U–Pb SHRIMP ages and tectonic setting of the Munster Suite of the Margate Terrane of the Natal Metamorphic Belt

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ABSTRACT

New U–Pb Zircon SHRIMP ages of 1091 ± 7.1 Ma and 1093.1 ± 5.8 Ma have been determined for two discrete phases of the Munster Suite. The Munster Suite is a calc-alkaline mafic to intermediate suite of intrusive igneous rocks that form part of the southern-most tectonic Terrane of the Mesoproterozoic-aged Natal Metamorphic Belt. Previously published geochemical data indicate that the discrete phases of the Suite are consanguineous and that these rocks originated within an oceanic island arc environment. The new age determinations now show that the different phases are also coeval. Moreover, the ages also indicate that the intrusions were, within statistical error, coeval with S-type granites within the Terrane. This is interpreted to indicate that magmatic underplating provided both the magma by way of a number of progressively more evolved pulses to produce the Munster Suite, as well as the heat necessary for crustal melting to produce the S-type granites within an island arc environment. Therefore, these new age determinations indicate a period of crustal growth at *circa* 1090 Ma. This moreover, is a maximum constraint on the age of the northward-verging structures within the Margate Terrane.

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1. Introduction

U–Pb zircon ages have proven to be invaluable in elucidating the timing and sequence of tectonic events in many metamorphic belts (Skridlaite et al., in press; Mallmann et al., 2007; D'el-Rey Silva et al., 2007; Wang et al., 2007; Santosh et al., 2006a,b). This type of information permits the interpretation of tectonic histories of individual belts, as well as the interpretation of their tectonic setting and an understanding of crustal processes that formed and deformed them (Mallmann et al., 2007; Paulsen et al., 2007; Santosh et al., 2006a,b). Moreover, this information constitutes important evidence on which global correlations are based, which in turn, are used for reconstruction of continental evolution (Paulsen et al., 2007; D'el-Rey Silva et al., 2007; Wang et al., 2007; Casquet et al., 2006). An example of this is the need for information on the tectonic evolution of the Natal Metamorphic Belt to resolve the, currently equivocal, Neoproterozoic position of the Kalahari craton in relation to Rodinia (Jacobs et al., 2003; Dalziel et al., 2000; Jacobs et al., 1999).

The Natal Metamorphic Belt (NMB) comprises remnants of island arcs that accreted onto the southern margin of the Kaapvaal Craton (Jacobs et al., 1993), and is considered to be an extension of the Namaqualand Metamorphic Province in Southwestern Africa and the gneiss terranes of

Western Dronning Maud Land of East Antarctica (Nicholaysen and Burger, 1965; De Beer and Meyer, 1984; Jacobs et al., 1993).

There is a significant amount of literature on the intrusive and tectonic history of the Margate Terrane of the Natal Metamorphic Belt (NMB) (Gevers and Dunne, 1942; Du Toit, 1946; McIver, 1963, 1966; Grantham, 1983; Talbot and Grantham, 1987; Thomas, 1988a, 1989; Jacobs et al., 1993; Mendonidis et al., 2002; McCourt et al., 2006). In particular, the intrusive history of the southern part of the Margate Terrane has been documented in detail by Grantham (1983) and Mendonidis (1989) and an excellent summary of the salient events is provided by McCourt et al. (2006).

Previously published geochronological data has indicated that the maximum age of 1091 ± 9 Ma for the tectonism in the Margate Terrane (Mendonidis et al., 2002) is far younger than the ages that constrain the timing of the tectonism in the Tugela Terrane where the Syn-D3 (obduction event), post-D2 Wosi granitoid Suite (now called the Mtungweni granitoids) yielded an intrusive age of 1155 ± 1 Ma (Johnston et al., 2001), confirming the suggestion that the Margate Terrane was a younger accretion to the Natal Belt (Mccourt et al., 2006).

Field-based studies (Grantham, 1983; Mendonidis, 1989) have provided a relative intrusive history for the southern part of the Terrane. However, poor preservation of early (S1) fabrics in the intrusive rocks that otherwise display only a very well defined S2 foliation has necessitated further geochronological data in order to further understand the tectono-magmatic history of this Terrane. To

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this end, U–Pb SHRIMP ages for two samples from the Munster Suite were acquired in this study.

2. Geological setting

The Natal Metamorphic Belt (NMB) consists of three tectonic terranes (Thomas, 1989) (Fig. 1) that are interpreted as the remnants of island arcs that accreted onto the southern margin of the Kaapvaal Craton (Jacobs et al., 1993).

The Tugela Terrane comprises supracrustals of igneous and sedimentary origin that have island arc geochemical signatures (Arima et al., 2001), and that were obducted onto the southern margin of the Kaapvaal Craton (Matthews, 1972). The oldest rocks in the Tugela Terrane are the Kotangweni Tonalitic Gneisses, which pre-dated the D1-event and have an age of 1209 ± 5 Ma (Johnston et al., 2001). The

syn-D2 Mkondeni Diorite provided an age of 1161 ± 9 Ma (Johnston et al., 2001), and the post-D2 Wosi Granitoid Suite (now called the Mtungweni granitoids), which is considered to have intruded during the D3 obduction event, has an age of 1155 ± 1 Ma (Johnston et al., 2001). The Dulumbe paragneisses, which form the structurally highest tectonic unit, yielded a detrital zircon age of 1276 ± 10 Ma (Johnston et al., 2001). The southern margin of the Tugela Terrane is delineated by the Lilani-Matigulu shear zone. This shear zone also marks the southern extent of the underlying Kaapvaal Craton (Barkhuizen and Matthews, 1990), indicating that the entire Tugela Terrane overlies Archaean crust of the Kaapvaal Craton.

The Mzumbe Terrane covers a large area south of the Lilani-Matigulu shear zone. The oldest rocks of this terrane are supracrustals of the Mapumulo Group, of which the meta-andesites of the Quha Formation provided an eruption age of 1235 ± 9 Ma (Thomas et al.,

Fig. 1. Locality map showing the three terranes of the Natal Metamorphic Belt that accreted onto the southern Margin of the Kaapvaal Craton (McCourt et al., 2006).

1999). The tonalitic orthogneisses of the Mzombe TTG suite, which intruded the Mapumulo Group rocks, gave an age of 1207 ± 10 Ma (Thomas and Eglinton, 1990), which provides a maximum age for the D1/M1 event in this Terrane. The gabbroic component of the Equefa Suite gave a U–Pb SHRIMP age of 1082 ± 2 Ma, which is also a direct age of the D2 event since this was a syn-kinematic intrusion (Data of B.M. Eglinton reported in McCourt et al., 2006). A heating event at 1065 ± 15 Ma is indicated by U–Pb SHRIMP ages of metamorphic overgrowths on zircon grains from the Quha Formation.

A number of large charnockitic A-type plutons intruded both the Mzombe and Margate terranes. These plutons collectively form a rapakivi granite–charnockite association with A-type geochemical characteristics (Grantham et al., 2001). Some of these plutons contain a penetrative S_2 foliation (e.g. Port Edward pluton—Grantham, 1983), whereas others have undeformed cores (Thomas, 1988b), and they have been considered to be late- to post-tectonic relative to D_2 (Thomas et al., 1993a,b). U–Pb SHRIMP ages of these plutons, reported by Thomas et al. (1993a,b) and Eglinton et al. (2000), range from ~ 1025 to 1100 Ma, and Eglinton et al. (2003) have identified two distinct pulses of magmatism at ~ 1070 Ma and ~ 1030 Ma.

The Margate Terrane lies south of the Melville Thrust (Fig. 1) and can be visualized in terms of sheets of mafic and granitic rocks that intruded layers of metasedimentary rocks all of which define northward-verging F_2 folds (e.g. Talbot and Grantham, 1987). The lithostratigraphy of the Terrane, based on field relationships, places the Leisure Bay metasedimentary rocks as the oldest lithology that was intruded by the Glenmore Granite, which was, in turn intruded by the Munster Suite metabasites, and subsequently by the Margate Suite granites and then the Oribi Gorge Suite granitoids (Grantham, 1983; Mendonidis, 1989; McCourt et al., 2006). The tectonic history of the Margate Terrane has been outlined by Talbot and Grantham (1987), Mendonidis and Strydom (1989) and Mendonidis and Grantham (2003). Essentially, the Terrane has undergone two tectonic events, D1/M1 and D2/M2. D1 is characterized by a S_1 fabric and rootless isoclinal F_1 folds in the Leisure Bay metasedimentary rocks and locally preserved S_1 fabrics in some granites. M1 is characterized by low-pressure granulite facies metamorphism and anticlockwise cooling paths. D2 involved northward-verging folding of all the lithologies and the development of a pervasive southward-dipping S_2 foliation. The M2 metamorphism caused a second period of anatexis at higher pressures than those of M1.

Radiometric ages for a number of lithologies from the Margate Terrane have been determined (Table 1). In addition to these, detrital zircon grains from the Leisure Bay Formation, which is considered to be the oldest lithological unit in the Margate Terrane (Grantham, 1983; Mendonidis, 1989; Thomas, 1989), have yielded U–Pb SHRIMP ages ranging between ~ 1730 and ~ 1196 Ma (R.A. Armstrong, unpublished data).

Mendonidis et al. (2002) concluded that the 1091 ± 9 Ma age for the Glenmore Granite provides a maximum age for the D1/M1 event that affected the rocks of the Margate Terrane, since the Glenmore Granite preserves evidence of S_1 and S_2 fabrics (Talbot and Grantham, 1987). The younger intrusive lithologies were considered to have post-dated D1 because they do not preserve a S_1 fabric. However, Mendonidis and Strydom (1989) reported the presence of preserved S_1 fabrics in granites of the Margate Suite, suggesting that although the Munster does not

Fig. 2. Map showing the littoral distribution of the different phases of the Munster Suite.

preserve a S_1 fabric it did predate D1. It may be pertinent to note that the preserved S_1 foliations in both the Margate and Glenmore granites are restricted to localities adjacent to folded contacts against the Leisure Bay metasedimentary rocks. The ages of the S_1 and S_2 fabric in the Margate Terrane are constrained between a minimum of 1026 Ma, which is the age determined on the undeformed Mbizana microgranite dykes (Thomas et al., 1993a,b), and a maximum of 1091 ± 9 Ma, which is the age of the Glenmore Granite (Mendonidis et al., 2002).

3. The Munster Suite

The Munster Suite comprises folded sheet-like bodies of mafic to intermediate orthogneisses that have a very strongly developed southward-dipping S_2 foliation. These rocks are intrusive into the

Table 1

Published radiometric ages of lithologies of the Margate Terrane of the Natal Metamorphic Belt

Lithology	Age	Authors
Sikombe granite	1181 ± 15 Ma [U–Pb SHRIMP]	Thomas et al. (2003)
Glenmore granite	1091 ± 9 Ma [U–Pb SHRIMP]	Mendonidis et al. (2002)
Port Edward pluton (Oribi Gorge Suite)	1025 ± 8 Ma [U–Pb SHRIMP]	Eglinton et al. (2003)
Mbizana microgranite dykes	1026 ± 3 Ma [U–Pb SHRIMP]	Thomas et al. (1993a, b)

Fig. 3. Bivariate plots of the whole-rock geochemical data of the Munster Suite showing the constant Nb/Y ratio and smooth trends that suggest consanguinity between the various intrusive phases.

metasedimentary Leisure Bay granulites and the Glenmore Granite (Mendonidis and Strydom, 1989). Rocks of this suite vary compositionally from medium-grained, quartz-free, two-pyroxene mafic granulite (metabasites) to coarse-grained, porphyritic, two-pyroxene quartz–monzonorite (mangerite) (Mendonidis and Grantham, 1989). The distribution of these rocks is presented in Fig. 2. Detailed petrographic and geochemical descriptions are given by Mendonidis and Grantham (1989).

The different phases, namely the medium-grained metabasites, porphyritic monzonites and quartz–monzonites, crop out at different localities along the southern Natal littoral (Fig. 2). Consanguinity was demonstrated geochemically by Mendonidis and Grantham (1989) in terms of smooth trends on Harker diagrams and consistent Nb/Y ratios (Fig. 3). Grantham (1983) found field evidence that the monzonites post-dated the metabasites. This led him to conclude that the magma was tapped progressively from a deep-seated evolving magma chamber.

Whole-rock geochemical data published in Mendonidis and Grantham (1989) show that the Munster Suite is calc-alkaline in nature (Fig. 4). On a Pearson-type spidergram, the incompatible element pattern of the Munster Suite data is very similar to that of modern-day island arcs, but enriched for each element (Fig. 5). On the Na–Nb–Sr discrimination diagram (Vermeesch, 2006) the data plot in the island arc basalt field, whereas on the Ti–Si–Sr diagram (Vermeesch, 2006) the data straddle the island arc and the oceanic island basalt fields (Fig. 6). The data fall well within the oceanic island arc region on the TiO₂–P₂O₅–MnO diagram of Mullen (1983) (Fig. 6). On the Ti–Zr–Y of

Meschede (1986) and the Nb–Zr–Y diagram of Pearce and Cann (1973), many of the data points fall outside the indicated regions, suggesting a Zr enrichment in the samples (Fig. 7). Similarly, on the Zr/Y versus Zr discrimination diagram (Pearce and Norry, 1979) the data fall in the “within plate basalt” region characterized by high Zr contents (Fig. 7).

4. Geochronology

4.1. Sampling

Two samples were collected, one of the quartz–monzonites from the Palm Beach exposures (sample PM07/1), and one of the medium-grained mafic granulites from the Munster Headland (sample PM07/4).

Both samples were submitted to the Council for Geoscience at Pretoria for zircon extraction. At the Research School of Earth Science (Australian National University) zircon grains were handpicked and mounted in epoxy and polished.

4.2. Analytical procedure

Standards used for SHRIMP analyses were the zircon standard AS3 (Duluth Complex gabbroic anorthosite; Paces and Miller, 1989) and the RSES standard SL13. The SHRIMP data were reduced in a manner similar to that described by Compston et al. (1992) and Williams and Claesson (1987). U/Pb ratios in the unknowns were normalised to a ²⁰⁶Pb/²³⁸U value of 0.1859 (equivalent to an age of 1099.1 Ma) for AS3. The U and Th concentrations were determined relative to those measured in the SL13 standard. Correction for common Pb was made from the measured ²⁰⁴Pb and the appropriate common Pb isotopic compositions assuming the Cumming and Richards (1975) model.

4.3. Quartz–monzonites from the Palm Beach exposures (sample PM07/1)

Zircon grain morphology was studied under cathodoluminescence. The zircons were mostly anhedral and fractured with only occasional subhedral grains preserving prism faces (Fig. 8). Most zircons showed metamorphic rounding and resorption features. Most grains appeared to be magmatic, but many of the grains were zoned and some structurally complex with zones of high U and Th contents and metamictisation contrasting with less structured areas. Some of these zones possibly represent inherited cores. Metamorphic rims are commonly present, characterized by high U and Th contents.

The data from the quartz–monzonitic sample (PM07/1) are presented in Table 2. A total of 19 spots on 16 grains were analysed, of

Fig. 4. AFM plot of Irvine and Baragar (1971) showing the calc-alkaline nature of the Munster Suite rocks.

Fig. 5. Pearson-type spider diagrams comparing the incompatible element concentrations to those of some modern-day island arcs. The number of elements used in the diagrams was constrained by the data available in Mendonidis and Grantham (1989). The diagrams on the left are MORB-normalised (Pearce, 1983) and those on the right normalized to the average oceanic island arc (Sun, 1980). Data for the modern-day island arcs are from Mozier et al. (1997) (New Hebrides), Machado et al. (2005) (South Shetland Arc) and Elburg et al. (2007) (Sunda Arc).

Fig. 6. Geochemical tectonic discrimination ternary diagrams: a. Nb–Na–Sr (Vermeesch, 2006) b. Ti–Si–Sr (Vermeesch, 2006) c. TiO₂–MnO–P₂O₅ (Mullen, 1983). MORB=mid ocean ridge basalt; OIB=oceanic island basalt; IAB=island arc basalt; OIA=oceanic island alkali basalt; OIT=oceanic island tholeiite; CAB=island arc calc-alkaline basalt; IAT=island arc tholeiite.

which 12 were considered to be on magmatic grains/zones. These generated an age of 1091 ± 7.1 Ma (Fig. 9), which probably represents the age of magmatic crystallization of the quartz–monzonite.

Fig. 7. Geochemical tectonic discrimination diagrams: a. Ti–Zr–Y ternary diagram after Pearce and Cann (1973); A= island arc tholeiites, B= mid ocean ridge basalts, C= calc-alkali basalts, D= within plate basalts. b. Zr–Nb–Y ternary diagram after Meschede (1986); AI= within plate alkali basalts, AII= within plate alkali basalts and tholeiites, B= E-type MORB, C= within plate tholeiites and volcanic arc basalts, D= N-type MORB and volcanic arc basalts. c. Zr/Y versus Zr plot of Pearce and Norry (1979); A= volcanic arc basalts, B= MORB, C= within plate basalts, D= MORB and volcanic arc basalts, E= type MORB and within plate basalts.

Table 2

Summary of SHRIMP U–Pb zircon data for sample PM07/1

Grain spot ^a	% ²⁰⁶ Pb _c	ppm U	ppm Th	²³² Th/ ²³⁸ U	ppm ²⁰⁶ Pb _c *	(1) ²⁰⁶ Pb/ ²³⁸ U age	(1) ²⁰⁷ Pb/ ²⁰⁶ Pb age	% discordant	(1) ²⁰⁷ Pb _c */ ²⁰⁶ Pb _c *	±%	(1) ²⁰⁷ Pb _c */ ²³⁵ U	±%	(1) ²⁰⁶ Pb _c */ ²³⁸ U	±%	Err corr
1.1r	0.20	111	57	0.53	16.8	1044 ±12	1057 ±24	1	0.07457	1.2	1.807	1.7	0.1757	1.2	0.710
1.2m	0.00	829	181	0.23	133	1101 ±10	1096.5 ±6.4	0	0.07606	0.32	1.954	1.1	0.1863	1	0.955
1.3c	0.00	232	99	0.44	36.8	1092 ±13	1119 ±12	2	0.07693	0.6	1.957	1.4	0.1845	1.3	0.903
2.1m	0.07	64	38	0.61	10.4	1120 ±14	1099 ±41	–2	0.0762	2.1	1.992	2.5	0.1897	1.4	0.558
3.1m	0.00	516	188	0.38	81.9	1094 ±11	1077.7 ±8.5	–2	0.07534	0.42	1.92	1.1	0.1849	1.1	0.928
4.1m	0.00	358	110	0.32	56.7	1092 ±11	1088 ±10	0	0.07574	0.51	1.927	1.2	0.1846	1.1	0.903
5.1c	0.08	106	78	0.76	16.8	1092 ±13	1109 ±21	2	0.07653	1.1	1.948	1.7	0.1847	1.3	0.767
5.2r	–	1259	42	0.03	140	786.2 ±7.6	1015.5 ±6.4	23	0.07305	0.32	1.307	1.1	0.1297	1	0.956
6.1m	0.00	508	213	0.43	80.6	1092 ±11	1087.1 ±8.7	0	0.0757	0.43	1.927	1.1	0.1846	1.1	0.926
7.1m	0.00	578	121	0.22	91	1085 ±11	1065.1 ±8.5	–2	0.07487	0.42	1.893	1.1	0.1833	1.1	0.929
8.1m	0.00	622	234	0.39	100	1106 ±11	1095.9 ±9.4	–1	0.07603	0.47	1.962	1.2	0.1872	1.1	0.913
9.1m	0.00	516	217	0.43	80.9	1080 ±11	1096 ±8.8	1	0.07603	0.44	1.912	1.1	0.1824	1.1	0.924
10.1r	0.00	270	149	0.57	41.2	1054 ±11	1031 ±15	–2	0.0736	0.75	1.803	1.4	0.1777	1.1	0.832
11.1m	0.00	321	122	0.39	49	1056 ±11	1075 ±11	2	0.07526	0.57	1.846	1.2	0.1779	1.1	0.889
12.1r	0.03	752	50	0.07	64.1	610.1 ±6.2	924 ±12	34	0.06984	0.6	0.956	1.2	0.0993	1.1	0.869
13.1m	0.00	350	123	0.36	56.4	1108 ±11	1116 ±11	1	0.07679	0.55	1.986	1.2	0.1876	1.1	0.895
14.1m	0.00	329	108	0.34	51.9	1088 ±11	1086 ±18	0	0.07564	0.89	1.918	1.4	0.1839	1.1	0.778
15.1m	0.02	468	161	0.36	71.8	1060 ±11	1091 ±10	3	0.07585	0.51	1.868	1.2	0.1787	1.1	0.904
16.1r	0.00	183	153	0.86	27.5	1042 ±11	1044 ±18	0	0.07411	0.87	1.793	1.5	0.1754	1.2	0.806

Errors are 1-sigma; Pb_c and Pb* indicate the common and radiogenic portions, respectively.

Error in Standard calibration was 0.16% (not included in above errors but required when comparing data from different mounts).

(1) Common Pb corrected using measured ²⁰⁴Pb.^a Zircon characterisation: m=magmatic, zoned; c=core; r=rim or reworked zone.

4.4. Medium-grained mafic granulites (metabasites) from the Munster headland (sample PM07/4)

The morphologies of the grains from this sample were very similar to those of sample PM07/1 (Fig. 8).

A total of 17 grains were analysed (Table 3). The magmatic zones provided an age of 1093.1 ± 5.8 Ma, which is probably a crystallization age (Fig. 10). The single metamorphic rim that was analysed gave a 207/206 age of 1021 ± 22 Ma (Table 3, spot 4.1). A core provided a 207/206 age of 1238 ± 13 Ma (Table 3, spot 14.1).

4.5. Rim data

A Concordia plot of the rim data from sample PM07/1 gives an age of 1074 ± 27 Ma and a concordia plot of all the rim analyses from both samples provides an age of 1065 ± 23 Ma. These (low precision) data suggest a heating event some 20–30 Ma after intrusion.

5. Discussion

The intrusive ages of 1091 ± 7.1 Ma and 1093 ± 5.8 Ma for these two phases of the Munster Suite are statistically identical indicating that they are coeval. This, in turn, lends some support to the interpretation that these lithologies are consanguineous and derived from a common magma chamber.

Moreover, these ages are also identical to those of the Glenmore Granite which is intruded by Munster Suite metabasites (1091 ± 9 Ma; Mendonidis et al., 2002), as well as to that of the Portobello Charnockites that intruded the Munster Suite quartz–monzonorites at Palm Beach (1093 ± 7.3 Ma; Mendonidis and Armstrong, unpublished data).

These data, therefore, suggest that there was an evolving mafic magma chamber (underplating?) beneath the Margate arc, which not only provided the magma for the Munster Suite intrusions, but also the advective heat source for crustal melting that generated the coeval S-type Glenmore and Portobello Granites. Thus there was a ~1093 Ma magmatic event during which calc-alkaline mafic rocks (Munster Suite) and S-type granites intruded the Leisure Bay granulites in the Margate Terrane.

The plots of the geochemical data recorded in Mendonidis and Grantham (1989) onto various discrimination diagrams are equivocal.

Fig. 8. Cathodoluminescence images of some zircon grains from sample PM07/1 (a) and PM07/4 (b).

Table 3

Summary of SHRIMP U–Pb zircon data for sample PM07/4

Grain spot ^a	% ²⁰⁶ Pb _c	ppm U	ppm Th	²³² Th/ ²³⁸ U	ppm ²⁰⁶ Pb _c *	(1) ²⁰⁶ Pb/ ²³⁸ U age	(1) ²⁰⁷ Pb/ ²⁰⁶ Pb age	% discordant	(1) ²⁰⁷ Pb* ²⁰⁶ Pb*	±%	(1) ²⁰⁷ Pb* ²³⁵ U	±%	(1) ²⁰⁶ Pb* ²³⁸ U	±%	Err corr
1.1 m	0.04	619	67	0.11	96	1070 ±10	1096.9 ±9.5	2	0.07607	0.48	1.893	1.2	0.1805	1.1	0.912
2.1 m	0.03	417	147	0.36	66.9	1104 ±11	1091 ±11	–1	0.07586	0.55	1.954	1.2	0.1868	1.1	0.891
3.1 m	0.05	286	86	0.31	44.6	1077 ±11	1077 ±15	0	0.0753	0.73	1.888	1.3	0.1818	1.1	0.841
4.1r	0.14	177	74	0.43	25.8	1009 ±11	1021 ±22	1	0.07327	1.1	1.712	1.6	0.1695	1.2	0.745
5.1 m	0.00	534	165	0.32	83.7	1080 ±11	1105.7 ±9.4	2	0.0764	0.47	1.921	1.2	0.1824	1.1	0.916
6.1 m	0.02	509	178	0.36	81.5	1102 ±11	1106 ±12	0	0.07643	0.59	1.965	1.2	0.1865	1.1	0.876
7.1 m	0.03	616	192	0.32	97.9	1093 ±11	1091.7 ±7.8	0	0.07587	0.39	1.934	1.1	0.1849	1.1	0.939
8.1 m	0.02	291	103	0.37	47.1	1113 ±11	1082 ±11	–3	0.0755	0.55	1.962	1.2	0.1884	1.1	0.894
9.1 m	0.05	744	181	0.25	117	1086 ±10	1087.6 ±7.7	0	0.07572	0.39	1.915	1.1	0.1834	1	0.937
10.1 m	0.03	351	138	0.41	55.3	1087 ±11	1095 ±10	1	0.07601	0.52	1.924	1.2	0.1836	1.1	0.901
11.1 m	0.00	603	143	0.24	94.7	1083 ±10	1100.8 ±7.7	2	0.07622	0.38	1.923	1.1	0.183	1	0.939
12.1 m	0.02	633	154	0.25	100	1093 ±10	1090 ±7.4	0	0.07581	0.37	1.931	1.1	0.1847	1	0.942
13.1 m	0.00	128	101	0.81	20.5	1098 ±12	1104 ±16	1	0.07633	0.81	1.955	1.5	0.1857	1.2	0.833
14.1c	–	160	71	0.46	29.3	1247 ±13	1238 ±13	–1	0.08169	0.67	2.403	1.3	0.2133	1.2	0.865
15.1 m	0.02	535	211	0.41	83.4	1074 ±10	1096.9 ±8.9	2	0.07607	0.44	1.902	1.1	0.1813	1.1	0.922
16.1 m	0.00	417	139	0.35	67.6	1115 ±11	1084 ±9.1	–3	0.07558	0.46	1.967	1.2	0.1888	1.1	0.922
17.1 m	–	697	238	0.35	107	1062 ±10	1097.3 ±7	3	0.07608	0.35	1.878	1.1	0.179	1	0.948

Errors are 1-sigma; Pb_c and Pb* indicate the common and radiogenic portions, respectively.

Error in standard calibration was 0.17% (not included in above errors but required when comparing data from different mounts).

(1) Common Pb corrected using measured ²⁰⁴Pb.^a Zircon characterisation: m=magmatic, zoned; c=core; r=rim or reworked zone.

However, the Pearce-type spidergrams indicate a marked Nb depletion relative to MORB and oceanic island basalts (Fig. 5), which is a characteristic of island arc basalts thought to be due to rutile remaining in the restite of partially melted subducted slab (Kelemen et al., 1993). The other incompatible elements also follow the same pattern as that of modern island arcs (Fig. 5), but all show higher concentrations. The high Zr concentrations explain the data points that plot within within-plate regions of the discrimination diagrams that use Zr as a discriminant parameter (Fig. 7). Pearce et al. (1995) argued that very little Zr and a small percentage of the P and Ti concentrations in island arc magmas are contributed by the subducting slab so their origins must be from the mantle wedge overlying the slab and contamination. Therefore, other reasons for the observed enrichment of incompatible elements in the Munster rocks are needed. One possible reason may be that the Munster Suite is more evolved than those of other arcs, supporting the notion of a deeper evolving magma chamber. Other possible explanations include crustal contamination and higher tem-

peratures. With regards the former, Eglington et al. (1986, 1989) have provided Nd data that suggest that the NMB is largely juvenile crustal material which would eliminate an opportunity for contamination, but the immediately preceding intrusion of the S-type Glenmore Granite suggests that there probably was an opportunity for contamination. Higher concentrations of Zr, Ti and P in the Munster Suite and other lithologies from this region have been discussed by Grantham et al. (2001) who suggest that the cause is high magmatic temperatures. However, although high magmatic temperatures are needed for such high concentrations, they are not the origin.

All things considered, the data suggest that the Munster Suite formed within an island arc context with high heat flow and that it tapped an underlying magma chamber.

The concept of mafic magmatic underplating beneath an arc has been mooted before. For example, Murphy (2006) states that during a prolonged history of subduction, the dip and location of the subduction zone may vary causing the locus of arc magmatism to migrate,

Fig. 9. Wetherill U–Pb Concordia plot of the SHRIMP analyses for the quartz–monzonorites (Munster Suite) cropping out along Palm Beach (sample PM07/1). The Concordia curve is calibrated in millions of years.

Fig. 10. Wetherill U–Pb Concordia plot of the SHRIMP analyses for the metabasites (Munster Suite) cropping out along the Munster Headland (sample PM07/4). The Concordia curve is calibrated in millions of years.

which in turn causes intermittent switching from compressional to extensional environments, and that during the periods of extension, arcs have a steep geothermal gradient facilitating underplating of the crust by mafic magma which may transfer sufficient heat to induce anatexis.

Magmatic underplating is also supported by the petrologic work of Mendonidis and Grantham (2003) who reported petrographic and thermobarometric evidence for low-pressure, high-temperature metamorphism and anticlockwise pressure–temperature–cooling paths for the M1 event from the Leisure Bay granulites (e.g. Waters 1988, 1989, 1990). This, furthermore, suggests that the M1 metamorphism recorded by the Leisure Bay granulites was related to this ~1093 Ma magmatic event. The younger ages provided by the rim overgrowths on the zircon grains suggest that M2 occurred some 20–30 Ma later, roughly at the same time as the intrusions of the A-type granitoids of the Oribi Gorge Suite.

Another important consideration is the similarity of these new Munster Suite ages with those of the widespread A-type magmatism in the Natal belt which is characterized by a large number of plutons that range in age from ~1100 to ~1025 Ma (Eglington et al., 2003; Grantham et al., 2001). Although there is a general southward-younging spatial-age distribution of these A-type plutons (Grantham et al., 2001), summed probability distribution plots of these ages indicate two distinct pulses of magmatism at ~1070 and ~1030 Ma (Eglington et al., 2003). The Munster Suite pre-dated both pulses, but appears to have been coeval with the northern-most A-type intrusion.

6. Conclusions

U–Pb SHRIMP data indicate crystallization ages of 1091 ± 7.1 Ma and 1093 ± 5.8 Ma for the quartz–monzonorites and metabasites, respectively, of the Munster Suite. The coeval nature of the intrusions supports the earlier interpretation that these lithologies are consanguineous. Moreover, these data also indicate that the Munster Suite is coeval with the S-type granitic rocks in the area (e.g. Glenmore Granite data at 1091 ± 9 Ma). Therefore, it is concluded that there was a period of magmatism and crustal growth of the Margate Terrane at about 1093 Ma during which the Leisure Bay metasedimentary rocks were intruded by granitic and mafic magmas. This, together with evidence of low-pressure granulite facies metamorphism and antic-

lockwise P–T–t paths in the Leisure Bay granulites (Mendonidis and Grantham, 2003) leads to the proposal that there was mafic underplating beneath the Margate arc that provided both the magma for the Munster Suite and the heat for the generation of the S-type granites. This, in turn, suggests that there was a period of extension during the development of the arc that is now the Margate Terrane. The deformational fabrics within the dated lithologies indicate that deformation and accretion of the Terrane occurred after ± 1093 Ma. The few analysed metamorphic zircon rims provided data suggesting a thermal event about 20–30 Ma after magma crystallization, roughly coeval with the A-type magmatism in the Margate Terrane.

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