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Rb-Sr isotope constraints on the timing of late to post-Archæan tectonometamorphism affecting the southeastern Kaapvaal Craton

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ABSTRACT—Biotite separates from Archæan granitoid lithologies on the Kaapvaal Craton north of the Proterozoic Namaqua-Natal Belt in south eastern South Africa exhibit Rb-Sr model dates of 967 ± 24 Ma for samples from within 25 km of the present northern limit of the Proterozoic thrust front. Samples from further north (>50 km to 170 km) have model Rb-Sr dates of 2614 ± 74 Ma. The younger dates are interpreted as dating cooling after northwards emplacement of Proterozoic crust onto the Kaapvaal Craton, whereas the older dates are presumed to relate to an Archæan metamorphic episode, possibly associated with intrusion of the post-Pongola granites. © 2000 Elsevier Science Limited. All rights reserved.

RÉSUMÉ—Des biotites ont été séparées de granitoïdes archéens du craton du Kaapvaal au nord de la ceinture protérozoïque de Namaqua-Natal dans le SE de l'Afrique du Sud. Celles provenant d'échantillons à moins de 25 km de la limite nord du front de charriage protérozoïque fournissent des âges-modèles Rb-Sr de 967 ± 24 Ma. Les échantillons prélevés plus au nord (>50 km à 170 km), possèdent des âges-modèles Rb-Sr de 2614 ± 74 Ma. Les âges les plus jeunes sont interprétés comme correspondant à la fermeture du système isotopique lors du mouvement vers le nord de la croûte protérozoïque sur le craton du Kaapvaal. Les âges les plus anciens sont supposés correspondre à un épisode métamorphique archéen, peut-être en association avec des intrusions de granites post-Pongola. © 2000 Elsevier Science Limited. All rights reserved.

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INTRODUCTION

Mapping of the Namaqua-Natal Belt in the Natal sector of the belt has shown that various lithologies along the northern margin of the belt were thrust northeast over the southern edge of the Kaapvaal Craton (Matthews, 1959, 1972, 1981; Jacobs *et al.*, 1993). Dating of various units within the belt (Nicolaysen and Burger, 1965; Barton, 1983; Eglington *et al.*, 1989; Thomas *et al.*, 1993) has shown that these suites are Proterozoic in age (~1200 to ~1000 Ma) and were formed from juvenile material. In contrast, the cratonic suites north of the belt are Archæan in age (Burger and Coertze, 1973; Charlesworth, 1981; Barton, 1983; Matthews *et al.*, 1989; Farrow *et al.*, 1990; de Beer and Eglington, 1991).

The present paper reports the results of Rb-Sr isotope work performed during the late 1970s on various Archæan granitoid samples and their biotite separates collected north of the Proterozoic thrust front in a traverse extending from within 50 m of the frontal zone (NyaWoshane River sample, Table 1, Fig 1) to near Piet Retief, about 170 km north of the front (Fig. 1). These previously unpublished data are

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Table 1. Rb-Sr isotope data for granitoids and biotite separates

	Sample	Rb	Sr	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$
Anhalt leuco-tonalite	EPR 2	78.60	452.5	0.5034	0.7252
	EPR 2 bi	653.6	28.24	89.65	4.1706
Granitoid on Mhlatuze River	OG 170 a	119.3	114.2	3.063	0.8430
	OG 170 a bi	706.9	22.46	104.9	2.2628
	OG 170 a pg	47.45	165.1	0.8402	0.8143
	OG 170 b	105.5	72.73	4.276	0.8995
	OG 170 c	124.2	117.4	3.102	0.8435
	OG 170 d	104.9	113.6	2.708	0.8457
	OG 170 d ii	108.3	118.7	2.674	0.8415
	OG 170 e	110.6	69.97	4.658	0.8965
	OG 170 e ii	110.1	70.22	4.618	0.8916
	OG 135	121.2	130.8	2.712	0.8266
	OG 136	107.4	147.0	2.133	0.7991
	OG 137	125.2	148.7	2.463	0.8204
Mvunyana granodiorite	BG 1	158.8	204.0	2.275	0.8087
	BG 1 bi	972.1	20.69	273.6	11.0588
Natal Spa granitoid	NS 1	123.1	302.3	1.184	0.7578
	NS 4	61.16	590.6	0.2998	0.7153
	NS 4 bi	405.3	21.24	69.52	3.3570
	NS 8	61.66	551.1	0.3240	0.7163
	NS 11	48.24	645.3	0.2164	0.7116
Granitoid at Nkandla mica mine	OG 174 a	200.6	297.2	1.967	0.7790
	OG 174 a bi	1091	29.65	125.4	2.5269
	OG 174 b	190.6	266.3	2.086	0.7849
	OG 174 b bi	1084	34.74	103.6	2.2176
	MM 1	201.3	300.3	1.953	0.7791
	MM 2	205.6	301.7	1.986	0.7802
	MM 3	199.6	263.8	2.205	0.7803
Nseleni granitoid	NGC 1/5	46.50	333.0	0.4045	0.7211
	NGC 1/5 bi	467.1	18.46	81.01	1.7966
Granitoid on NyaWoshane River	FW 2	73.21	600.4	0.3532	0.7185
	FW 2 bi	405.0	23.40	53.71	1.4490
Granitoid on Maphophoma River	MO 2	62.43	264.7	0.6842	0.7352
	MO 2 bi	24.55	30.85	2.322	0.7944
Granitoid on White Mfolozi River	WUG 1	170.2	113.0	4.443	0.9067

1σ: analytical precision for $^{87}Rb/^{86}Sr$ is 1.5%; for $^{87}Sr/^{86}Sr$ it is 0.0003. Error correlation is assumed to be zero for whole rock samples and 0.76 for biotite separates. Uncertainties are assumed to have been defined on the basis of 60 replicates.

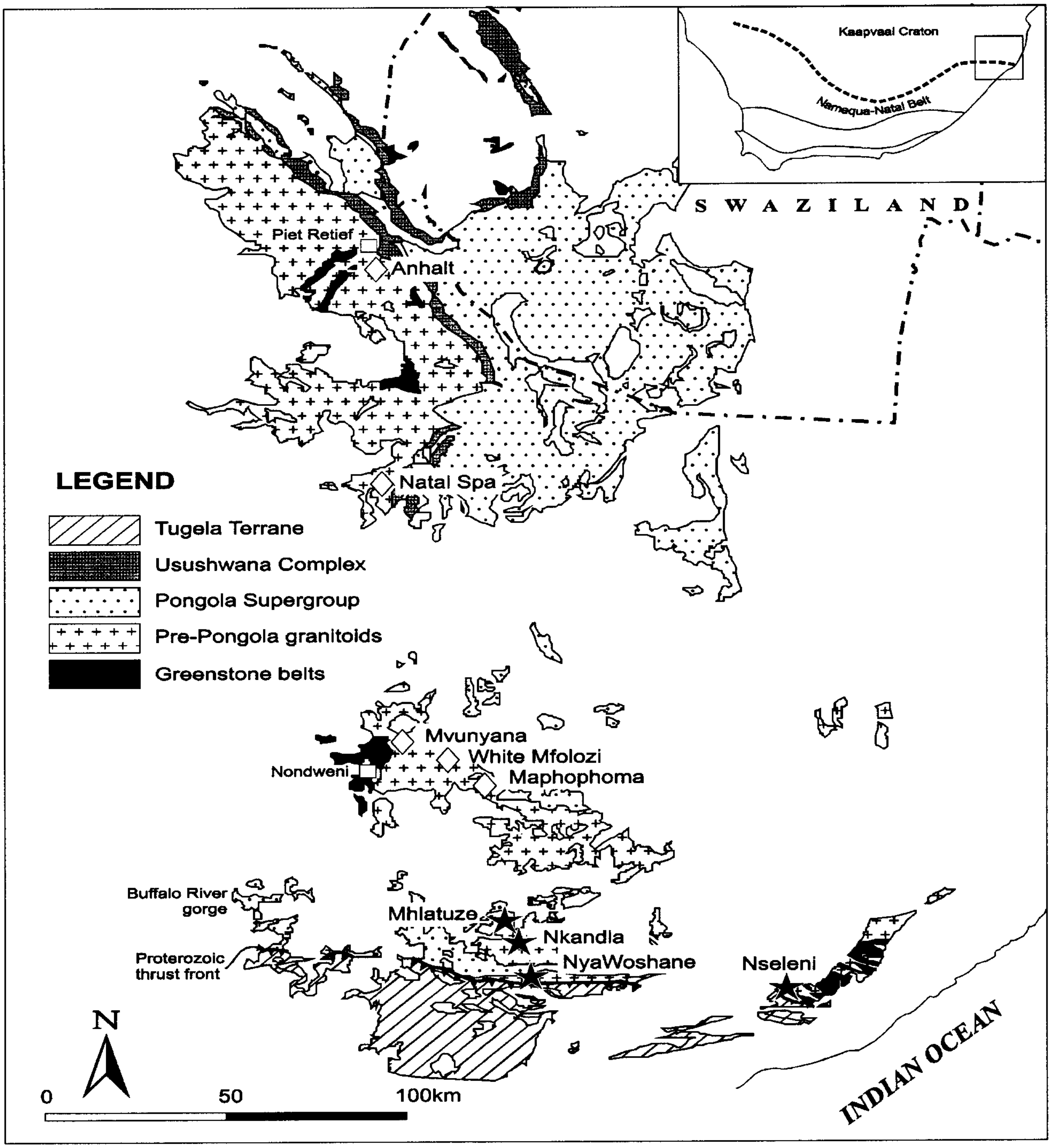

Figure 1. Map showing the distribution of Archaean basement in the south eastern Kaapvaal Craton relative to the present exposure of the Proterozoic thrust front. Sample localities are identified by filled stars (biotite dates <1000 Ma) and diamonds (biotite dates ~2600 Ma). Inset shows the area of the main diagram relative to the southern margin of the Kaapvaal Craton (dashed curve) and the Namaqua-Natal Belt as delineated by de Beer and Meyer (1984).

important in the context of the development of the Namaqua-Natal Belt and Gondwana reconstructions. In some cases the data have been combined with published results for specific localities, as noted in the text and tables.

The purpose of the study of these rocks was to identify isotopic evidence of elevated temperatures in rocks marginal to the frontal zone of the Proterozoic thrust belt in order to ascertain the extent and timing of the thrusting. The Rb-Sr isotope systematics of biotite was used for this purpose because biotite is ubiquitous in the Archæan granites of the south-eastern Kaapvaal Craton and its relatively low Rb-Sr blocking temperature of ~300°C is ideally suited for detecting increased crustal temperatures due to tectonic loading by overthrusting. The data reported

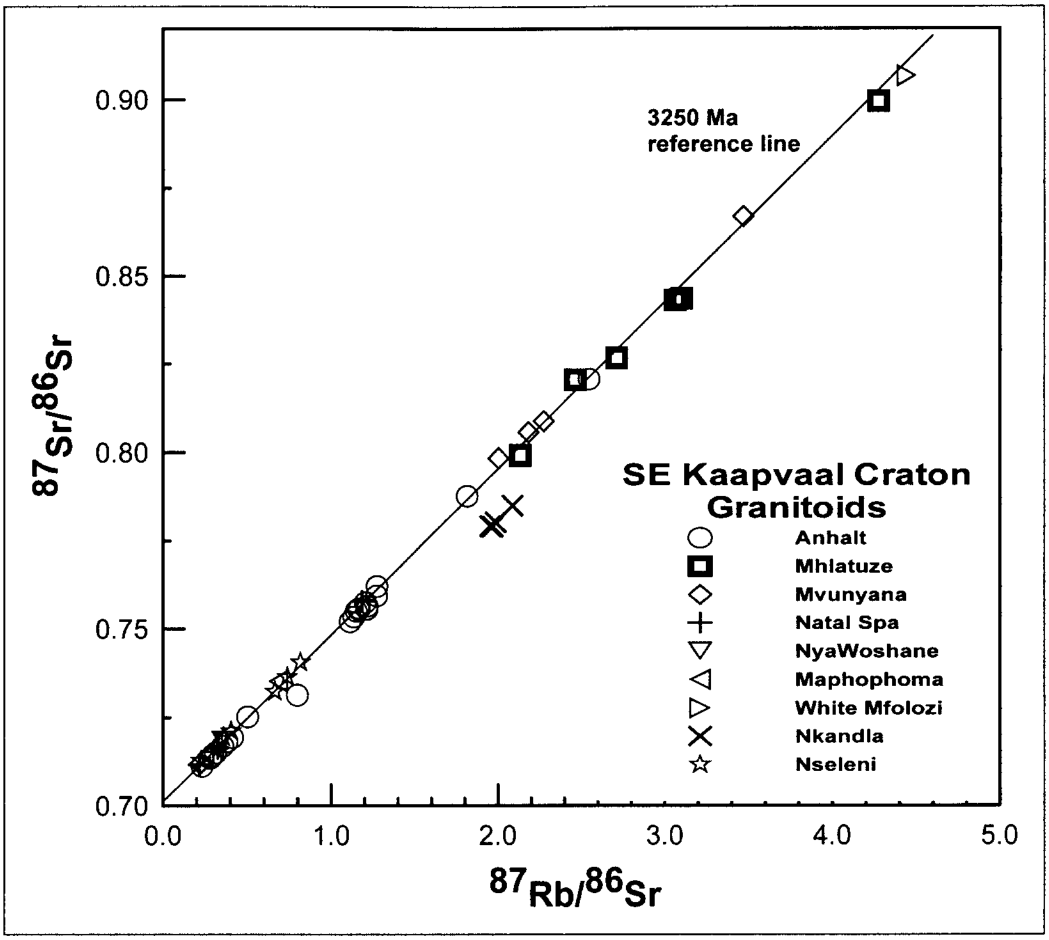

Figure 2. *Rb-Sr isochron plot for granitoid whole rock data from the southeastern Kaapvaal Craton. Source of data referenced in Table 2. Note the scatter of the data about a 3250 Ma reference line.*

here were part of a larger project to consider the Meso- to Neo- Proterozoic metamorphic evolution of southern Africa and Western Dronning Maud Land, Antarctica. Implications of the data in this latter context have been discussed in detail by Barton and Moyes (1990).

ANALYTICAL TECHNIQUE

Standard sample dissolution techniques using HF were used for all samples. Rubidium and Sr concentrations and $^{87}Sr/^{86}Sr$ were determined by isotope dilution at the Hugh Allsopp Laboratory (previously part of the Bernard Price Institute), University of the Witwatersrand, following separation of the elements using cation exchange columns. All $^{87}Sr/^{86}Sr$ ratios were normalised to a $^{86}Sr/^{88}Sr$ value of 0.1194. Analytical uncertainties are given in Table 1. Following Brooks *et al.* (1972), the error correlation between $^{87}Rb/^{86}Sr$ and $^{87}Sr/^{86}Sr$ for biotite analyses is assumed to be 0.76. Allsopp *et al.* (1979) provide additional details of analytical techniques followed at the Hugh Allsopp Laboratory during the late 1970s when the analyses reported here were performed.

All geochronological calculations have been performed using the GEODATE for Windows package following procedures described by Harmer and Eglington (1989). Dates obtained are presented in Table 2. Uncertainties for these dates are quoted at ±95% confidence levels.

RESULTS

Elworthy (*unpubl. data* SA Antarctic Programme) initially regressed 15 of the 22 whole rock samples from Table 1 to obtain a date of ~3200 Ma, and this result has been referenced in Charlesworth (1981) and Barton (1983) as relating to a widespread magmatic event in the south eastern Kaapvaal Craton. More recent mapping in the region (Charlesworth, 1981; Hunter *et al.*, 1983; Hunter *et al.*, 1986; Matthews *et al.*, 1989; Hunter *et al.*, 1992) has identified a number of petrographically and geochemically distinct granitoid suites although the spatial extent of these different granitoids has not been defined. Regression of all

Table 2. Regression results for various granitoids from the south eastern Kaapvaal Craton.

Lithology	Isotope system	Whole-rock date (Ma)	Source of whole-rock data	Initial ratio	F	n	MSWD	Biotite - whole-rock date (Ma)
Anhalt leucotonalite	Rb-Sr	3254±39	4, 5	0.7002±3	1.78	20 of 23	1.39	2671±82
Natal Spa granitoid	Rb-Sr	3288±139	5	0.7010±8	3.15	4 of 6	0.42	2638±80
Mvunyana granodiorite	Rb-Sr	3295±34	3, 5	0.7013±3	2.53	6 of 6	0.74	2611±80
White Mfolozi granite	Rb-Sr	3162±80	1					
Maphophoma granitoid	Rb-Sr		5					2501±99
Mhlatuze granitoid	Rb-Sr	3177±199	5	0.702±8	2.53	6 of 8	2.21	975±30
Nkandla granitoid	Rb-Sr	3184±1937	5	0.69±6	3.15	4 of 5	0.07	990±30
	Rb-Sr		5					987±30
Nseleni granitoid	Rb-Sr	3168±74	2	0.7025±4	2.53	6 of 6	2.43	933±28
NyaWoshane granitoid	Rb-Sr		5					958±29

Model biotite-whole rock dates are given for biotite separates where available. All dates in Ma. Data from 1: Allsopp (*unpubl.*) reported in Burger and Coertze (1973); 2: Barton (1983); 3: Matthews *et al.* (1989); 4: Farrow *et al.* (1990); 5: this paper.

available whole-rock Rb-Sr data (Table 1; Barton, 1983; Farrow *et al.*, 1990; Matthews *et al.*, 1989) provides an errorchron date of 3244 ± 68 Ma (errors augmented by √(MSWD/F). The data are plotted in Figure 2. Inspection of the data indicates that, whilst the various granitoids appear to be coeval (as previously reported by Elworthy, *unpubl. data*), initial Sr ratios vary (Figure 3). This is not unexpected, given the extensive variation in petrography and chemistry of the rocks sampled and the large extent of the area considered. It is also apparent from regression of the total data set that the minerals provide younger dates than the whole rock data alone.

For further interpretation, the data were split according to locality and known rock type prior to being regressed. In some cases the whole-rock data reported (Table 1) have been combined with more recent work by Matthews *et al.* (1989 - Mvunyana granodiorite) and Farrow *et al.* (1990 - Anhalt leucotonalite) and regressed to obtain the dates listed in Table 2. For other localities, the unpublished data of Elworthy have been regressed alone.

DISCUSSION

Rb-Sr results, together with those of Pb-Pb and U-Pb zircon studies reported elsewhere, (Matthews *et al.*, 1989; Reimold *et al.*, 1993) from numerous localities near the south eastern margin of the Kaapvaal Craton (Table 2, Figure 1 and summary in De Beer and Eglington, 1991) provide dates in the range ~3160 Ma to ~3300 Ma. All Rb-Sr results are within error of a weighted average value of 3277 ± 37 Ma. These dates are comparable with those reported by De Wit *et al.* (1987) and Armstrong *et al.* (1990) for intrusive granitoid suites associated with the second major phase of deformation in the Barberton greenstone belt (De Wit *et al.*, 1992; De Beer and Eglington, 1991). They are distinctly older than the ~3107 Ma sheet-like Lochiel/Mpuluzi batholiths (Kamo and Davis, 1990; De Beer and Eglington, 1991 and references therein). All these granitoids form the basement to the supracrustal rocks of the Pongola Supergroup (e.g. Matthews, 1967; Burger and Coertze, 1973). Their intrusion over such a wide area presumably reflects stabilisation and cratonisation within this sector of the Kaapvaal Craton during this period. It is also worth noting that two members of this extensive suite of granitoids intrude pre-existing greenstones: the Mvunyana granodiorite into the Nondweni greenstone (Matthews *et al.*, 1989) and the Anhalt leucotonalite into the Assegaai and Commondale greenstones (Farrow *et al.*, 1990). Dating of the granitoids therefore provides a minimum age for these greenstones and indicate that they must be older than the ~3.2 Ga date reported for the Nondweni belt (Wilson and Carlson, 1989). Unpublished zircon data for the Witkop Formation of the Nondweni Group (~3406 Ma: Armstrong and Wilson, *unpubl. data*) are consistent with this interpretation (Versfeld and Wilson, 1992)

Biotite mineral dates in the samples analysed show two distinct groups of about 933 – 990 Ma and 2501 – 2673 Ma (Table 2). The younger dates are all from localities within 25 km of the present northern margin of the Proterozoic Namaqua-Natal Belt whereas the

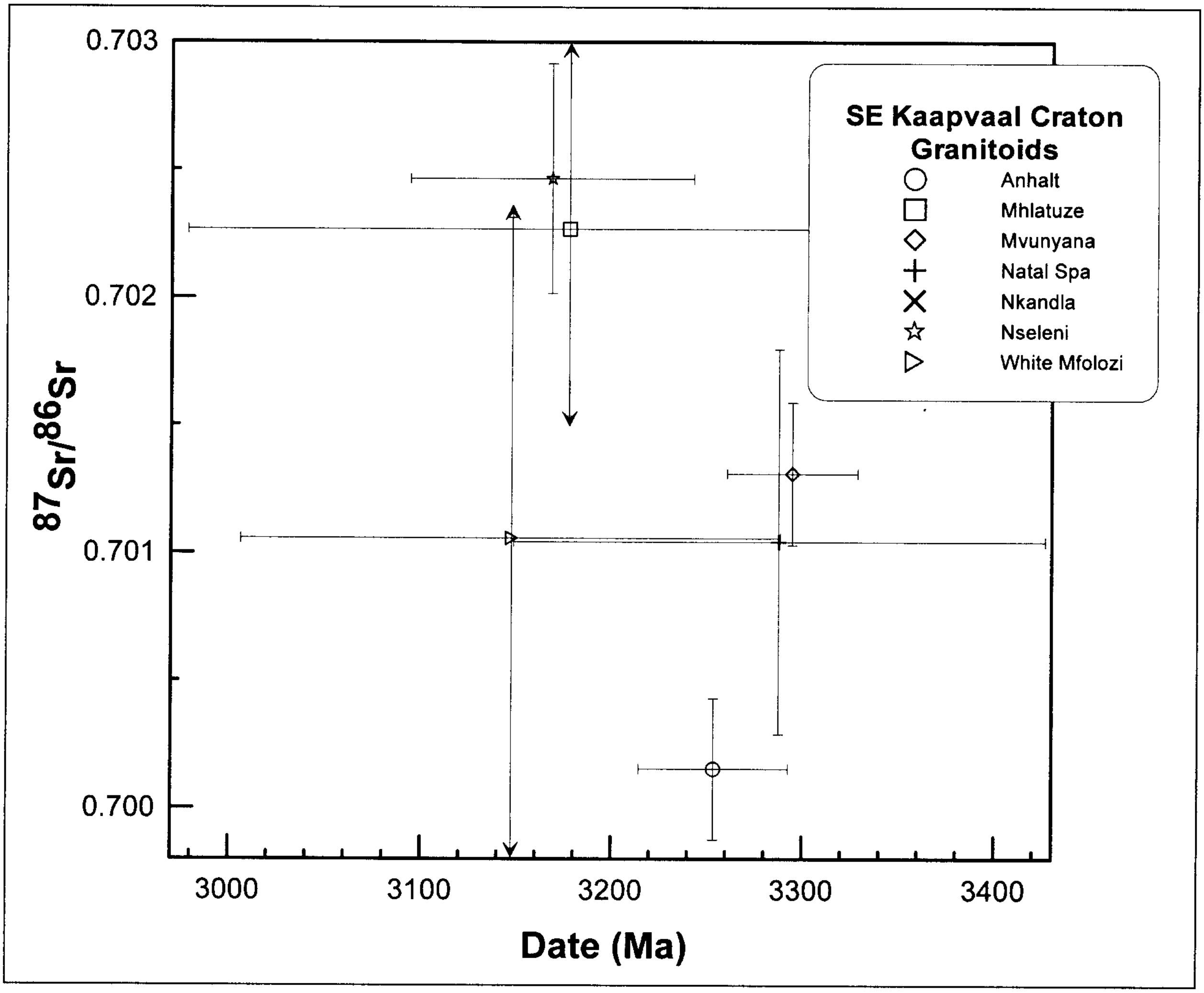

Figure 3. *Plot of initial $^{87}Sr/^{86}Sr$ relative to whole rock regression dates for various Archaean granitoids from the southeastern Kaapvaal Craton. The more precisely defined results illustrate that there is substantial isotopic heterogeneity between the different localities sampled.*

older dates occur more than 50km north of the front (Figs 1 and 4). No samples are available from the intervening area. The regional distribution of the ~2.6 Ga biotite dates (weighted average is 2614 ± 74 Ma), extending over a distance of at least 100km from the Maphophoma River to Piet Retief (Figure 1) indicates that this portion of the Kaapvaal Craton cooled to below ~300°C at this time and has not subsequently been heated above this temperature. These blocking temperatures may either be related to a widespread thermal overprint, to cooling associated with uplift and erosion, or to partial resetting. The consistency of dates over such a wide area is taken as evidence against partial resetting, hence the dates obtained are considered to have geological significance. A regional overprint of this nature is not,. however, evident further north in Swaziland and along the southern margin of the Barberton greenstone belt, where biotite mineral dates are typically around 2700 to 2800 Ma (Barton *et al.*, 1983a,b). The ~2.6 Ga date is slightly younger than dates obtained from post-Pongola granite plutons (Layer *et al.*, 1989; Maphalala and Kröner, 1993; Reimold *et al.*, 1993; Robb *et al.*, 1993; Thomas *et al.*, 1997) and for partial melts in the Mkondo Suite of Swaziland (Condie *et al.*, 1996) (see Fig. 5). It is thus possible that these cooling dates are in some way linked to the intrusion of the younger post-Pongola plutons or, at least, to the event which produced them. Unpublished whole rock Rb-Sr and Sm-Nd data from granite and tonalite in the Buffalo River Gorge, just north of the Proterozoic thrust front also provide errorchron dates of ~2650 Ma (Eglington, Dixon and Matthews, *unpubl. data*), providing further evidence for an event in the southeastern Kaapvaal Craton which caused resetting of isotope systematics throughout the region.

The ~970 Ma biotite mineral dates (weighted

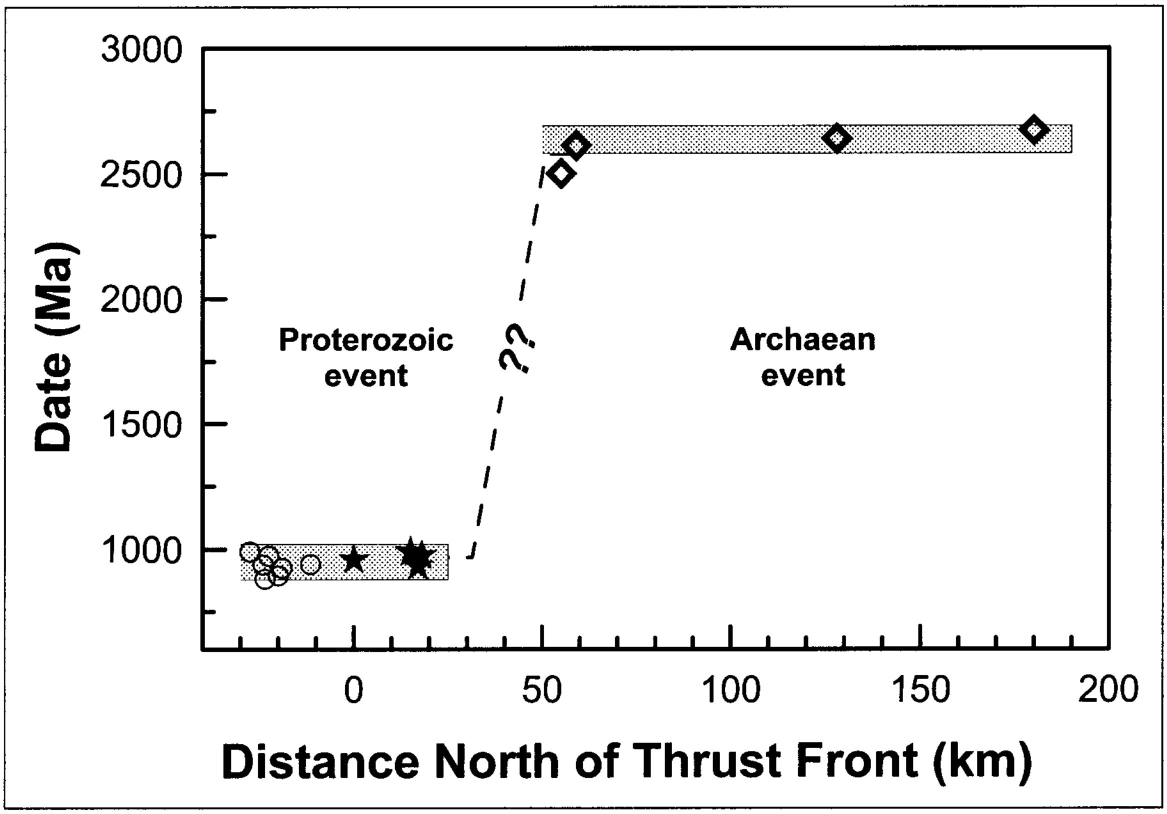

***Figure 4.** Variation in Rb-Sr biotite whole rock dates relative to distance north of the Proterozoic thrust front. Note the abrupt change in biotite dates from a weighted average of 967±24 Ma ★ to 2614±74 Ma ◇ in the interval 25 to 50 km north of the present exposure of the Proterozoic Natal thrust front. Also shown ○are biotite dates for syn- to late- orogenic granitoid intrusions from the Mzumbe and Margate Terranes of the Proterozoic belt (Thomas* et al., *1993).*

average of 967±24 Ma) obtained from samples within 25km of the Proterozoic thrust front are similar to dates obtained for biotite from lithologies within the Tugela, Mzumbe and Margate Terranes of the Proterozoic belt itself (Nicolaysen and Burger, 1965; Eglington *et al.*, 1989; Thomas *et al.*, 1993; Jacobs and Thomas, 1996) and are interpreted as recording cooling ages, i.e. the time when biotite last cooled through its blocking temperature of about 300°C. Presumably this thermal overprint dates cooling after an increase in temperature due to thickening of the crust in this section of the Kaapvaal Craton as a result of overthrusting of the Proterozoic lithologies from the south (Figs 1 and 6). These biotite cooling ages thus effectively provide a minimum estimate for the age of thrusting in this section of the Namaqua-Natal Belt and provide important additional constraints on the development of the Belt in general. Jacobs *et al.* (1997) have recently obtained direct evidence of the timing of thrusting within the Proterozoic Tugela Terrane just south of the thrust front by dating metamorphic hornblende in thrusts using the Ar-Ar technique. Their results indicate that thrusting within this terrane occurred in the period 1135±9 to 1077±11 Ma but no direct evidence is yet available to indicate whether this thrusting can be related to the entire Natal Belt or is limited to the Tugela Terrane. The work of Jacobs *et al.* (1997) also indicates that major thrusting and strike-slip tectonic activity within the entire Natal sector of the Namaqua-Natal Belt continued until ~980 Ma.

The northern limit of the 'thermal overprint' dates suggests that extensive thicknesses of allochthonous Proterozoic material did not extend much beyond ~30km north of the present outcrop of the Natal Thrust Front. Geophysical studies reported by de Beer and Meyer (1984) have shown that the southern edge of the Kaapvaal Craton is probably situated some 30–40 km south of the present northern margin of the belt (see also Matthews, 1981 and Fig. 6), coincident with a zone of steep foliation which was interpreted as the root zone for nappes in the Tugela Terrane (Matthews, 1981) and which has been interpreted as a major oblique sinistral strike-slip zone, the Lilani-Matigulu Shear Zone (Jacobs *et al.*, 1993). Together, the extent of the preserved Tugela Nappe Complex and the resetting of biotite dates further north, implies that Proterozoic thrust sheets extended for at least

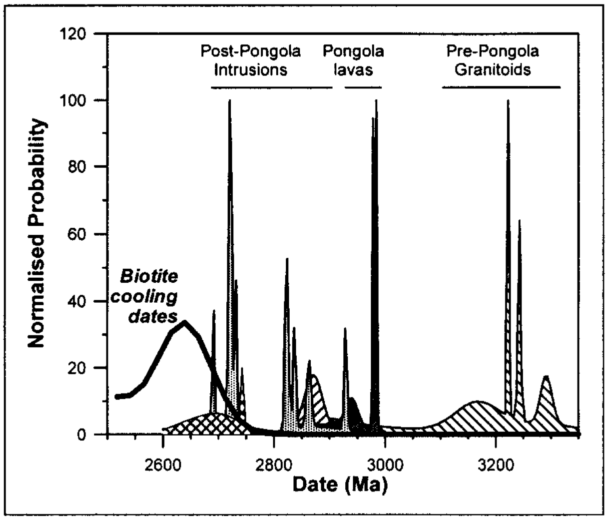

Figure 5. Probability distribution of dates for rocks from the south eastern Kaapvaal Craton (Barton, 1983). Dates for pre-Pongola granitoids (diagonal pattern) (Matthews et al., *1989; Farrow* et al., *1990; Reimold* et al., *1993; this paper) are distinguished from those for Pongola Supergroup lavas (dense stipple) (Hegner* et al., *1984, 1994; Walraven and Pape, 1994), the Usushwana Complex (diagonal pattern) (Hegner* et al., *1984; Walraven and Pape, 1994) and granites which intrude the Pongola Supergroup (medium stipple). Cross-hatched histogram represents reset whole rock Rb-Sr and Sm-Nd dates in various granitoids such as those from the Buffalo River gorge near the southern limit of Archæan exposures in Natal (Eglington, Dixon and Matthews,* unpubl data*) and high-grade metamorphism of the Mkhondo Suite in Swaziland (Condie* et al., *1996). The Rb-Sr biotite dates reported here (thick solid line) are slightly younger than the younger (~2.7 Ga) post-Pongola granites. (Layer* et al., *1988,1989; Maphalala and Kröner, 1993; Reimold* et al., *1993; Robb* et al., *1993; Thomas* et al., *1997)*

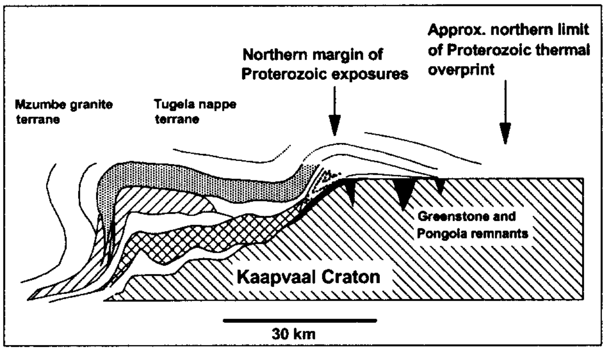

Figure 6. Simplified down-plunge section (after Matthews, 1981) of the northern portion of the Natal Belt and southeastern Kaapvaal Craton. The northern limit of Proterozoic thermal overprinting (as preserved by the isotope systematics of biotites) is shown relative to the current northern margin of Proterozoic exposures.

60–70 km onto the Kaapvaal Craton. Assuming that northwards thrusting of the Tugela Terrane did occur in the time period indicated by the Ar-Ar dating reported by Jacobs *et al.* (1997) with temperatures of about 500°C, and that temperatures subsequently cooled below 300°C at about 970 Ma, as indicated by the Rb-Sr biotite dates reported here, a cooling rate of ~2°C Ma^{-1} may be calculated. No indication of where detritus derived from erosion of the thrust nappes is preserved has, however, been recorded in southern Africa.

The ~970 Ma biotite dates contrast markedly with many biotite dates obtained from an essentially similar metamorphic complex in Western Dronning Maud Land, Antarctica (Barton and Moyes, 1990). The majority of the mica dates obtained from the Maudheim Province are ~500 Ma with ~970 Ma in some parts of the Heimefrontfjella (Barton and Moyes, 1990; Moyes and Barton, 1990; Jacobs *et al.*, 1995). The ~500 Ma dates are interpreted as reflecting blocking of the Rb-Sr system due to cooling following the Ross (or Pan-African) Orogeny (Barton and Moyes, 1990; Moyes and Barton, 1990; Jacobs *et al.*, 1995). Available data have been interpreted to indicate an eastwards increase in the extent of Pan-African overprinting within Western Dronning Maud Land (Jacobs *et al.*, 1993, 1995). This contrast is particularly important since recent reconstructions of Gondwana on geological and geochronological grounds have placed Western Dronning Maud Land and southern Africa in close juxtaposition (Barton and Moyes, 1990; Jacobs *et al.*, 1993).

Similar Pan-African biotite K-Ar dates have been reported by Allen and Tucholke (1981) from dredge samples of gneiss on the Agulhas Plateau, south east of Proterozoic exposures in South Africa and from the Maurice Ewing Bank (Beckinsale *et al.*, 1977), whilst hornblende, muscovite and biotite from the Cape Meredith Complex in the Falkland Islands preserve ~1000 Ma Ar-Ar dates (Jacobs *et al.*, 1999).

Jacobs and Thomas (1996) have also reported Pan-African titanite fission track dates from the Mzumbe and Margate Terranes. The biotite dates presented here, together with the titanite fission track results of Jacobs and Thomas (1996), indicate that crustal temperatures associated with Pan-African metamorphism were above the effective blocking for titanite fission tracks i.e. higher than ~250°C but less than that of biotite Rb-Sr (about 300°C). In each case, exact temperature constraints would depend on cooling rate and mineral size.

CONCLUSIONS

Rb-Sr isotope whole-rock studies of various Archæan granitoid suites situated within 200 km of the Namaqua-Natal Belt in south eastern Africa suggest that most of these lithologies formed during the period ~3300 Ma to ~3150 Ma. Two regional resetting episodes are evident in this area, as recorded by biotite Rb-Sr dates. One occurred at ~2600 Ma and is speculated to be related to post-Pongola tectonism and granite intrusion. The other occurred at ~967 Ma as a result of overthrusting of Proterozoic crust onto the south eastern margin of the Kaapvaal Craton up to at least 25 km north of the present exposures of the thrust front. The ~967 Ma model dates effectively date cooling of this section of crust after the overthrusting. The results of Jacobs *et al.* (1997) suggest that this overthrusting occurred during the period 1135-1077 Ma. Comparison with mica dates from elsewhere in the belt (Nicolaysen and Burger, 1965; Thomas *et al.*, 1993; Jacobs and Thomas, 1996) and the Ar-Ar dating of shear fabrics by Jacobs *et al.* (1997) suggests that the major Proterozoic regional tectonothermal events in the Natal sector of the Namaqua-Natal Belt were everywhere terminated by this time.

The ~967 Ma model biotite dates obtained in Natal are significantly older than the Pan-African dates evident in the eastern parts of Western Dronning Maud Land, Antarctica, the Agulhas Plateau and the Maurice Ewing Bank but are equivalent to those obtained from Heimefrontfjella and the Cape Meredith Complex, Falkland Islands. This difference constrains the proximity and fit of Africa and Antarctica in Gondwana reconstructions.

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