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Zircon geochronology of the Oribi Gorge Suite, KwaZulu-Natal, South Africa: constraints on the timing of trans-current shearing in the Namaqua–Natal Belt

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Abstract

The Oribi Gorge Suite is a voluminous suite of rapakivi granite-charnockite plutons which occur in the Mzumbe and Margate terranes of the eastern (Natal) sector of the Mesoproterozoic Namaqua–Natal Belt of Southern Africa. Previous geochronological studies have provided contradictory results for the age of emplacement of the suite.

New single zircon evaporation dates and detailed SHRIMP zircon analyses for three of the plutons confirm the previously observed complexity with two episodes of intrusion at ∼1070 and 1030 Ma. Metamorphic growth of zircon at ∼1030 Ma is also recorded from the Oribi Gorge pluton. The two intrusive episodes are further apart timewise (∼45 Ma) than expected for plutons belonging to a single suite. The range of ages probably reflects long-lived, post-collisional trans-current shearing in the eastern (Natal) sector of the Namaqua–Natal Belt when conditions suitable for formation of similar, megacrystic, A-type granitoids were repeated. Similar granitoids from the western (Namaqua) sector of the Belt indicate that these tectonic conditions were regional in extent.

Keywords: Oribi Gorge; Natal; Granitoid; Charnockite; Zircon; U–Pb; Mesoproterozoic

1. Introduction

Isotopic investigations of the Natal sector of the Mesoproterozoic Namaqua–Natal Belt during the last decade have constrained granitoid magmatism in the Mzumbe and Margate terranes to between ∼1.2 and 1.0 Ga, the ages of the oldest, pre-tectonic (Mzumbe Suite tonalite) and youngest post-tectonic (Mbizana microgranite) intrusive rocks, respectively (Thomas and Eglington, 1990; Thomas et al., 1993a). The exact intrusive sequence of the voluminous and compositionally variable granitoids which were emplaced between these dates has, however, been the subject of considerable debate; in part because of equivocal field relationships and because of conflicting results from different isotope systems. The former is a result of poor outcrop and the piecemeal way in which field mapping was conducted until the extensive mapping programme of the KwaZulu-Natal office of the Council for Geoscience was completed and published as 1:250,000 scale maps and various publications

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(Thomas, 1988a,b). Geochronological studies have obtained contradictory results for individual plutons with Rb–Sr systematics for the megacrystic granitoids, in particular, providing dates distinctly different to those suggested by ID-TIMS U–Pb zircon and zircon evaporation techniques (Eglington et al., 1986a, 1989a,b; Thomas, 1988a; Thomas et al., 1993b).

The Natal sector of the Namaqua–Natal Belt has been shown to comprise three discrete crustal blocks termed, from north to south, the Tugela, Mzumbe and Margate terranes (Thomas, 1994). A model for the development of the belt (Jacobs et al., 1993, 1997; Thomas et al., 1994; Jacobs and Thomas, 1994) contends that the Natal sector represents an oblique arc-continent collision orogen, with an early deformational event giving rise to NE-vergent re-folded, recumbent folds and thrusts and the development of a S- to SW-dipping pervasive metamorphic foliation. It was during this phase that the three tectonostratigraphic terranes of the sector were accreted to the southern margin of the Kaapvaal Craton. Continued northwards convergence gave rise to crustal thickening and the imposition of an oblique sinistral trans-current regime manifested in numerous WSW trending steep shear belts (Jacobs et al., 1993).

The Southern two arc-related terranes (Mzumbe and Margate terranes) are dominated by granitoids which make up >80% of their exposed areas. The late tectonic Oribi Gorge Suite is the most extensive (Fig. 1). Timing of intrusion of these plutons is important, both in terms of constraining local intrusive successions and in providing a minimum date for juxtaposition of the Margate and Mzumbe terranes since the suite is present in both terranes. Generation of the Oribi Gorge Suite has also been related to the trans-current shearing event, so dating the suite also constrains the timing of this event. This paper provides single zircon evaporation dates and detailed SHRIMP zircon analyses for three plutons in order to address these issues.

Petrographically and chemically similar rocks also occur in the western (Namaqua) sector of the Namaqua–Natal Belt where they are classified as the Spektakel Suite. As with the Oribi Gorge Suite, these units were emplaced late in the tectonic history of the belt, associated with shear zones (Thomas et al., 1996).

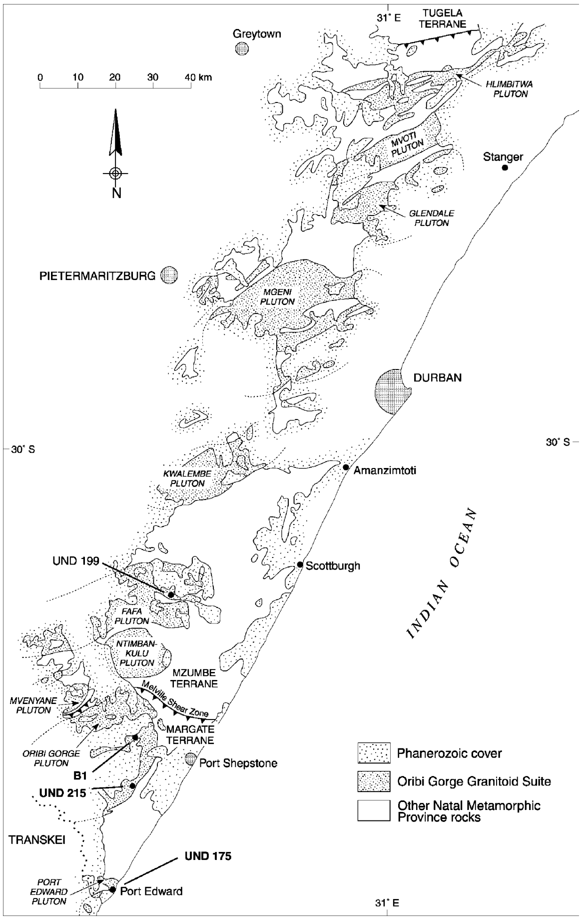

Fig. 1. Distribution of the Oribi Gorge Suite within the Mzumbe and Margate terranes, Natal sector of the Namaqua–Natal Belt. Localities of the dated samples are indicated.

2. Geological description and regional significance of the granitoids

The field geology, petrography and geochemistry of these granitoid units have been described elsewhere. Consequently, only a short summary, with references, is presented here. The Oribi Gorge Suite comprises ten plutons of very coarse-grained, porphyritic (locally rapakivi) granite and charnockite intrusive into metasediments of the Mapumulo Group (Mzumbe Terrane) and Mzimkulu Group (Margate Terrane), the Mzumbe, Humberdale, Sezela and Margate granitoid suites and the Equeefa metabasite (Eglington et al., 1986a; Talbot and Grantham, 1987;

Evans et al., 1987; Thomas, 1988b, 1994; Thomas et al., 1993b). The rapakivi phase is made up of K-feldspar phenocrysts set in a coarse-grained matrix of quartz, microcline, plagioclase, biotite, hornblende, ilmenite, apatite and zircon. The dark green porphyritic charnockite phase contains K-feldspar or plagioclase (in enderbites) with coarse-grained quartz, antiperthite, K-feldspar, hornblende, biotite, orthopyroxene ± clinopyroxene ± fayalite ± garnet, sulphide, zircon, apatite and graphite. The geochemistry is characterised by a wide range of SiO_2 values (57–75%) and tholeiitic, A-type, within-plate granite characteristics (high K_2O, Na_2O, FeO^T, P_2O_5, alkalis/CaO, $FeO^T/(FeO^T + MgO)$, Nb, Y, Zr, Zn, Ba).

A previous geochronological study of the suite has shown that U–Pb and Pb–Pb zircon dates of ~1.03–1.07 Ga are typically significantly older than Rb–Sr whole-rock and biotite dates (~950–850 Ma) from the same samples (Thomas et al., 1993b). In addition, a Pb–Pb evaporation date of 1068 ± 2 Ma, obtained from one intrusion (the Bomela locality of the Oribi Gorge pluton; Thomas et al., 1993b) is ~30 Ma older than the 1037 ± 18 Ma U–Pb date obtained for a bulk population of zircons in samples from different localities within the same pluton in Oribi Gorge (Thomas, 1988a). The Oribi Gorge granite and charnockite pluton lies within the granulite facies Margate Terrane, as does the Port Edward enderbite pluton (Rb–Sr date of 987 ± 19 Ma, Eglington et al., 1986b). The Mvenyane granite pluton (Rb–Sr date of 973 ± 17 Ma, Thomas, 1988b), Fafa granite pluton (ID-TIMS small sample U–Pb zircon date of 1029 ± 10 Ma, Thomas et al., 1993b) and Mgeni granite pluton (Rb–Sr date of 1030 ± 20 Ma, Eglington et al., 1989a) are the only members of the suite from the Mzumbe Terrane for which dates are available. Overgrowths on zircon in the Quha Formation, sampled close to the Ntimbankulu pluton, provide dates of ~1060 Ma and have been interpreted as dating intrusion of the pluton (Thomas et al., 1999).

The discrepancy in U–Pb and Pb–Pb zircon dates obtained from different plutons and exposures of plutons of the Oribi Gorge Suite raises the question whether the older zircon evaporation date obtained for the Bomela locality of the Oribi Gorge pluton is real or an artefact of the different technique. In order to test the various possibilities and to obtain a more comprehensive understanding of the geochronology of the entire suite, precise SHRIMP U–Pb dates were determined on the same zircon separates from three of the plutons.

3. Analytical procedures

Zircon separation was performed by Elijah Nkosi and Ed Retief, using the mineral separation facilities at the CSIR, subsequently, relocated to the Council for Geoscience, Pretoria. All Rb–Sr dating of Oribi Gorge Suite mineral separates and whole-rock powders referenced in this report were performed at one laboratory by BME. The zircon evaporation technique utilised follows published techniques (Kober, 1986, 1987). The specific application at the Council for Geoscience has been documented elsewhere (Grobler and Walraven, 1993). Data for each grain analysed were collected in blocks of 8–15 ratios at varying temperatures or until no lead was evaporated at a given temperature.

Fully representative aliquots of the zircons separated were taken to the Research School of Earth Sciences analytical facility, Australian National University (ANU), Canberra. They were mounted in epoxy resin together with the zircon standards SL13 and AS3 and characterised using transmitted and reflected light, back-scatter electron imaging and cathodoluminescence (CL) imaging, the latter two techniques on the SEM at the electron microscopy unit at ANU and at the Council for Geoscience. Analyses were performed on either SHRIMP I or II: spots were selected on the basis of the optical and CL images obtained.

Analysis on SHRIMP and subsequent data reduction were performed following previously documented techniques (Compston et al., 1984, 1992; Williams and Claesson, 1987; Claoue-Long et al., 1995). U/Pb in the unknowns were normalised to a $^{206}Pb^*/^{238}U$ value of 0.1859 (equivalent to an age of 1099.1 Ma) for AS3. U and Th concentrations were determined relative to those measured in the SL13 standard. Correction for common lead was made using the measured $^{204}Pb/^{206}Pb$ ratio and suitable adjustments for model common lead (Cumming and Richards, 1975). Unless otherwise stated, dates are based on $^{207}Pb^*/^{206}Pb^*$ ratios and an assessment of the concordance of the data.

Dates were calculated from SHRIMP U–Pb data using Geodate for Windows (Eglington and Harmer, 1999), following published techniques (Eglington and Harmer, 1993; Ludwig, 1998) and using recommended decay constants (Steiger and Jäger, 1977). Uncertainties in the SHRIMP results tables and plots are at 1σ whilst weighted averages and interpreted dates for all techniques are quoted with 95% confidence uncertainties.

4. Zircon descriptions

4.1. Port Edward enderbite

The zircon grains selected from the Port Edward pluton come from sample UND 175, one of the samples which was used in deriving the Rb–Sr isochron date of 987 ± 19 Ma (Eglington et al., 1986b). The zircons from this sample form a homogenous assemblage of mildly elongated (l/b ∼3) prismatic zircons with curvilinear to blunt terminations. Most crystals are clear with well developed growth zoning evident under CL. Sulphide blebs of different sizes are present in many grains. Fig. 2e illustrates the CL characteristics of a grain from this sample.

4.2. Oribi Gorge pluton

Zircons were selected from samples UND 215 and B1, the former from the Bomela locality near the south-east margin of the pluton and the latter from Oribi Gorge, near the centre of this ∼500 km^2 pluton. UND 215 was previously used to determine a preliminary evaporation zircon date of 1068 ± 2 Ma (Thomas et al., 1993b) and was also one of those from which a Rb–Sr isochron date of 859 ± 56 Ma was determined (Eglington et al., 1986b). Biotite from the same sample provides a 938 ± 10 Ma mineral—whole-rock date (Thomas et al., 1993b). A bulk population zircon concentrate from sample B1 was previously used, together with zircons from four other samples, to obtain an isochron U–Pb upper intercept date of 1037 ± 18 Ma (Thomas, 1988a). These five samples also provided a whole-rock Rb–Sr isochron date of 1003 ± 29 Ma (Thomas, 1988a).

Zircons from sample UND 215 comprise an heterogeneous assemblage with numerous morphological varieties. Most grains are sub-spheroidal, ovoid, stubby or moderately to strongly elongated. Evidence for corrosion is common with many grains being ‘necked’. Very rare sub-rounded cores are occasionally evident with most of the population exhibiting

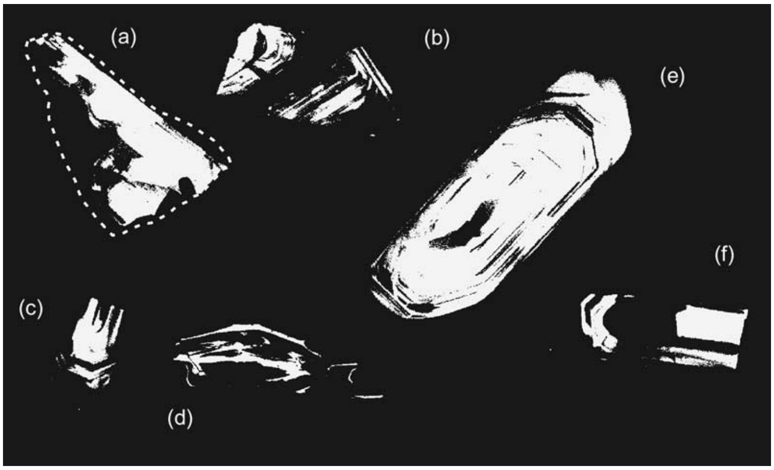

Fig. 2. Representative cathodoluminescence (CL) images for Oribi Gorge Suite samples. (a) and (b) B1 (Oribi Gorge pluton, Gorge locality); (c) and (d) UND 215 (Oribi Gorge pluton, Bomela locality); (e) UND 175 (Port Edward pluton); (f) UND 199 (Fafa pluton). With the exception of grains (a) and (d), most grains in all the samples are dominated by fine-scale magmatic growth zoning. Grains (a) and (d) show extensive resorption. Dashed white line around (a) delineates the boundary of the grain. Dark areas within this boundary are overgrowths and replacements which were sufficiently wide to date with SHRIMP.

growth zoning. Occasional, very narrow, rims are present. Euhedral and globular opaque inclusions, stubby to elongated microlites and fluid inclusions are noted in many grains. No distinct cores were evident under CL imaging amongst the grains mounted for SHRIMP analysis. CL images of typical crystals from this sample are exhibited in Fig. 2c and d.

Sample B1 contained grains with occasional distinct rims (Fig. 2a) and possible older cores evident in CL images. The majority of the population, however, exhibited clear growth zoning (Fig. 2a and b). As with sample UND 215, the grains often displayed rounded and 'necked' shapes thought to reflect magmatic corrosion.

4.3. Fafa pluton

This granite has previously been dated using zircons from sample UND 199 (Thomas et al., 1993b), providing a date of 1029 + 11/−10 Ma. This sample, together with five other whole-rock powders, provided a Rb–Sr isochron date of 878 ± 22 Ma (Eglington and

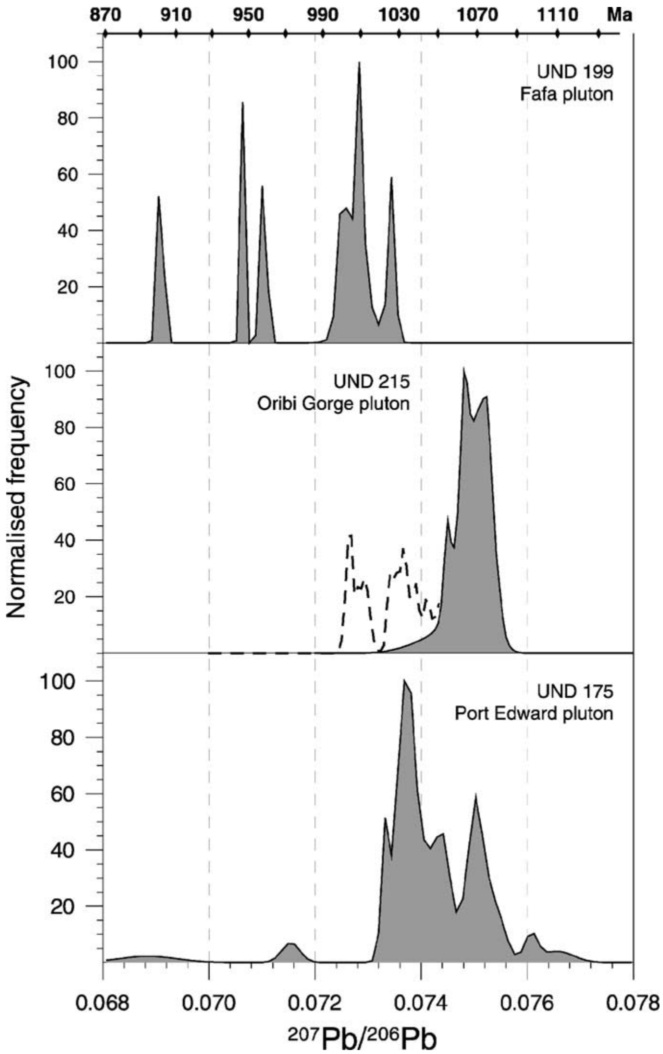

Fig. 3. Evaporation ^{207}Pb/^{206}Pb results for samples from the Oribi Gorge Suite. Samples are: UND 199, Fafa pluton; UND 215, Oribi Gorge pluton, high-temperature data shown as filled histogram, low-temperature data shown as dashed curve; UND 175, Port Edward pluton.

Kerr, 1989). Biotite from the same sample provides a 915 ± 19 Ma mineral—whole-rock date (Thomas et al., 1993b). Zircons were taken from the remaining concentrate from UND 199 for this study.

Elongate crystals (l/b ∼7) predominate over stubby and equant grains. Both strongly zoned and nearly structureless crystals with numerous sulphide and fluid inclusions occur together. The strongly zoned crystals consist of well developed, elongated interior domains with round terminations but growth zones are mirrored in the adjoining outer domain, indicating that the interiors are not xenocrystic cores. CL images support this interpretation. The interior domains are typically strongly metamict and altered, suggesting that early crystallisation of zircon was enriched in U relative to the later crystallising phase (e.g. see Fig. 2f).

5. Zircon evaporation dating results

Four zircon grains from sample UND 199 of the *Fafa granite* were evaporated (Table 1). They gave a multimodal summed probability distribution (Fig. 3). The form of the distribution can not be related to variations in evaporation temperature, nor to variations in Th/U content (as indicated by $^{208}Pb/^{206}Pb$). The main

Table 1
Summarised results for evaporation analysis of samples UND 175, Port Edward pluton; UND 215, Oribi Gorge pluton; UND 199, Fafa pluton

Grain	Temperature (°C)	Number of ratios	$^{207}Pb/^{206}Pb$	Precision	$^{208}Pb/^{206}Pb$	Precision
Sample: Fafa granite UND 199						
1	1445	19	0.07285	0.00056	0.03964	0.00154
	1480	63	0.07284	0.00012	0.06091	0.00070
	1340	26	0.07344	0.00013	0.07921	0.00172
2	1445	45	0.06909	0.00011	0.05604	0.00035
	1480	43	0.07251	0.00017	0.07633	0.00081
3	1410	35	0.07103	0.00012	0.07998	0.00144
	1480	127	0.07278	0.00028	0.08679	0.00118
4	1445	51	0.07061	0.00006	0.07632	0.00059
Sample: Oribi Gorge pluton (Bomela locality) UND 215						
1	1393	40	0.07495	0.00022	0.05440	0.00050
	1410	45	0.07491	0.00013	0.06580	0.00030
	1445	18	0.07513	0.00014	0.08210	0.00170
	1460	19	0.07432	0.00053	0.08330	0.00050
2	1370	86	0.07274	0.00005	0.03370	0.00020
	1393	86	0.07362	0.00008	0.03680	0.00090
	1410	45	0.07461	0.00008	0.03910	0.00130
	1445	91	0.07484	0.00007	0.04180	0.00020
3	1393	17	0.07424	0.00020	0.03310	0.00040
	1445	8	0.07472	0.00042	0.06050	0.00040
4	1393	25	0.07397	0.00016	0.04870	0.00010
5	1445	51	0.07524	0.00007	0.04380	0.00100
	1460	37	0.07522	0.00013	0.05680	0.00030
6	1480	72	0.07516	0.00007	0.04790	0.00240
Sample: Port Edward enderbite UND 175						
1	1393	35	0.07342	0.00011	0.07856	0.00093
	1445	9	0.07468	0.00088	0.10012	0.0002
2	1445–1480	108	0.07452	0.00016	0.08649	0.00218
3	1410–1480	99	0.07367	0.00009	0.11105	0.01018
4	1445–1480	81	0.07312	0.00005	0.07438	0.00093

Data for each grain analysed were collected in blocks of 8–15 ratios. The table presents weighted averages of several blocks of data in cases where these were collected at constant temperature. Data for grains 2, 3 and 4 of sample UND 175 for differing temperatures all have equivalent $^{207}Pb/^{206}Pb$ ratios, hence weighted averages are presented.

summed probability peak occurs at 0.0727 (equivalent to a date of ~1005 Ma) with lesser peaks at 0.0706 (945 Ma), 0.0692 (905 Ma) and 0.0745 (1055 Ma).

Six grains of sample UND 215 from the *Oribi Gorge charnockite* (*Bomela locality*) were evaporated (Table 1) and provided a multimodal summed probability distribution (Fig. 3). Omission of the lower temperature components of the distribution provides an essentially unimodal distribution with a peak at $^{207}\mathrm{Pb}/^{206}\mathrm{Pb} = 0.0748$, equivalent to a date of ~1068 Ma. No Th/U variation is evident in the evaporation data.

Four zircon grains from the *Port Edward pluton* (UND 175) were evaporated and the results are summarised in Table 1 and portrayed in Fig. 3. The summed probability distribution for the $^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$ ratios is bimodal with the major peak at a $^{207}\mathrm{Pb}/^{206}\mathrm{Pb}$ value of 0.0732 (equivalent to a date of ~1020 Ma) and a lesser peak at 0.0746 (equivalent to a date of ~1060 Ma). There is no distinction between low- and high-temperature evaporation results for the grains, nor are any variations in Th/U content of the evaporated phases evident.

6. SHRIMP U–Pb dating results

6.1. Port Edward enderbite

Twelve spots were analysed on eleven grains from sample UND 175, concentrating on areas exhibiting growth zoning revealed by CL imaging. Together, the data define a concordia date of 1025 ± 8 Ma (probability of fit = 0.43, Fig. 4, Table 2). No distinct cores were evident amongst the grains mounted or analysed. The SHRIMP result is similar to the major peak obtained from evaporation analysis (Thomas et al., 1993b). The older peak obtained in the evaporation

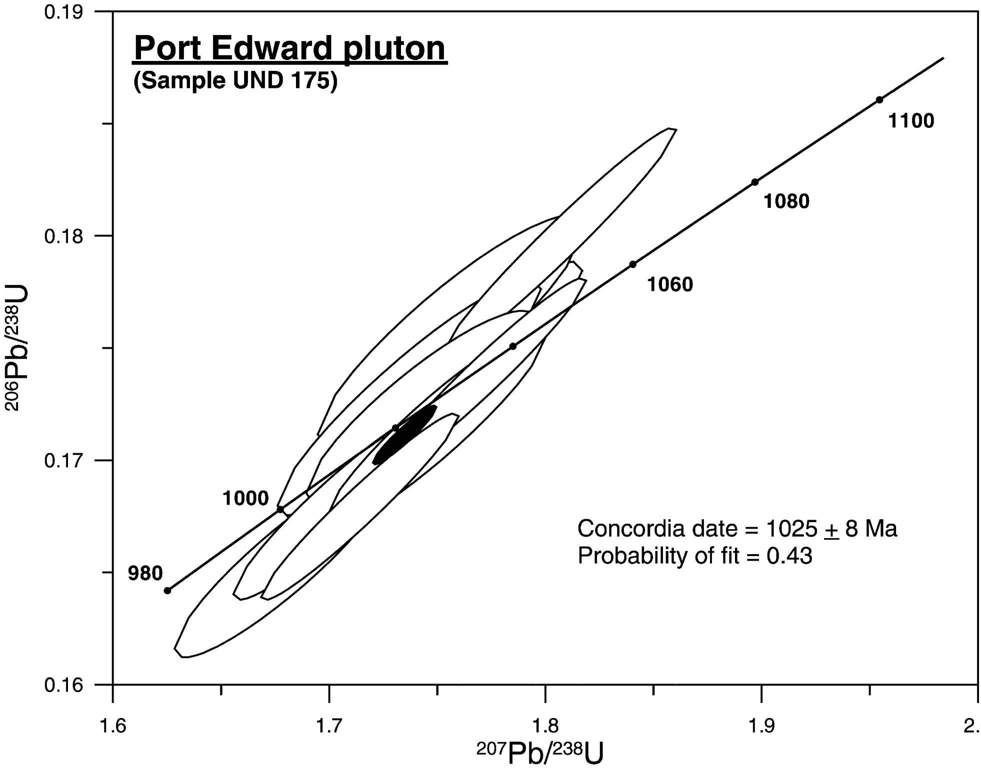

Fig. 4. Wetherill plot of SHRIMP analyses for sample UND 175 from the Port Edward enderbite. The individual analyses (1σ error ellipses), define a concordia date and weighted average error ellipse shown in black.

spectrum thus presumably represents some older component present in the population but not analysed or resolvable in the limited number of spots determined with SHRIMP.

6.2. Oribi Gorge pluton

Sixteen spots were analysed on sixteen grains from sample UND 215, again concentrating on areas exhibiting growth zoning in the CL images (Table 3). These sixteen spots define a concordia date of 1082 ± 7 Ma (probability of fit = 0.44, Fig. 5), similar to, but not statistically equivalent to the 1068 ± 5 Ma evaporation result provided earlier (Thomas et al., 1993b).

Forty spot analyses were determined for seventeen grains of sample B1 (Table 4). Unlike the grains mounted for sample UND 215, this sample contained discernible rims (see Fig. 2a), cores and domains with prominent growth zoning. These domains have been treated separately in the geochronological calculations. Where spots analysed span two domains, as identified in subsequent SEM imaging, these analyses have been omitted from the calculations. The association of the spots with specific domains are marked accordingly in Table 4.

The concordia date for the six core domains analysed is 1071 ± 12 Ma (probability of fit = 0.53, Fig. 6) whereas the magmatic domains (omitting one rather discordant analysis, spot 10.3) define a concordia date of 1063 ± 5 Ma (probability of fit = 0.97, Fig. 6). These two sets of analyses are statistically equivalent and together, define a concordia date of 1064 ± 5 Ma (probability of fit = 0.96) The seven rim spots analysed define a concordia date of 1029 ± 8 Ma (probability of fit = 0.71, Fig. 6). The rims have higher U/Th ratios than the other domains, suggesting growth under different conditions. Since the rims cut across and replace the prominent growth zoning (assumed to be of magmatic origin) and are distinctly younger, they are considered to reflect metamorphic overgrowths.

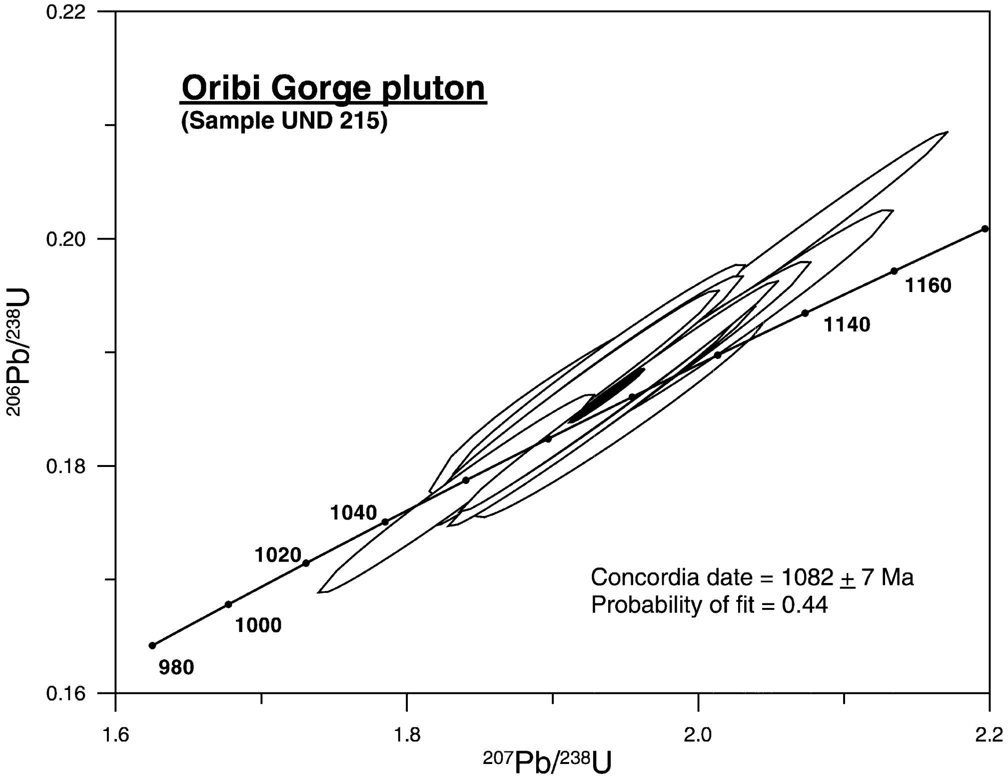

Fig. 5. Wetherill plot of SHRIMP analyses for sample UND 215 from the Bomela locality, Oribi Gorge pluton. The individual analyses (1σ error ellipses), define a concordia date and weighted average error ellipse shown in black.

Table 2
SHRIMP U–Pb results for sample UND 175, Port Edward pluton

Grain spot	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	^{204}Pb/^{206}Pb	f_{206} (%)	Radiogenic ratios						Ages (in Ma)						Concentration (%)
							^{206}Pb/^{238}U	±	^{207}Pb/^{235}U	±	^{207}Pb/^{206}Pb	±	^{206}Pb/^{238}U	±	^{207}Pb/^{235}U	±	^{207}Pb/^{206}Pb	±	
1.1	144	48	0.34	24	0.00007	0.115	0.1680	0.0035	1.704	0.039	0.0735	0.0006	1001	19	1010	15	1029	16	97
2.1	282	61	0.21	46	0.00004	0.074	0.1679	0.0034	1.714	0.037	0.0740	0.0004	1001	19	1014	14	1043	11	96
3.1	177	50	0.28	30	0.00008	0.134	0.1723	0.0035	1.743	0.043	0.0733	0.0009	1025	19	1024	16	1023	24	100
4.1a	230	64	0.28	41	0.00004	0.067	0.1798	0.0042	1.807	0.044	0.0729	0.0004	1066	23	1048	16	1011	11	105
4.1b	254	71	0.28	42	0.00004	0.062	0.1654	0.0034	1.678	0.041	0.0736	0.0008	987	19	1000	16	1030	21	96
5.1	230	51	0.22	39	0.00001	0.017	0.1738	0.0036	1.772	0.039	0.0739	0.0004	1033	20	1035	14	1039	11	99
6.1	212	48	0.23	36	0.00007	0.117	0.1714	0.0036	1.749	0.042	0.0740	0.0007	1020	20	1027	16	1042	18	98
7.1	175	39	0.22	30	0.00010	0.175	0.1758	0.0042	1.756	0.050	0.0725	0.0009	1044	23	1030	19	999	27	105
8.1	213	49	0.23	35	0.00008	0.143	0.1674	0.0034	1.698	0.038	0.0736	0.0006	998	19	1008	15	1029	15	97
10.1	127	38	0.30	22	0.00011	0.184	0.1717	0.0038	1.736	0.046	0.0733	0.0009	1022	21	1022	17	1023	25	100
11.1	149	46	0.31	26	0.00009	0.154	0.1728	0.0043	1.737	0.050	0.0729	0.0008	1028	24	1022	19	1011	24	102
12.1	196	41	0.21	33	0.00009	0.161	0.1737	0.0042	1.758	0.048	0.0734	0.0008	1033	23	1030	18	1025	22	101

Notes: (1) Uncertainties given at the 1σ level. (2) f_{206} denotes the percentage of ^{206}Pb that is common Pb. (3) For concentration, 100% denotes a concordant analysis.

Table 3
SHRIMP U–Pb results for sample UND 215, Oribi Gorge pluton

Grain spot	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	$^{204}Pb/^{206}Pb$	f_{206} (%)	Radiogenic ratios						Ages (in Ma)						Concentration (%)
							$^{206}Pb/^{238}U$	±	$^{207}Pb/^{235}U$	±	$^{207}Pb/^{206}Pb$	±	$^{206}Pb/^{238}U$	±	$^{207}Pb/^{235}U$	±	$^{207}Pb/^{206}Pb$	±	
1.1	422	111	0.26	78	0.00004	0.08	0.1861	0.0084	1.945	0.089	0.0758	0.0004	1100	46	1097	31	1090	11	101
2.1	216	79	0.37	41	0.00009	0.16	0.1876	0.0076	1.931	0.081	0.0747	0.0006	1108	41	1092	28	1060	15	105
3.1	152	61	0.40	30	0.00006	0.11	0.1927	0.0082	2.024	0.090	0.0762	0.0007	1136	44	1124	31	1100	17	103
4.1	69	37	0.54	14	0.00028	0.48	0.1864	0.0077	1.928	0.092	0.0750	0.0015	1102	42	1091	33	1070	40	103
5.1	230	58	0.25	42	0.00004	0.07	0.1857	0.0076	1.941	0.081	0.0758	0.0004	1098	41	1096	28	1091	11	101
6.1	307	75	0.24	56	0.00002	0.04	0.1848	0.0076	1.939	0.082	0.0761	0.0004	1093	42	1095	29	1097	12	100
7.1	184	34	0.18	34	0.00000	0.00	0.1888	0.0076	1.975	0.083	0.0759	0.0006	1115	41	1107	29	1092	16	102
8.1	175	76	0.43	34	0.00007	0.12	0.1865	0.0076	1.944	0.082	0.0756	0.0005	1102	41	1097	29	1085	13	102
9.1	235	67	0.28	44	0.00002	0.04	0.1885	0.0076	1.932	0.082	0.0743	0.0006	1113	42	1092	29	1051	17	106
10.1	248	77	0.31	50	0.00003	0.06	0.1991	0.0085	2.062	0.089	0.0751	0.0004	1171	46	1136	30	1071	10	109
11.1	393	103	0.26	73	0.00001	0.02	0.1864	0.0075	1.916	0.080	0.0746	0.0005	1102	41	1087	28	1057	13	104
12.1	158	61	0.39	30	0.00004	0.07	0.1838	0.0075	1.927	0.081	0.0761	0.0005	1088	41	1091	28	1097	12	99
13.1	290	106	0.36	56	0.00004	0.07	0.1881	0.0076	1.935	0.081	0.0746	0.0005	1111	41	1093	28	1058	15	105
14.1	316	90	0.28	58	0.00003	0.05	0.1837	0.0074	1.914	0.079	0.0756	0.0004	1087	40	1086	28	1084	11	100
15.1	326	89	0.27	60	0.00004	0.07	0.1845	0.0075	1.948	0.083	0.0766	0.0007	1092	41	1098	29	1110	19	98
16.1	347	101	0.29	62	0.00004	0.07	0.1776	0.0072	1.834	0.077	0.0749	0.0006	1054	40	1058	28	1066	15	99

Notes: (1) Uncertainties given at the 1σ level. (2) f_{206} denotes the percentage of ^{206}Pb that is common Pb. (3) Correction for common Pb made using the measured $^{204}Pb/^{206}Pb$ ratio. (4) For concentration, 100% denotes a concordant analysis.

Table 4
SHRIMP U–Pb results for sample B1, Oribi Gorge pluton

Grain spot	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	^{204}Pb/^{206}Pb	f_{206} (%)	Radiogenic ratios						Ages (in Ma)						Concentration (%)
							^{206}Pb/^{238}U	±	^{207}Pb/^{235}U	±	^{207}Pb/^{206}Pb	±	^{206}Pb/^{238}U	±	^{207}Pb/^{235}U	±	^{207}Pb/^{206}Pb	±	
1.1.1	251	82	0.33	46	0.00010	0.165	0.1823	0.0032	1.870	0.055	0.0744	0.0016	1080	18	1071	20	1052	44	103
1.1.2*	237	77	0.33	42	0.00009	0.145	0.1769	0.0031	1.822	0.047	0.0747	0.0013	1050	17	1054	17	1061	35	99
2.1r	584	42	0.07	94	0.00001	0.017	0.1713	0.0027	1.739	0.030	0.0736	0.0004	1019	15	1023	11	1030	10	99
2.2	104	36	0.35	19	0.00001	0.017	0.1765	0.0058	1.812	0.078	0.0745	0.0018	1048	32	1050	29	1054	49	99
2.3r	608	41	0.07	98	0.00001	0.017	0.1722	0.0028	1.749	0.033	0.0737	0.0006	1024	16	1027	12	1032	16	99
2.4r	596	43	0.07	98	0.00004	0.074	0.1742	0.0025	1.752	0.031	0.0729	0.0007	1035	14	1028	12	1012	18	102
2.5r	486	45	0.09	79	0.00007	0.110	0.1727	0.0025	1.749	0.032	0.0735	0.0007	1027	14	1027	12	1027	20	100
2.6	112	35	0.31	20	0.00009	0.153	0.1768	0.0026	1.833	0.056	0.0752	0.0019	1050	14	1057	20	1073	50	98
4.1c	290	88	0.30	53	0.00002	0.026	0.1829	0.0030	1.916	0.036	0.0760	0.0006	1083	16	1087	13	1095	16	99
4.2c	112	40	0.35	21	0.00002	0.038	0.1817	0.0029	1.890	0.040	0.0755	0.0009	1076	16	1078	14	1081	24	100
4.3	448	85	0.19	80	0.00001	0.017	0.1840	0.0027	1.889	0.035	0.0745	0.0007	1089	15	1077	12	1054	19	103
5.1	267	97	0.36	49	0.00010	0.162	0.1817	0.0033	1.895	0.044	0.0756	0.0010	1076	18	1079	16	1085	26	99
5.2	103	42	0.40	19	0.00005	0.082	0.1823	0.0032	1.888	0.047	0.0751	0.0011	1079	18	1077	17	1071	31	101
5.3r	893	42	0.05	146	0.00001	0.023	0.1747	0.0025	1.780	0.033	0.0739	0.0008	1038	14	1038	12	1039	21	100
6.1m	1290	193	0.15	233	0.00006	0.096	0.1881	0.0030	1.929	0.033	0.0744	0.0004	1111	16	1091	12	1051	10	106
6.2	272	104	0.38	48	0.00001	0.024	0.1734	0.0031	1.767	0.042	0.0739	0.0010	1031	17	1033	16	1039	28	99
6.3	201	74	0.37	37	0.00001	0.017	0.1796	0.0029	1.854	0.040	0.0749	0.0009	1065	16	1065	14	1065	25	100
7.1	189	65	0.34	33	0.00015	0.247	0.1743	0.0030	1.806	0.043	0.0751	0.0011	1036	16	1047	16	1072	30	97
9.1	322	96	0.30	58	0.00001	0.017	0.1781	0.0031	1.835	0.035	0.0747	0.0005	1056	17	1058	13	1061	14	100
9.2	636	148	0.23	111	0.00001	0.017	0.1781	0.0025	1.834	0.030	0.0747	0.0005	1056	14	1058	11	1061	14	100
9.3	208	73	0.35	38	0.00000	0.006	0.1789	0.0029	1.834	0.041	0.0743	0.0010	1061	16	1058	15	1050	28	101
10.1	329	107	0.33	61	0.00005	0.091	0.1829	0.0032	1.891	0.040	0.0750	0.0008	1083	17	1078	14	1068	21	101
10.2c	86	43	0.49	16	0.00059	1.003	0.1765	0.0034	1.763	0.078	0.0725	0.0027	1048	19	1032	29	999	79	105
10.3	855	95	0.11	83	0.00010	0.169	0.1026	0.0014	0.983	0.018	0.0695	0.0007	629	8	695	9	915	21	69
10.4c	417	183	0.44	76	0.00002	0.031	0.1766	0.0026	1.837	0.035	0.0754	0.0008	1049	14	1059	12	1080	21	97
10.5	350	113	0.32	63	0.00003	0.059	0.1807	0.0026	1.853	0.031	0.0744	0.0005	1071	14	1065	11	1052	15	102
11.1	494	155	0.31	91	0.00009	0.154	0.1828	0.0029	1.888	0.035	0.0749	0.0006	1082	16	1077	12	1067	16	101
11.2	399	193	0.48	78	0.00004	0.068	0.1847	0.0031	1.893	0.039	0.0743	0.0008	1093	17	1079	14	1051	21	104
12.1c	123	65	0.53	24	0.00030	0.506	0.1853	0.0039	1.949	0.062	0.0763	0.0016	1096	21	1098	21	1102	43	99
12.2m	1088	235	0.22	189	0.00013	0.213	0.1775	0.0028	1.774	0.032	0.0725	0.0005	1053	15	1036	12	999	15	105
12.3c	163	70	0.43	30	0.00003	0.055	0.1791	0.0031	1.845	0.040	0.0747	0.0009	1062	17	1062	14	1061	23	100
12.4	518	162	0.31	93	0.00001	0.017	0.1783	0.0025	1.856	0.030	0.0755	0.0005	1058	14	1066	11	1082	14	98
13.1	138	49	0.36	25	0.00001	0.017	0.1788	0.0029	1.861	0.042	0.0755	0.0011	1060	16	1067	15	1082	28	98
14.1	417	132	0.32	75	0.00000	0.002	0.1792	0.0029	1.835	0.035	0.0743	0.0006	1063	16	1058	12	1049	16	101
15.1r	639	31	0.05	107	0.00002	0.030	0.1794	0.0027	1.814	0.029	0.0733	0.0003	1064	15	1050	11	1023	9	104
16.1	209	82	0.39	39	0.00001	0.017	0.1818	0.0030	1.881	0.036	0.0750	0.0006	1077	16	1074	13	1069	17	101
17.1	524	166	0.32	94	0.00001	0.010	0.1782	0.0026	1.837	0.031	0.0748	0.0005	1057	14	1059	11	1062	14	100
18.1	250	79	0.32	45	0.00001	0.017	0.1772	0.0027	1.830	0.033	0.0749	0.0006	1052	15	1056	12	1066	16	99
19.1r	713	100	0.14	116	0.00006	0.098	0.1706	0.0025	1.724	0.032	0.0733	0.0007	1015	14	1018	12	1022	20	99
19.2	175	57	0.32	31	0.00017	0.290	0.1758	0.0033	1.801	0.062	0.0743	0.0020	1044	18	1046	23	1049	55	100

Notes: (1) Uncertainties given at the 1σ level. (2) f_{206} denotes the percentage of ^{206}Pb that is common Pb. (3) Correction for common Pb made using the measured ^{204}Pb/^{206}Pb ratio. (4) For concentration, 100% denotes a concordant analysis. (5) * Denotes repeat analysis on the same spot. (6) CL and other characteristics: r: dark CL, low Th/U phase; c: apparent core; m: mixed analysis.

Table 5
SHRIMP U–Pb results for sample UND 199, Fafa pluton

Grain spot	U (ppm)	Th (ppm)	Th/U	Pb* (ppm)	^{204}Pb/^{206}Pb	f_{206} (%)	Radiogenic ratios						Ages (in Ma)						Concentrtion (%)
							^{206}Pb/^{238}U	±	^{207}Pb/^{235}U	±	^{207}Pb/^{206}Pb	±	^{206}Pb/^{238}U	±	^{207}Pb/^{235}U	±	^{207}Pb/^{206}Pb	±	
1.1	123	40	0.33	23	0.000174	0.30	0.1842	0.0094	1.886	0.110	0.0743	0.0017	1090	51	1076	40	1049	48	104
2.1	736	143	0.19	126	0.000058	0.10	0.1758	0.0028	1.797	0.031	0.0742	0.0003	1044	15	1045	11	1046	9	100
3.1	184	58	0.32	33	0.000215	0.37	0.1782	0.0028	1.796	0.038	0.0731	0.0009	1057	15	1044	14	1018	25	104
4.1	127	78	0.62	25	0.000413	0.70	0.1786	0.0039	1.803	0.059	0.0733	0.0016	1059	22	1047	22	1021	44	104
4.2	527	116	0.22	81	0.000307	0.52	0.1573	0.0025	1.585	0.033	0.0731	0.0008	942	14	964	13	1016	23	93
5.1	52	22	0.42	10	0.000457	0.78	0.1775	0.0039	1.800	0.095	0.0736	0.0033	1054	22	1046	35	1029	94	102
5.2	480	95	0.20	82	0.000057	0.10	0.1760	0.0028	1.794	0.032	0.0739	0.0005	1045	15	1043	12	1040	13	101
6.1	75	17	0.22	13	0.000873	0.94	0.1754	0.0039	1.767	0.053	0.0731	0.0013	1042	21	1033	20	1016	36	103
7.1	465	94	0.20	73	0.000303	0.52	0.1605	0.0027	1.615	0.037	0.0730	0.0009	960	15	976	14	1014	26	95
8.1	391	140	0.36	68	0.000102	0.17	0.1705	0.0029	1.732	0.034	0.0737	0.0006	1015	16	1020	13	1032	16	98
9.2	756	138	0.18	126	0.000082	0.14	0.1711	0.0028	1.741	0.032	0.0738	0.0005	1018	16	1024	12	1037	13	98
10.1	1439	38	0.03	125	0.001276	2.17	0.0921	0.0015	0.934	0.020	0.0736	0.0009	568	9	670	11	–	–	–
10.2	117	43	0.37	21	0.000278	0.47	0.1795	0.0038	1.836	0.057	0.0742	0.0015	1064	21	1058	21	1046	40	102
10.3	500	91	0.18	85	0.000765	1.30	0.1740	0.0028	1.775	0.040	0.0740	0.0011	1034	15	1036	15	1042	29	99
11.1	263	59	0.22	45	0.000115	0.20	0.1744	0.0030	1.768	0.036	0.0735	0.0007	1037	16	1034	13	1028	19	101
12.1	75	24	0.33	13	0.000305	0.52	0.1779	0.0047	1.819	0.065	0.0741	0.0016	1056	26	1052	24	1045	44	101
13.1	58	24	0.42	11	0.000405	0.69	0.1811	0.0043	1.848	0.086	0.0740	0.0027	1073	24	1063	31	1042	76	103
14.1	61	14	0.23	11	0.000683	0.66	0.1787	0.0045	1.879	0.061	0.0762	0.0013	1060	25	1074	22	1101	36	96

Notes: (1) Uncertainties given at the 1σ level. (2) f_{206} denotes the percentage of ^{206}Pb that is common Pb. (3) Correction for common Pb made using the measured ^{204}Pb/^{206}Pb ratio. (4) For concentration, 100% denotes a concordant analysis.

Table 6
Summary of results for various Oribi Gorge Suite plutons

Pluton		Technique	Date (Ma) ± 95% confidence uncertainity	Interpretation	Reference
Mgeni		Zr bulk population	1030 ± 20	Emplacement	Eglington et al. (1989b)
		Ap bulk population	940 ± 7	Cooling	Eglington et al. (1989b)
		Rb–Sr wr	1001 ± 35	Emplacement	Eglington et al. (1989b)
		Rb–Sr bi	~940	Cooling	Nicolaysen and Burger (1965)
Fafa		Zr SHRIMP	1037 ± 10	Emplacement	This study
		Zr ID-TIMS	1029 + 11/−10	Emplacement	Thomas et al. (1993b)
		Zr ID-TIMS + SHRIMP	1037 ± 7	Emplacement	Thomas et al. (1993b); this study
		Rb–Sr wr	878 ± 22	Cooling	Eglington and Kerr (1989)
		Rb–Sr bi	915 ± 19	Cooling	Thomas et al. (1993b)
Mvenyane		Rb–Sr wr	991 ± 39	Cooling	Thomas (1988a)
		Rb–Sr bi	973 ± 17	Cooling	Thomas et al. (1993b)
Oribi Gorge (in Oribi Gorge)	Cores	Zr SHRIMP	1071 ± 12	Inheritance	This study
	Magmatic	Zr SHRIMP	1063 ± 5	Emplacement	This study
	Cores + magmatic	Zr SHRIMP	1064 ± 5	Emplacement	This study
	Rims	Zr SHRIMP	1029 ± 8	Metamorphic overgrowths	This study
		Bulk population	1038 ± 18	Mixture of inheritance, magmatic and metamorphic growth	Thomas (1988a)
		Rb–Sr wr	1003 ± 29		Thomas (1988a)
		Rb–Sr bi	924 ± 49	Cooling	Thomas et al. (1993b)
		Rb–Sr bi	882 ± 18	Cooling	Thomas et al. (1993b)
Oribi Gorge (Bomela locality)		Zr SHRIMP	1082 ± 7	Mixture of inheritance and magmatic growth	This study
		Zr evaporation	1068 ± 2	Mixture of inheritance and magmatic growth	Thomas et al. (1993b)
		Rb–Sr wr	891 ± 56	Cooling	Eglington et al. (1986b)
		Rb–Sr bi	938 ± 10	Cooling	Thomas et al. (1993b)
Oribi Gorge (both localities)	Cores + magmatic	Zr SHRIMP	1070 ± 4	Emplacement	This study
Port Edward		Zr SHRIMP	1025 ± 8	Emplacement	This study
		Rb–Sr wr	987 ± 19	Cooling	Eglington et al. (1986b)
		Rb–Sr bi	~990	Cooling	Nicolaysen and Burger (1965)

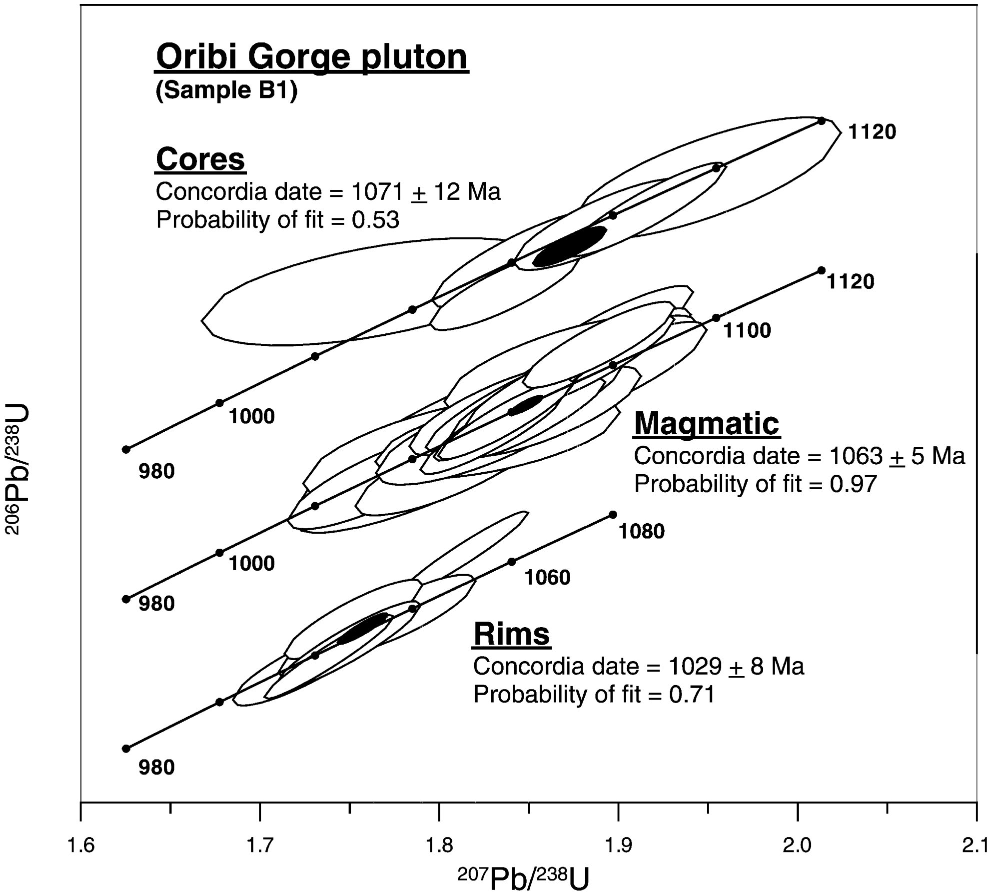

Fig. 6. Wetherill plot of SHRIMP analyses for core, magmatic and rim in zircons for sample B1 from Oribi Gorge near the centre of the Oribi Gorge pluton. The individual analyses (1σ error ellipses), define concordia dates with weighted average error ellipses shown in black.

Data for the core and magmatic features of sample B1 are also statistically similar to the data for sample UND 215. Combining these results provides a concordia date of 1070 ± 4 Ma (probability of fit = 0.48) which is considered the best estimate for intrusion of the Oribi Gorge pluton.

6.3. *Fafa granite*

Eighteen spots were analysed on fourteen grains of sample UND 199, primarily concentrating on areas with clear growth zoning evident on the CL images. Data are provided in Table 5. Regression of the data for all eighteen spots provides an upper intercept date of 1037 ± 10 Ma with a lower intercept of 22 ± 82 Ma (probability of fit = 0.97, Fig. 7). Attempts to date domains which resembled cores did not provide older dates consistent with inheritance. The date of 1037 ± 10 Ma is within error of the small sample, ID-TIMS result but is older than the dominant peak evident in the evaporation data (Thomas et al., 1993b). Regressing the combined ID-TIMS and SHRIMP data provides a date of 1032 ± 7 Ma (probability of fit = 0.95) which is considered the age of emplacement of this pluton.

Results for the various Oribi Gorge Suite plutons are summarised in Table 6.

7. Discussion of zircon geochronology

The Oribi Gorge Suite in KwaZulu/Natal comprises several late- to post-tectonic megacrystic granitoids

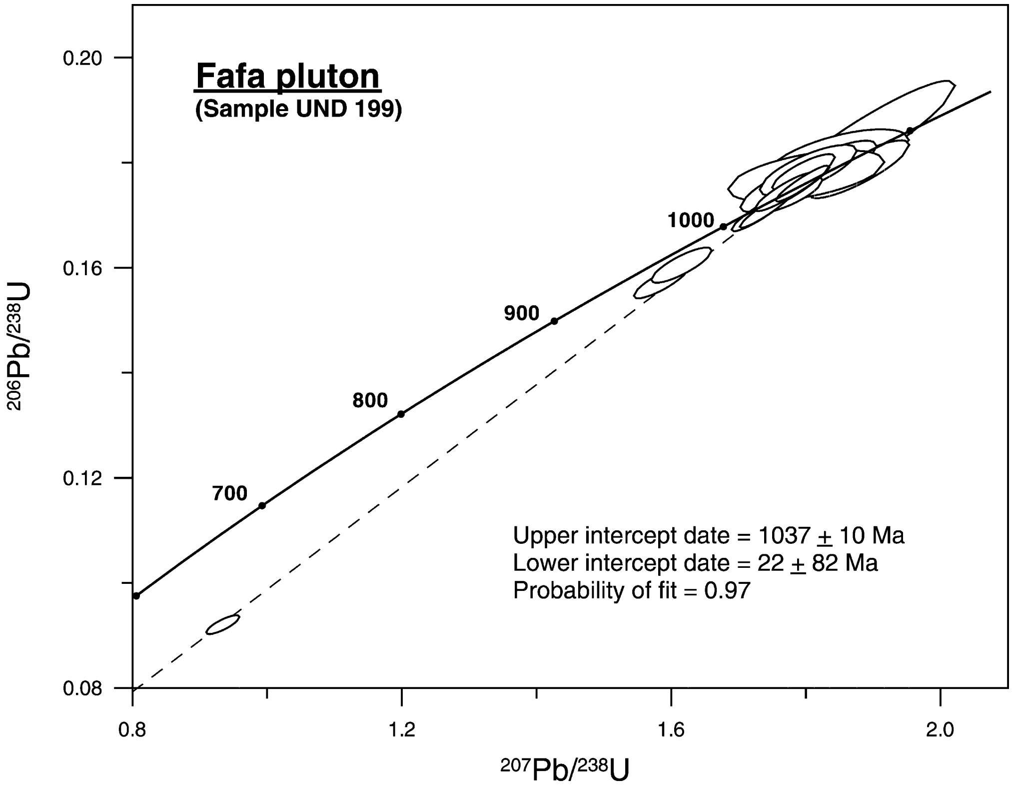

Fig. 7. Wetherill plot of SHRIMP analyses of domains exhibiting concentric growth zoning in zircons for sample UND 199 from the Fafa pluton. The individual analyses (1σ error ellipses), define an upper intercept date of 1037 ± 10 Ma.

(Thomas, 1988a,b). The zircon data presented here for the Fafa, Port Edward and Oribi Gorge plutons have provided a range of dates from ∼1071 to 1025 Ma. Considering all the available data, there appear to have been two episodes of intrusion at ∼1070 and 1030 Ma (Fig. 8) with metamorphic growth of zircon at ∼1030 Ma in the case of the Oribi Gorge pluton.

The range of ∼45 Ma (1070–1025 Ma) is too large for the plutons to belong to one coeval suite, but no features have previously been evident in the zircons to identify any form of inheritance or younger overgrowth. Results other than ∼1025 Ma are only apparent from the Oribi Gorge pluton (and possibly also in the Ntimbankulu pluton, see below) but the variation calls into doubt the correlation of all plutons included in the suite as coeval. The Oribi Gorge pluton has been dated from two localities: bulk population U–Pb zircon from samples within Oribi Gorge (Thomas, 1988a; Thomas et al., 1993b) and from a locality near Bomela railway siding. Rb–Sr dating from these localities provides evidence for substantial open-system behaviour (Eglington et al., 1986a; Thomas et al., 1993b), despite the presence of fayalite at the Bomela locality. Dating of core, magmatic and rim features from sample B1 demonstrates that the Oribi Gorge pluton was emplaced at ∼1070 Ma and was subsequently metamorphosed at ∼1030 Ma. Older cores within the magmatic domains have ages statistically equivalent to the magmatic domains, suggesting that the source material for these cores was only slightly older than the magmatism which produced the Oribi Gorge pluton or that zircon growth occurred in two pulses within the magma. The ∼1070 Ma date obtained for the Oribi Gorge pluton is similar to that inferred for the Ntimbankulu pluton (Thomas et al., 1999), based on the growth of ∼1060 Ma rims on older zircons in the Quha Formation close to the margin of the pluton. In contrast, the Fafa and Port

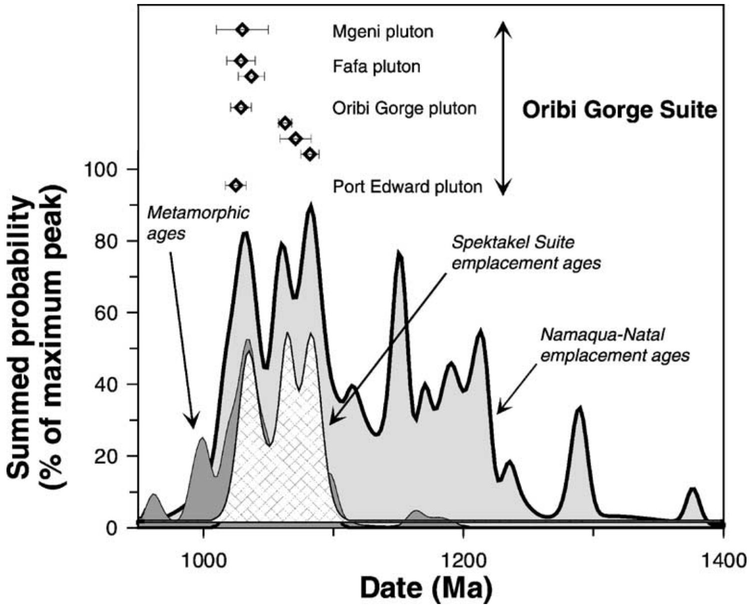

Fig. 8. Plot of dates obtained for the Oribi Gorge Suite relative to summed probability distributions of dates from the Namaqua–Natal Belt and from late-orogenic granitoids of the Spektakel Suite in the Western (Namaqua) sector of the belt (Barton, 1983; Thomas et al., 1996; Robb et al., 1999; Eglington, 2000a,b).

Edward plutons were intruded at ∼1030 Ma. Since all the Oribi Gorge Suite plutons are thought to have been produced as a result of melting associated with trans-current shearing late in the history of the belt, this activity must have been repeated at least twice (in this sector of the belt) over a period of 45 Ma.

Approximately 1030 (Port Edward and Fafa plutons) and 1070 Ma emplacement dates are evident from Oribi Gorge Suite plutons in both the Margate and Mzumbe terranes. These terranes must therefore have been juxtaposed by at least 1070 Ma. This is consistent with Ar–Ar dates which suggest that the principle foliation-defining tectonism was concluded by ∼1130 Ma when the Tugela Terrane was thrust onto the southern edge of the Kaapvaal Craton (Jacobs et al., 1997).

Biotite—whole-rock dates for the various units provide an indication of the post-intrusion metamorphic history of these rocks. In all cases, biotite model dates are about 950–980 Ma, indicating that there has not been any significant (>300 °C) metamorphic overprint subsequent to this time and that post-intrusion cooling must have been quite rapid.

Late tectonic, porphyritic granitoid-charnockites, classified as the Spektakel Suite, are also observed ∼1200 km to the west in the Namaqua sector of the belt (Thomas et al., 1996; Eglington, 2000a). These granitoids were intruded at the same time as the Oribi Gorge Suite, coincident with the principle period of high-grade metamorphism, at least as preserved in the geochronological record (Fig. 8). Similar ages are also apparent for megacrystic granite from borehole intersections of basement in the intervening area (Eglington and Armstrong, 2003). The large geographic spread of these various granitoids suggests that the orogenic processes involved in their formation are regional in extent, probably associated with the escape tectonic structures late in the evolution of the belt (Jacobs et al., 1993) when localised transtensional conditions occurred along the sinistral shear zones.

8. Conclusions

Timing of intrusion of the Oribi Gorge Suite plutons is important, both in terms of constraining local intrusive successions and in providing a minimum date for juxtaposition of the Margate and Mzumbe terranes since the suite is present in both terranes. The dates from various domains of zircons from the suite range from ~1071 to 1025 Ma, indicating that terrane accretion was complete by this stage. There appear to have been two episodes of intrusion at ~1070 and 1030 Ma. Metamorphic growth of zircon at ~1030 Ma is evident in the Oribi Gorge pluton. Considering only those dates interpreted as dating emplacement, the resulting range of ~45 Ma (1070–1025 Ma) is larger than expected for plutons belonging to a single coeval suite.

The dating implies episodic generation during the late-tectonic trans-current shearing event, so this activity occurred over a period of at least 45 Ma. This is consistent with the assertions of Jacobs and Thomas (1994) and Jacobs et al. (1997) that the shearing event was a long-lived tectonic episode.

Similar ages for late tectonic porphyritic granitoid-charnockites are also observed in the Namaqua sector of the belt, more than 1000 km further west. The wide spread in similar granitoid emplacement suggests that the processes involved relate to major regional orogenic tectonism, probably associated with the escape tectonic structures late in the evolution of the belt (Jacobs et al., 1993).

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