1995; Clifford *et al.*, 2004). These intrusions were derived from the partial melting of two different crustal protoliths with similar, ∼1700 to ∼2000 Ma, Sm–Nd model ages. The protolith of the Nababeep gneiss is chemically undetermined, whereas that of the Concordia granite was either peraluminous granite, possibly contaminated by HFSE-enriched magma from a deep source (Raith, 1995; Clifford *et al.*, 1995, 2004), or juvenile crust of high-K (-HFSE?) andesitic composition (Duchesne *et al.*, 1999).

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The undeformed and high-U 1186 ± 15 Ma Kweekfontein granite may also represent an anatectic melt of a heterogeneous and enriched lower crustal source (Robb, 1986; Clifford *et al.*, 2004). Similarly, the moderately enriched 1035 ± 7 Ma Rietberg granite and syenite in the northwestern part of the Okiep Terrane (Figs 2 and 4; Clifford *et al.*, 2004) display a low $(^{87}Sr/^{86}Sr)_i \sim 0{\cdot}705$ that is consistent with a deep-seated source (Barton, 1983).

The origin of the large swarm of norite, anorthosite and related rocks of the Koperberg Suite remains controversial, but most authors view their enrichment in incompatible elements as the result of contamination of tholeiitic melts by ~1700–2100 Ma crust (Boer *et al.*, 1993; Brandriss & Cawthorn, 1996; van Zwieten *et al.*, 1996). McIver *et al.* (1983) hypothesized instead the contamination of REE-enriched alkaline mantle-derived magma by peraluminous, crustal anatectic melts; others derived the Koperberg Suite from the direct melting of a dry, dioritic lower crust (Clifford *et al.*, 1995, 2004; Duchesne *et al.*, 1999). Given that the above mechanisms are not normally observed to produce extreme enrichments in REE, U and Th, Conradie & Schoch (1988) and Andreoli *et al.* (1994) proposed that the Koperberg Suite was derived by melting a fertile mantle source. The prevailing view is that the high levels of U and Th (and Rb, REE, etc.) in the Okiep Terrane north of the Buffels River shear zone derive from the reworking of highly enriched repositories of sedimentary or igneous origin in the lower crust. Sm–Nd model ages for this crustal component in the Koperberg Suite falls in the ~1600–2000 Ma (T_{CHUR}) or ~1900–2200 Ma (T_{DM}) age ranges (Table 4; Clifford *et al.*, 1995, 2004). This time span is not too different from that of the ~1700–2000 Ma crustal remnants in the Aggeneys and Richtersveld Terranes (see above), and may define an enlarged northern province formed in a mature island arc, in which the mantle source was enriched by subduction zone metasomatism (cf. Heaman *et al.*, 2002).

South of the Buffels River Shear Zone, we note a significant change in the amplitude and width of the anomalies, a feature that may imply a major crustal discontinuity (Figs 2 and 4). Furthermore, detrital zircons from metasediments south of the shear zone yield crystallization ages that in nearly all cases do not exceed ~1300 Ma (Raith *et al.*, 2003). This age stands in sharp contrast with that of the metapelites and quartzites from the Springbok area, which were deposited between ~1300 and ~1650 Ma, and whose detrital zircons yield ~1900 Ma ages (Robb *et al.*, 1999). More specifically, detrital zircon grains in a supracrustal granulite from Bitterfontein were deposited in a basin with a *maximum* age of 1157 Ma (Raith *et al.*, 2003). This sedimentary episode, previously unrecognized, received detritus from a ~1250 ± 50 Ma source region (Raith *et al.*, 2003) and was of regional extent because igneous zircons in metavolcanic granulites from Vaalputs yield an age of 1137 ± 17 Ma (Ashwal *et al.*, 1997). Quartzite and calcic granofelses are also common in the Okiep and Aggeneys Terranes, but rare south of the shear zone, where metavolcanic rocks appear to be prevalent (Reid *et al.*, 1987*b*; Moore, 1989; Robb *et al.*, 1999; Macey *et al.*, 2006). In view of the above, we propose to use this high-angle (60° to vertical) and up to ~2 km wide shear zone as the southern limit of the Okiep Terrane (Fig. 4; Joubert, 1971, 1986; Blignault *et al.*, 1983). The crustal block south of the shear zone is referred instead as the Vaalputs Terrane (Fig. 2). In view of these features, the Buffels River shear zone may not be comparable to major, typically shallow, extensional detachment faults (Parrish, 1995 and references therein).

The Vaalputs Terrane

The timing of collision of the Okiep and Vaalputs Terranes is constrained by the age of the characteristic intrusions within the two regions. The coupling occurred *after* the regionally widespread emplacement of granites and orthogneisses in the Vaalputs Terrane between 1109 ± 17 Ma and 1065 ± 2 Ma (Ashwal *et al.*, 1997; Raith *et al.*, 2003; Frimmel, 2004), but *before* the common age of metamorphism and of emplacement of the Koperberg Suite at 1030 ± 10 Ma (Table 4; Clifford *et al.*, 1995, 2004; Ashwal *et al.*, 1997; Robb *et al.*, 1999). The existing data suggest that the Vaalputs Terrane is extensive because its distinctive megacrystic granites, here referred to as the Southern Megacrystic Suite (Fig. 2), correlate with similar rocks in southern Natal (Thomas *et al.*, 1996; Ashwal *et al.*, 1997; Knoper *et al.*, 2001; Grantham *et al.*, 2001; Eglington *et al.*, 2003; Frimmel, 2004).

In the Vaalputs Terrane, the temporal evolution of the crust and its U and Th inventories are less clearly defined than in the Okiep (and Aggeneys) region. However, samples from Bitterfontein and Vaalputs point to a crustal age significantly less than that near Springbok and Aggeneys, as only one detrital zircon core was found yielding a Pb–Pb age of ~1700 Ma, all others having crystallized between ~1300 and ~1170 Ma (Ashwal *et al.*, 1997; Raith *et al.*, 2003). Similarly, the Sm–Nd model ages of granites and Koperberg Suite rocks from Garies, Vaalputs and Steenkampskraal (T_{CHUR}: ~1040–1200 Ma, T_{DM}: ~1570–1710 Ma) are distinctly younger than comparable rocks near Springbok (Table 4; Clifford *et al.*, 1995, 2004; Ashwal *et al.*, 1997; Yuhara *et al.*, 2001). If the model proposed for the enriched crust of the Okiep Terrane is correct (i.e. subduction zone metasomatism → enriched volcanics → erosion → enriched sediments → deep burial and anatexis → enriched granite plutons and contamination

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of Koperberg Suite), then the same complex cycle might have been repeated in the Vaalputs Terrane. Here the process would have been responsible for the enriched and, locally, hyper-enriched character of the Southern Megacrystic and Koperberg Suites (Columns 5–8, Table 1; Table 4; Jack, 1980; Andreoli *et al.*, 1994; Reid *et al.*, 2002).

Causes of metamorphism

One school of thought holds that the high-grade metamorphic event ($T \sim 750$–$850°C$, $P \sim 4$–6 kbar) peaked at ~1030 Ma and was caused by magmatic underplating of the crust, with heat transfer mainly caused by magmatic convection (Waters, 1989; Robb *et al.*, 1999). A different model suggests that the granulite-facies metamorphism was caused by continental crustal doubling during the Kibaran event at ~1210 – 1180 Ma, which increased the thermal gradient to ~35°C/km ($T \sim 800$–$850°C$, $P \sim 6$–7 kbar; Clifford *et al.*, 1995, 2004; Raith & Harley, 1998). This episode was followed by slow isobaric cooling until ~1020–1040 Ma ($T \sim 580$–$660°C$, $P \sim 5{\cdot}8 \pm 0{\cdot}5$ kbar). The latter model requires a persistence of granulite-facies conditions for ~170 Myr after the Kibaran event but this has been questioned (Gibson *et al.*, 1996; Robb *et al.*, 1999).

Studies by Kramers *et al.* (2001) and Chamberlain & Sonder (1990) have shown that high-grade conditions may be attained by radioactive heating if the crust is sufficiently enriched in K, U and Th. Calculations based on the data provided in our work, including the more conservative values of K, U and Th by Holland & Marais (1983), show that the heat production in the Namaquan crust at ~1000 Ma considerably exceeded that of the Northern Marginal Zone of the Limpopo belt, where granulite facies conditions were reached at ~2600 Ma due to radioactive heating (Table 7; Kramers *et al.*, 2001). Additional constraints for heat production, expressed as $H(\tau)$, may be obtained from published heat flow data for the metamorphic complex (Table 7). The latter suggest that the Vaalputs charnockitic granulites with $H(\tau) > 10\,\mu W/m^3$ may not have significantly deep roots because the heat flow at Loc. 7 (Fig. 2) is 61 mW/m^2, equal to the average for the metamorphic complex (Table 7). On the other hand, localities of higher than average heat flow (i.e. $>70\ mW/m^2$) were identified by Jones (1987) in the lower grade western Kakamas Terrane (81 mW/m^2; Table 7) and in northern Lesotho, where they are thought to reflect the presence of more radioactive rocks of the Namaquan Belt at depth (Jones, 1992). The presence of K, Th and U anomalies at depth is also inferred by the occurrence of these elements in most of the intrusions derived from, or passing through, the lower crust between ~1200 and ~1020 Ma. Clearly, while these synmetamorphic (?) intrusions probably did not purge all the U and Th from their deep seated enriched sources, they effectively transported heat-producing elements upward through the crust. From the data of Table 7, and values quoted by Kramers *et al.* (2001), we may derive an indication of how fast the peak conditions were attained. In the Limpopo area, these authors reported that a rock unit with the density of granite ($\rho = 2{\cdot}7\ g/cm^3$) and that is entirely insulated (a condition approachable with increasing depth in the crust) will heat up at a rate of 9·5°C/Myr, if $H(\tau)$ is $1\,\mu w/m^3$. Conditions approaching full thermal insulation and granitic bulk density may also characterize Domain D of Namaqualand (Fig. 2) where, however, the heat production is five times that of the Limpopo (i.e. $H(\tau) = 5\,\mu w/m^3$; Table 7). Consequently, the highest-T domain of Namaqualand could have experienced a heating rate approaching ~45–50°C/Myr, capable of increasing its temperature from medium amphibolite facies conditions (~600°C) to ~1000°C (Mouri *et al.*, 2003) in just 8 Myr, within the short time interval (<10 Myr at ~1030 Ma) during which the Koperberg Suite was intruded throughout the western Namaquan metamorphic complex (Clifford *et al.*, 2004).

Based on the available data, we propose here a model whereby the radioelement-rich ≥1200 Ma Okiep Terrane collided with the even more enriched Vaalputs Terrane at ~1040 Ma. The resulting tectonic imbrication transported the radioactive metasediments, metavolcanics and megacrystic granite plutons of the latter to lower crustal depths, where they contributed to the anomalous heating of the newly established Namaquan belt. According to our model, the rare corundum–quartz assemblages may record a transient, early high-P, ultra-high-T episode of the Vaalputs Terrane that was followed by ductile deformation, orogenic collapse (lateral spreading) and subsequent isobaric cooling (Waters, 1988; Mouri *et al.*, 2003).

Charnockite-forming processes

The charnockite veins of the western Namaquan metamorphic complex bear a striking similarity to the patchy and vein-like charnockites found in southern India and in Sri Lanka, which a number of authors (Janardhan *et al.*, 1979; Friend, 1985; Harley, 1989; Newton, 1992) have related to the circulation of CO_2-rich fluids and/or melts. On this basis and from our data, we propose that the Namaquan charnockite veins formed when water-deficient U-Th-REE-CO_2-rich melts or fluids started to propagate along dilatation structures within gneisses close to their solidus temperatures at the time of deformation (cf. Gibson *et al.*, 1996). In these veins, the replacement of orthopyroxene by hornblende and biotite suggests a late increase in aH_2O as a result of the local dehydration of their host rocks.

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Table 7: Heat flow and heat production [H(τ)] for the Namaquan metamorphic complex at 1050 Ma compared to average crust and other high-grade belts

Terrane/tectonic domain	K %	U ppm	Th ppm	mW/m²	[1]$H(\tau) = \mu W/m^3$	Comments
Aggeneys Terrane[2]	3·00	3·4	14·8	63 (55–74)[3]	2·66	Upper amphibolite-facies (Jones, 1987; Waters, 1988)
Kakamas Terrane (W sector)	5·2	7·7 [6·9]	20·1 [7]	81	4·783	Upper amphibolite-facies, charnockite plutons (*N* = 1; Jones, 1987)
OkiepTerrane (Springbok)	4·9 [1·1]	3·3 [2·2]	34·7 [17]	59 (59–60)	4·388	Lower granulite-facies; Nababeep gneiss (Column 4, Table 1; Jones, 1987)
OkiepTerrane (Springbok)	4·8 [1]	16·7 [13]	65·5 [38]	67 (61–76)	10·894	Lower granulite-facies; Concordia granite (Column 3, Table 1; Jones, 1987)
Vaalputs Terrane (Vaalputs)	3·9 (2·0–4·8)	5·06 (2·1–14)	47·6 (10–83)	61	5·725	Upper granulite-facies; borehole HLD-1, eastern Vaalputs site[5] (Jones, 1988; Waters, 1988)
Vaalputs Terrane (Vaalputs)	5	16·4	94·9	—	12·965	Upper granulite-facies; charnockitic orthogneiss, Vaalputs (Column 3, Table 4)
Vaalputs Terrane (Paulshoek)	5	51·2	400·5	—	46·295	Upper granulite-facies; charnockitic granulite (NAM 524; Fig. 5; Column 5, Table 4)
Grand average, Namaquan Province	3·238	5·5	29	61 (39–81)	4·402	Namaquan metamorphic complex and Richtersveld Terrane (*N* = 890; Holland & Marais, 1983)
Average upper continental crust	2·86	2·5	10·3		2·022	Wedepohl (1995)
Acadian belt—Appalachians, USA	3	7·7	10·9	(40–90)	3·264[6]	Upper amphibolite-facies, migmatites (Chamberlain & Sonder, 1990)
Limpopo Belt—Southern Zimbabwe	2·2	2·6	13·8	(49–78)	3·26[7]	Granulite-facies, Northern Marginal Zone (Kramers *et al.*, 2001)

[1]Heat production calculated after formula [1] quoted by Kramers *et al.* (2001) and heat production constants by Rybach (1976). *N*, number of boreholes/samples.
[2]Includes boreholes in undifferentiated terranes east of the Aggeneys Terrane (Praekelt *et al.*, 1997).
[3]See Table 1 for explanations of brackets;
[4]*P-T*: conditions for Vaalputs as proposed by Mouri *et al.* (2003).
[5]Loc. 7, Fig. 2; K, U, Th data are weighted averages of main lithologies in 1000 m borehole (thicknesses in parentheses): Column 1, Table 4 (~600 m), Column 6, Table 1 (~100 m) and Column 4, Table 5 (~300 m; Andreoli, 1996).
[6]Heat production calculated at T = 400 Ma.
[7]Heat production calculated at T = 2600 Ma.

Geochemical data in Table 2 (Fig. 3b) also indicate that trace amounts of U and Th infiltrated the host rocks by more than 10–20 cm from the veins (Columns 1–7, Table 2 and Fig. 3b; Andreoli *et al.*, 1994). Where more infiltrating melt was available and the fractures/shear zones linked and expanded, especially in the proximity of D_3 steep structures, the charnockite veins coalesced, forming pegmatitic dykes and larger bodies of megabreccia charnockite mapped by Kisters (1993).

The charnockitic granulites of Namaqualand are different, typically foliated and can be traced to a less deformed, lighter coloured precursor, an observation indicative of metamorphic re-crystallization of a granitic/gneissic protolith under prograde granulite-facies conditions (Jackson, 1979; Andreoli *et al.*, 1986; Robb *et al.*, 1999; Hiroi *et al.*, 2001; Mouri *et al.*, 2003; Clifford *et al.*, 2004). Evidence presented by Waters & Whales (1984) and Baars (1990) militates against a transition from gneiss to granulite through a regional influx of metasomatizing H_2O-deficient fluids; instead it supports dehydration as a consequence of partial melting. However, in the area of the Vaalputs–Paulshoek anomaly (Figs 2 and 5), this prograde metamorphism from gneiss to granulite involves an increase in Th, U and REE (Tables 1 and 3, and Fig. 3a and c). It is, therefore, likely that the same anomaly, or at least a significant part of it, maps out areas where prograde metamorphism was accompanied by an

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heterogeneous introduction of REE–Th–U–CO_2-rich fluids akin to those responsible for the veins. The propagation of these fluids could have been structurally controlled because the U anomaly, which cuts across the boundaries of several stratigraphic units, is bound by two sets of NNW-trending faults (Fig. 5).

In contrast to the charnockites described above, the less enriched charnockite plutons, such as the Klein Lieslap intrusion near Kliprand, probably represent granitic magmas generated by very high temperature partial melting of lower crustal rocks under water-deficient conditions (Column 7, Table 3; Fig. 3c; cf. Frost & Frost, 1987).

U-, Th-, CO_2-enriched fluids: possible sources and constraints

Following a considerable period of controversy, it is now largely accepted that the charnockite veins of southern India and Sri Lanka were initiated by CO_2-rich fluids released from mafic intrusions with high contents of volatiles (Janardhan *et al.*, 1979; Friend, 1985; Frost & Frost, 1987; Harley, 1989; Newton, 1992). Given the mutual similarities, it is likely that the same interpretation may apply to the charnockite veins of the western Namaquan metamorphic province for of the following reasons:

(1) The high U- and Th-charnockite veins, dykes, megabreccia charnockites and charnockitic granulites occur invariably in areas also intruded by the mafic Koperberg Suite. Pegmatitic charnockites, in particular, are often clustered around, above or on the extension of Koperberg Suite intrusions (Boshoff, 1951; Andreoli *et al.*, 1986, 1992, 1994; Saunders *et al.*, 1995; Read *et al.*, 2002).

(2) The propagation of the charnockite-forming fluids/melts exploited the same sets of steeply dipping ductile shears (D_3 structures) followed by the Koperberg Suite (Kisters, 1993; Gibson *et al.*, 1996; Watkeys, 1996).

(3) Near Springbok, megabreccia granite gradational to charnockite has a (SHRIMP) age of 1018 $\pm$ 20 Ma, within error of both granulite facies metamorphism ($\sim$1040–1020 Ma) and Koperberg Suite intrusion (1029 $\pm$ 10 and 1037 $\pm$ 8 Ma, respectively; Clifford *et al.*, 1995; 2004; Ashwal *et al.*, 1997; Robb *et al.*, 1999).

(4) The charnockite veins/dykes display REE patterns similar to those of the Koperberg Suite (Fig. 6) and tend to have a higher content of U, Th and refractory elements (e.g. Cr, Ca, Mg and Fe; Table 2, Columns 8–10) than their host granitoids. These features are more likely to relate the charnockite-forming fluids/melts to the spatially associated Koperberg Suite than to hypothetical, unexposed charnockitic plutons.

In the model preferred (cf. Frost & Frost, 1987), the mafic Koperberg Suite magma ponded near the base of the crust and partially assimilated it, before final emplacement at ca. 1030 Ma as plugs and dykes variably enriched in the LILE, HFSE and CO_2. Upon crystallization under granulite facies conditions, residual melts/fluids were injected into their host rocks forming dykes/veins of charnockite or patches of granulites enriched in radioactive elements and the REE (Andreoli *et al.*, 1994), as discussed earlier. The reason why the Koperberg Suite is enriched in CO_2, F, HFSE and LILE, including U and Th, remains speculative. Hypothetically, it could have been acquired through the assimilation of highly metamorphosed carbonatite, an igneous rock enriched in U, Th and the REE (Burke *et al.*, 2003), or of carbonate-bearing granulites enriched by subduction zone metasomatism. Alternatively, the Koperberg Suite could have originated from the partial melting of a moderately enriched upper mantle source (cf. Rollinson, 1993).

CONCLUSIONS

Our study of Namaqualand suggests that the individual terranes, separated from each other by major tectonic boundaries, consist of rocks with distinctly different metamorphic assemblages and distinctly different concentrations of U and Th. Thus an increase of the radioelements broadly mirrors an increase in metamorphic grade. We propose that the Buffels River shear zone splits the Okiep Terrane into a U- and Th-enriched (lower-T granulite-facies) Okiep Terrane *sensu stricto* in the north from the Vaalputs Terrane in the south, where even more enriched rocks are found in upper-T granulite-facies.

Heat production data calculated back in time to the Mesoproterozoic strongly support a model where the bulk K, U, Th contents of the Namaqualand crust are primarily responsible for high geothermal gradients, and high-grade metamorphism, at $\sim$1030 Ma, across the whole of the western metamorphic complex crust. Therefore, the metamorphic grade reached by each terrane at any particular time, mainly at $\sim$1200 Ma and at $\sim$1030 Ma, is then related to two main factors: depth of burial and its thermal productivity. Clearly, our suggestion could support the model of post-1030 Ma isobaric cooling for the western metamorphic complex, as proposed by Waters (1989). It could also explain how elevated temperatures ($T = 850$–$600°C$) were maintained in the Okiep Terrane over the $\sim$200 Myr span of the Namaquan Orogeny, between $\sim$1200 Ma and its end at $\sim$1000 Ma, as proposed by Clifford *et al.* (2004). However, the reason for the exceptional U- and Th-enrichment of the Namaquan crust remains speculative. Whatever the cause of this enrichment, our results may

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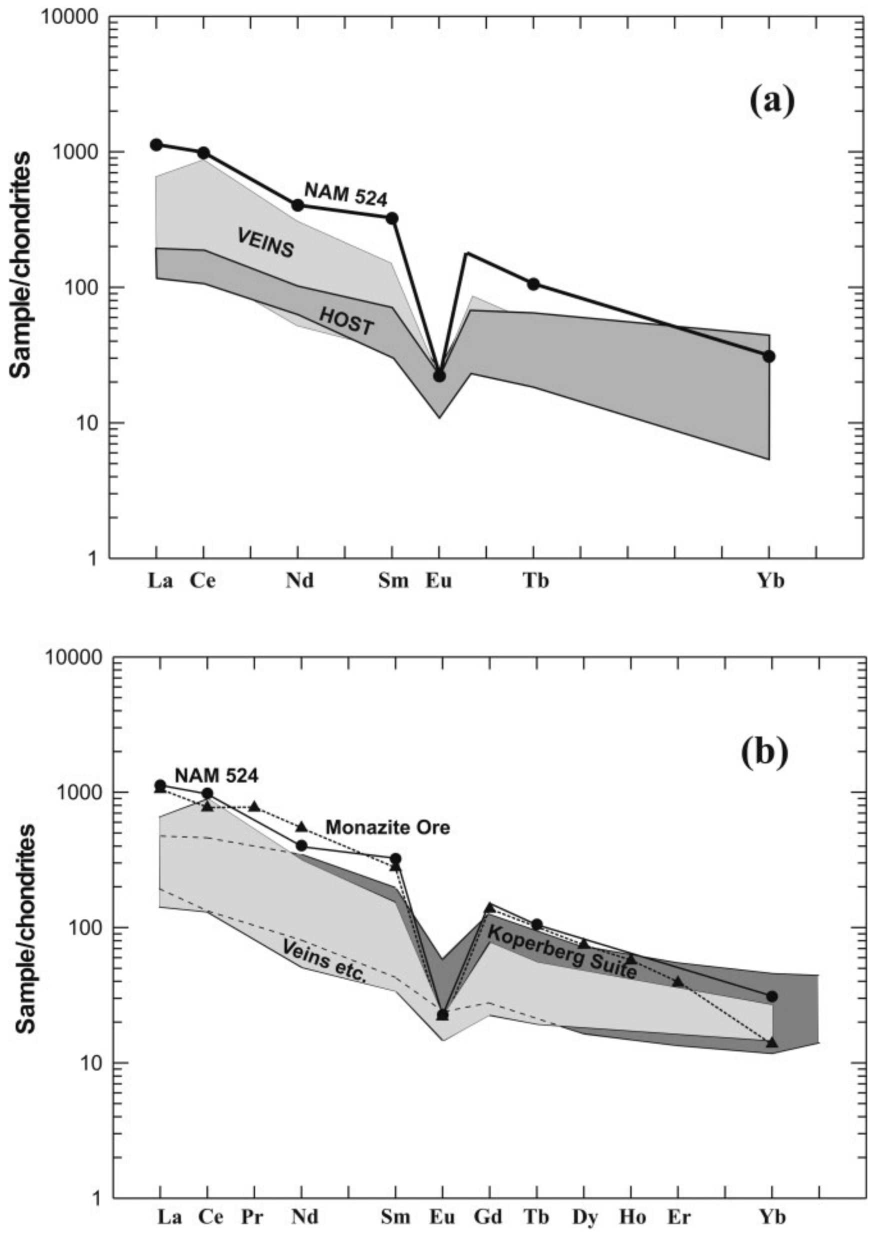

Fig. 6. Field of chondrite-normalized REE plots for charnockite veins (light gray) and a foliated charnockitic granulite (closed circles, NAM 524) in relation to fields of (a) gneissic host rocks and (b) noritic rocks of the Koperberg Suite (after Conradie & Schoch, 1988); closed triangles, monazite ore from Steenkampskraal with values divided by 100 (sample NAM 46 c, Andreoli *et al.*, 1994). Chondrite abundances from Anders & Grevesse (1989).

apply to other high-U and -Th belts, especially in southern Africa, that were once part of the Gondwana assembly (Andreoli & Hart, 1990). The term 'Erlank Anomaly' has recently been proposed to express this mosaic of highly enriched granulite-facies belts of Archaean to Proterozoic age in southern Africa (Fig. 1; Andreoli *et al.*, 2003). In general, the phenomena we describe may relate to the origin of those very ancient 'High-μ' crustal provinces whose origin remains an enigma (Barton *et al.*, 1983; Kramers *et al.*, 2001; Kamber *et al.*, 2003).

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