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U-Pb monazite data relating to metamorphism and granite intrusion in the northwestern Khomas Trough, Damara Orogen, central Namibia*

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U-Pb monazite data are reported from the Donkerhuk Granite and associated granitic rocks as well as from metasediments of the Kuiseb Formation in the northwestern part of the Khomas Trough, Damara Orogen, central Namibia. Monazites from an upper amphibolite facies metapelite of the Kuiseb Formation show, within limits of error, a concordant $^{206}Pb/^{238}U$ age of 513 ± 5 Ma. Monazites from anatectic domains of migmatites, which locally occur in the very north of the Khomas Trough in the vicinity of the Donkerhuk Granite, yield $^{206}Pb/^{238}U$ apparent ages ranging between 520 and 527 Ma, and provide a lower limit for the temperature peak of regional metamorphism. The late-tectonic intrusion of granitic melts into the metasedimentary series and the migmatite zone is indicated by $^{206}Pb/^{238}U$ monazite ages between 505 and 507 Ma which postdate the metamorphic peak. Although most data are concordant within limits of error, monazite fractions extracted from migmatites appear to plot systematically above the concordia curve and thus the geologic ages have to be qualified.

Introduction

So far, most available geochronological data from the Damara Orogen are restricted to granitic intrusions which only indirectly constrain the timing of deformational and metamorphic events. Few attempts have been made in directly dating the widely distributed, medium- to high-grade metasediments. In the course of a study on, the tectonic setting of the Khomas Trough, some emphasis was put on the contact relationships along its northern margin between the metasediments of the Kuiseb Formation, locally occurring migmatites and the Donkerhuk Granite which intruded into the Okahandja Lineament Zone (Fig. 1). In this paper, U-Pb monazite data as well as geological evidence are presented to put constraints on the timing of deformation, metamorphism (with special regard to the anatectic event) and magmatism in the northwestern Khomas Trough during the final stages of the Damaran orogeny. Dating of monazites in the Damara Orogen has previously only been applied to the alaskitic intrusions in the Central Zone (Briqueu *et al.*, 1980).

U-Pb monazite ages are commonly interpreted as indicating either the time of crystallization of igneous rocks close to their emplacement (Schärer & Allègre, 1983; Schärer, 1984) or the peak of metamorphism in high-grade metamorphic rocks (Köppel & Grünenfelder, 1975; Köppel *et al.*, 1980; Black *et al.*, 1984), but cooling ages corresponding to blocking temperatures of 650-700°C and even higher have also been discussed (Copeland *et al.*, 1988). The relationship between the Donkerhuk Granite, the migmatites and the metasediments was studied in the area of the Davetsaub and Khomaskaan rivers southeast of Otjimbingwe (Fig. 2). The area forms part of a traverse across the Khomas Trough along the Khomaskaan and Koam rivers, between Otjimbingwe 104 and the farm Usambara 304, about 120 km west of Windhoek (Fig. 1). Detailed studies of the geology of the Kuiseb Formation in this area have been published by Kukla *et al.* (1988, 1989, 1990c).

Geological Setting

The Khomas Trough is situated in the NE-trending inland branch of the Damara Orogen and comprises several thousand metres of predominantly metagreywackes and metapelites of the Kuiseb Formation, the uppermost lithostratigraphic unit of the Swakop Group (SACS, 1980). Up to four phases of ductile deformation can be recognized with open to isoclinal folds verging consistently to the southeast. The structural regime shows a markedly heterogeneous distribution of strain with high- and low-strain zones developed (Kukla *et al.*, 1988, 1989, 1990c; Kukla & Stanistreet, 1991). Within the study area, the Khomas Trough is bordered towards the north, against the Central Zone of the orogen, by the late-tectonic Donkerhuk Granite intrusion. The metamorphic overprint of the Kuiseb Formation is characterized by amphibolite facies assemblages with the temperature peak of metamorphism occurring late in the deformational history (Faupel, 1974; Nieberding, 1976; Hoffer, 1977; Kasch, 1983; Sawyer, 1981; Preussinger, 1990). A reaction isograd scheme has been established by Hoffer (1977). The metamorphism is pressure dominated in the southern Khomas Trough

*This paper is dedicated to Prof. B. Grauert of the Zentrallabor für Geochronologie, Universität Münster on the occasion of his 60th birthday.

as indicated by kyanite-bearing assemblages, but more temperature dominated in the northern part where sillimanite-biotite assemblages are more typical. Local partial melting of the Kuiseb Formation metasediments occurred in the vicinity of the Donkerhuk Granite. Estimates for the metamorphic P-T conditions obtained from silicate parageneses range between 560°C/6 kb for the southern and 630-660°C/4-4.5 kb for the northern Khomas Trough (Hoffer, 1977; Klemd & Okrusch, 1990; Kukla *et al.*, 1990a, 1990c; Preussinger, 1990). The Donkerhuk Granite postdates the main regional deformation as well as the temperature peak of metamorphism. However, it intruded a still hot environment, thus not producing an extensive thermal aureole (Faupel, 1974; Kukla *et al.*, 1990a). Melting experiments on rock samples from the Donkerhuk Granite yielded solidus temperatures of 640 and 646°C at PH20 = 5 kb (Winkler, 1983), while the stability range of primary muscovite provided P-T estimates of a 3.5 kb minimum and a maximum of 675°C for the emplacement of the two-mica granite (Faupel, 1974).

In the Khomaskaan river section of the study area (farm Nomatsaus 28, Fig. 2) hardly any overprint of the sillimanite-muscovite-bearing metasediments can be observed at the immediate granite contact. In contrast, some kilometres to the west in the Davetsaub gorge (farm Davetsaub 29), an extensive migmatization of the metasediments occurred (Fig. 2). According to Nieberding (1976), Hoffer (1977) and Sawyer (1981), this migmatization is caused by the thermal effects of the Donkerhuk intrusion. Hoffer (1977) and Sawyer (1981, 1983) even attribute the growth of sillimanite, at least in part, to a thermal overprint in a contact aureole.

According to our investigations in the Davetsaub river area, at least two different ,stages of migmatization can be distinguished: a first generation of thin, apparently *in situ*, leucosome bands parallels the main fabric of the rocks and is discordantly cut by a second generation of massive leucosomes. Nieberding (1976), who mapped the distribution of the migmatites in the same area, discriminated between three types of leucosomes of *in situ* as well as intrusive character. The following structural relationships can be observed in the Davetsaub gorge: (1) xenoliths of metasediment within the two-mica granite display the regional s_2 and s_3 cleavages and partly an s_4 crenulation cleavage, (2) thin granite apophyses are folded by the s_4 crenulation cleavage - from these two observations it can be concluded that the late s_4 crenulation is contemporaneous with the granite intrusion, (3) granites and pegmatites show intrusive contacts within the migmatites and cross-cut the migmatitic structures with rather sharp contacts - this implies that the leucosomes in the migmatites were already crystallized when the granitic melts intruded, (4) the migmatites do not follow the granite border, but occur in an irregular fashion as is illustrated by the Davetsaub and the Khomaskaan sections (Fig. 2) - the eastern border of the Davetsaub migmatite complex is discordant with respect to the regional strike of lithological units.

Previous geochronological work

In previous investigations Blaxland *et al.* (1979) obtained Rb-Sr whole-rock ages of 521 ± 15 Ma and 523 ± 8 Ma for the Donkerhuk Granite which they in-

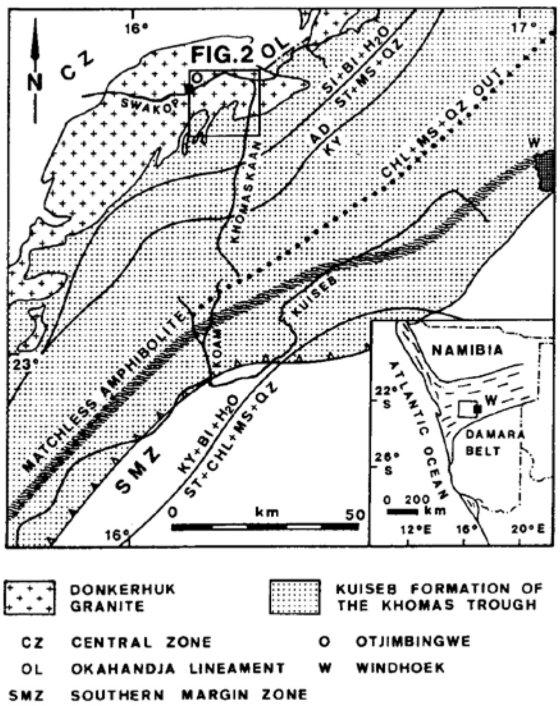

Fig. 1: Simplified geological map of the central Khomas Trough; the reaction isograd scheme after Hoffer (1977) is indicated.

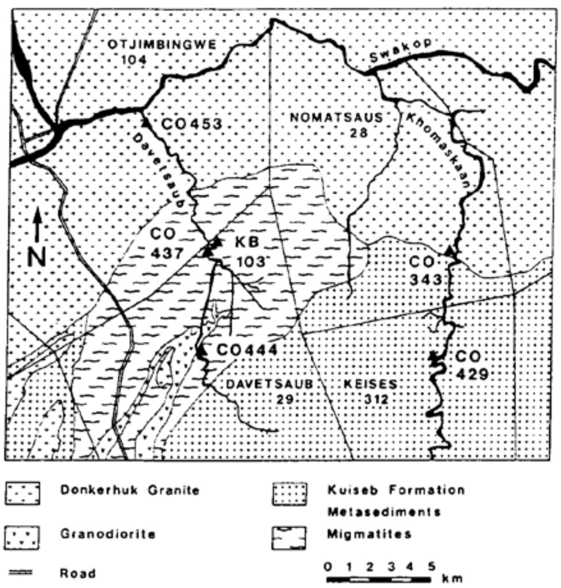

Fig. 2: Simplified geological map showing the contact between the Kuiseb Formation metasediments and the Donkerhuk Granite as well as the distribution of migmatites southeast of Otjimbingwe (after Nieberding, 1976).

terpreted as the time of intrusion. Rb-Sr mineral ages between 505 and 485 Ma obtained by these authors for the Donkerhuk Granite and one migmatite sample of the Kuiseb Formation were interpreted as subsequent cooling stages. These data suggest ,that the peak of regional metamorphism occurred at 530 Ma. Haack *et al.* (1988) further reported a Rb-Sr hornblende-whole-rock age of 524 ± 7 Ma (1σ) for the Otjimbingwe syenite, which has been emplaced pre- to syn-s_2 and was subsequently intruded by the Donkerhuk Granite. This age was interpreted by the authors as the resetting of the Rb-Sr system during the intrusion of the granite. Haack and Hoffer (1976) published K-Ar biotite ages for both the Donkerhuk Granite (420-499 Ma) and metapelites of the southern Damara Orogen (462-491 Ma) which were taken as cooling below a 300°C isotherm. Recent investigations on the Rb-Sr systematics in whole rocks and minerals from small-scale rock profiles from the Kuiseb Formation metasediments of the Khomas Trough yielded rather uniform mineral ages of 485 to 495 Ma (Kukla *et al.*, 1990a, b) in contrast to highly complex whole-rock data.

U-Pb monazite dating

Analytical procedure

Samples of 5-10 kg were crushed and monazites extracted by means of heavy liquid and magnetic separation. Prior to dissolution, hand-picked monazite fractions (1-4 mg) were washed in 2N HNO_3. The chemical procedure for separation of V and Pb followed the method of Krogh (1973) except that 6N HCI was used for decomposition of the crystals. A $^{235}U/^{208}Pb$ mixed spike was used for isotope dilution. Isotope ratios were measured on a NBS-type Teledyne solid-source mass spectrometer in a single-collector mode at the Zentrallabor für Geochronologie in Münster. U and Pb were loaded on rhenium single filaments with Ta_2O_5/H_2O and silica gel/H_3PO_4, respectively.

Lead isotope ratios were corrected for mass fractionation with 0.12%/amu as estimated from measurements of the NBS SRM 981 and 982 standards. For common lead correction, isotopic compositions according to the model of Stacey and Kramers (1975) were employed. Model ages of 510 Ma for magmatic rocks and 520 Ma for the migmatites and the metapelite sample from the Kuiseb Formation were chosen. The isotopic composition of the initial lead, however, might be different. Isotopic ratios of $^{208}Pb/^{204}Pb = 37.5$, $^{207}Pb/^{204}Pb = 15.52$ and $^{206}Pb/^{204}Pb = 17.72$ were used for blank corrections. Decay constants used are those recommended by Steiger & Jäger (1977), while errors are quoted on a 2σ level. Uncertainties ranging between 0.6 and 0.9% (2σ) level are assigned to the $^{206}Pb/^{238}U$ and $^{207}Pb/^{235}U$ ratios and include analytical errors as well as uncertainties in blanks, initial lead and spike.

Investigated samples

According to the work of Smith and Barreiro (1990), monazite forms at or near the P-T conditions of the staurolite isograd in pelitic schists. In the investigated pelite samples, a sufficient number of crystals of recognizable size were recovered only in the high-grade, sillimanite-muscovite-bearing rocks of the Kuiseb Formation in the northern Khomas Trough. Monazites are best developed in the migmatized metasediments of the Kuiseb Formation in the vicinity of the Donkerhuk Granite. An *in situ* anatexis is indicated for sample KB103 by thin leucosome bands paralleling the main fabric of the rock. Since monazites are nearly exclusively concentrated in the anatectic domains of the migmatites, we interpret the monazites as having formed during the anatectic event. The monazite-bearing sample CO437 represents a more discordant, massive type of leucosome as described above. In general, monazite crystals from migmatitic rocks are typically clear, partly euhedral, and reach grain sizes of 200 µm in contrast to the much smaller monazite crystals of the sillimanite-bearing metasediments. In addition, monazites from the following granitic rocks have been analysed:

- one sample from the Donkerhuk Granite (CO343) close to the contact zone,
- a xenolith of foliated granodiorite (CO453) incorporated into the Donkerhuk Granite as already mentioned by Nieberding (1976),
- a foliated granitic veinlet which intruded into the migmatites (CO444).

Sample localities are shown in Fig. 2.

Analytical results

Analytical results from monazite fractions are presented in Table 1 and Fig. 3. Monazites from migmatites and granites form two clusters of $^{206}Pb/^{238}U$ ages which do not overlap. Monazites from the migmatite samples KB103 and CO437 show scatter in their $^{206}Pb/^{238}U$ ages between 520 and 527 Ma. However, some of the data plot slightly above the concordia curve in Fig. 3b. Monazites from the sillimanite-bearing metapelite CO429 occupy an intermediate position with a $^{206}Pb/^{238}U$ age of 513 Ma, whereas monazites from the granitic samples CO444 and CO453 both yield, within limits of error, a concordant $^{206}Pb/^{238}U$ age of 507 Ma. A concordant age of 505 ± 4 Ma (2σ) has been obtained for the monazite fraction from the Donkerhuk Granite sample CO343. Uncertainties for the $^{207}Pb/^{235}U$ and $^{206}Pb/^{238}U$ apparent ages are in the order of 3-5 Ma.

Discussion and Conclusions

There are geological arguments against the formation of the migmatites entirely as products of contact metamorphism in the thermal aureole of the Donkerhuk Granite. Firstly, it seems improbable that the intruding

TABLE 1: Sample localities and U-Pb monazite data

Sample		Locality	Coordinates E	Coordinates S	Sieve fraction (µm)	Weight of sample (mg)
KB103	Migmatite (composite), (1)	Davetsaub 29	16°12′13″	22°24′15″	60-125	1.65
KB103	Migmatite (composite), (2)	Davetsaub 29	16°12′13″	22°24′15″	125-180	2.10
KB103	Migmatite (composite), (3)	Davetsaub 29	16°12′13″	22°24′15″	60-125	1.48
KB103	Migmatite (Neosome), (4)	Davetsaub 29	16°12′13″	22°24′15″	60-180	3.06
CO437	Migmatite (Neosome)	Davetsaub 29	16°12′09″	22°20′20″	125-180	4.04
CO429	Kuiseb Formation Pelite	Keises 312	16°18′15″	22°27′00″	<80	1.02
CO343	Donkerhuk Granite (white)	Nomatsaus 28	16°18′40″	22°24′35″	60-180	0.61
CO444	Granitic Vein (foliated)	Davetsaub 29	16°11′45″	22°26′45″	60-180	2.21
CO453	Granodiorite (foliated)	Otjimbingwe 104	16°10′14″	22°21′00″	60-180	1.49

Sample	Conc. U (ppm)	Conc. Pb (ppm)	Conc. Pb_{rad} (ppm)	Measured Ratios $^{206}Pb/^{204}Pb$	Measured Ratios $^{207}Pb/^{206}Pb$	Measured Ratios $^{208}Pb/^{206}Pb$	Isotopic Ratios* $^{206}Pb/^{238}U$	Isotopic Ratios* $^{207}Pb/^{235}U$	Isotopic Ratios* $^{207}Pb/^{206}Pb$	Apparent Ages (Ma) $^{206}Pb/^{238}U$	Apparent Ages (Ma) $^{207}Pb/^{235}U$	Apparent Ages (Ma) $^{207}Pb/^{206}Pb$
KB103	10141	1693	1690	15065	0.058633	1.231930	0.084333	0.670547	0.057668	522	521	517
KB103	10441	1718	1715	17139	0.058528	1.184251	0.084869	0.674666	0.057655	525	524	518
KB103	13417	2257	2252	14964	0.058645	1.225468	0.085182	0.677360	0.057673	527	525	517
KB103	10310	1713	1711	17557	0.058244	1.213468	0.084669	0.669982	0.057390	524	521	508
CO437	7731	1874	1870	9867	0.059033	2.274386	0.083942	0.666174	0.057558	520	518	513
CO429	10701	1039	1036	18616	0.058465	0.300119	0.082890	0.659252	0.057683	513	514	518
CO343	7027	1374	1369	4739	0.060449	1.709206	0.081518	0.644947	0.057381	505	505	506
CO444	5965	1303	1296	4378	0.060806	2.016868	0.081767	0.648063	0.057483	507	507	510
CO453	12839	2456	2445	5856	0.059708	1.636539	0.081855	0.645818	0.057222	507	506	500

*after correction

granitic melt varied strongly in temperature between the adjacent Davetsaub and Nomatsaus areas, and therefore the total absence of migmatites in the Khomaskaan river section is difficult to explain. Secondly, the different types of leucosomes in the Davetsaub river section show discordant contacts to each other, thereby indicating an *in situ* generation of leucosomes as well as the intrusion of melts from deeper structural levels. Thirdly, all granitic intrusions discordantly cross-cut the migmatitic structures with rather sharp contacts which implies that the leucosomes in the migmatites were already crystallized when the granitic melts intruded. By contrast, there is a gradual transition from the Kuiseb schists into the migmatite zone which indicates the prograde character of regional metamorphism.

Monazites from migmatites and granites form two clusters in the concordia diagram (Fig. 3). However, a geologically relevant difference of the ages is not directly evident from these data because some of the monazite fractions appear to plot slightly above the concordia curve. If we neglect systematic errors affecting all analyses (e.g. the uncertainty of the U-Pb ratio in the spike solution), it becomes even more evident that monazites from the migmatite samples plot systematically above the concordia curve, while the other monazites apparently yield more concordant data. There are two ways to explain the different behaviour of data points in the concordia diagram: (1) Predominant incorporation of ^{230}Th from the U decay sequence might have caused excess ^{206}Pb (Schärer, 1984). In this case the geologic ages would be best approximated by the ^{207}Pb/^{206}Pb apparent ages. (2) Although the initial lead incorporated during crystallization is a very subordinate component of monazites (cf. Table 1), the isotopic composition of this initial lead has some influence on the position of the data points. Calculation of the initial lead composition using a higher model age shifts the overconcordant data points towards the concordia curve, but this is of minor importance in the case of high ^{206}Pb/^{204}Pb ratios and can not account for a high degree of discordance. In this case, the geologic ages would tend towards the ^{206}Pb/^{238}U apparent ages.

Depending on the cause for the slight discordance of monazite data, the time interval between the anatexis of the metasediments and the subsequent intrusion of granitic melts may vary by some millions of years, but in either case a discontinuity of events, i.e. the migmatization of the Kuiseb Formation metasediments and the subsequent intrusion of the Donkerhuk Granite, is constrained. In the case of the granitic samples, we believe that the U-Pb monazite ages reflect the time of crystallization subsequent to the intrusion into the country rocks, since the temperature of the intruding melts should not have significantly exceeded the assumed blocking temperature for lead in monazites (Copeland *et al.*, 1988). In contrast, the anatectic event providing an upper limit for the regional metamorphic peak is less well constrained, but must fall within the range of the apparent ages for the migmatite monazites. The temperature peak of metamorphism may further be approximated by the monazite data for the Kuiseb Formation metapelite sample.

In conclusion, the sequence of events reflected by the U-Pb monazite data is in accordance with the field relationships. The 515 to 525 Ma anatectic event was postdated by granitic intrusions at 505 ± 5 Ma and a contemporaneous weak deformation (s_4). With regard to previously published data, the results of this study are inconsistent with the data of Blaxland *et al.* (1979), while in the case of the Otjimbingwe syenite, one could

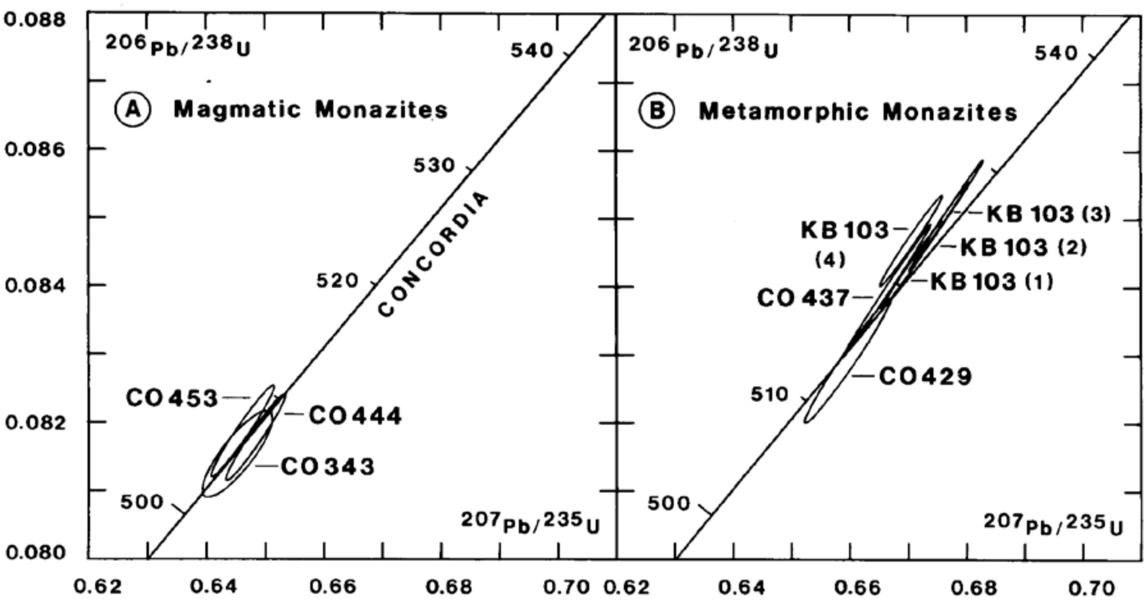

Fig. 3: Concordia diagrams showing U-Pb monazite data (A) from migmatites and Kuiseb Formation metapelite and (B) from granitic rocks.

speculate upon a reinterpretation of the hornblende-whole-rock age of Haack *et al.* (1988) as a resetting of the Rb-Sr system in the course of the regional metamorphic overprint.

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