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Research Paper

Stenian A-type granitoids in the Namaqua-Natal Belt, southern Africa, Maud Belt, Antarctica and Nampula Terrane, Mozambique: Rodinia and Gondwana amalgamation implications

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A B S T R A C T

We carried out SHRIMP zircon U-Pb dating on A-type granitic intrusions from the Namaqua-Natal Province, South Africa, Sverdrupfjella, western Dronning Maud Land, Antarctica and the Nampula Province of northern Mozambique. Zircon grains in these granitic rocks are typically elongated and oscillatory zoned, suggesting magmatic origins. Zircons from the granitoid intrusions analyzed in this study suggest ~1025–1100 Ma ages, which confirm widespread Mesoproterozoic A-type granitic magmatism in the Namaqua-Natal (South Africa), Maud (Antarctica) and Mozambique metamorphic terrains. No older inherited (e.g., ~2500 Ma Achean basement or ~1200 Ma island arc magmatism in northern Natal) zircon grains were seen. Four plutons from the Natal Belt (Mvoti Pluton, Glendale Pluton, Kwalembe Pluton, Ntimbankulu Pluton) display 1050–1040 Ma ages, whereas the Nthlimbitwa Pluton in northern Natal indicates older 1090–1080 Ma ages. A sample from Sverdrupfjella, Antarctica has ~1091 Ma old zircons along with ~530 Ma metamorphic rims. Similarly, four samples analysed from the Nampula Province of Mozambique suggest crystallization ages of ~1060–1090 Ma but also show significant discordance with two samples showing younger ~550 Ma overgrowths. None of the Natal samples show any younger overgrowths. A single sample from southwestern Namaqualand yielded an age of ~1033 Ma.

Currently available chronological data suggest magmatism took place in the Namaqua-Natal-Maud-Mozambique (NNMM) belt between ~1025 Ma and ~1100 Ma with two broad phases between ~1060–1020 Ma and 1100–1070 Ma respectively, with peaks at between ~1030–1040 Ma and ~1070–1090 Ma. The age data from the granitic intrusions from Namaqualand, combined with those from Natal, Antarctica and Mozambique suggest a crude spatial-age relationship with the older >1070 Ma ages being largely restricted close to the eastern and western margins of the Kalahari Craton in northern Natal, Mozambique, Namaqualand and WDML Antarctica whereas the younger <1060 Ma ages dominate in southern Natal and western Namaqualand and are largely restricted to the southern and possibly the western margins of the Kalahari Craton. The older ages of magmatism partially overlap with or are marginally younger than the intracratonic Mkondo Large Igneous Province intruded into or extruded onto the Kalahari Craton, suggesting a tectonic relationship with the Maud Belt. Similar ages from granitic augen gneisses in Sri Lanka suggest a continuous belt stretching from Namaqualand to Sri Lanka in a reconstituted Gondwana, formed during the terminal stages of amalgamation of Rodinia and pre-dating the East African Orogen. This contiguity contributes to defining the extent of Rodinia-age crustal blocks, subsequently fragmented by the dispersal of Rodinia and Gondwana.

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1. Introduction

Late Mesoproterozoic crystallization ages have been widely reported from the Namaqua-Natal Belt in South Africa, the Maud Belt of western Dronning Maud Land (WDML) in Antarctica and the Nampula and Barue Complexes of the Mozambique Belt of southeastern Africa (e.g., Pinna et al., 1993; Thomas et al., 1993; Jacobs et al., 1999; Robb et al., 1999; Johnston et al., 2001; Manhica et al., 2001; Eglington et al., 2003; Jacobs et al., 2003; Paulsson and Austrheim, 2003; Clifford et al., 2004; Mendonidis et al., 2008, 2015; Macey et al., 2010, 2018; Bailie et al., 2011, 2017; Spencer et al., 2015). These belts are structurally contiguous around the proto-Kalahari Craton (Kaapvaal Craton/Limpopo Belt/Zimbabwe Craton and Grunehogna Craton) on reconstruction of Gondwana (Martin and Hartnady, 1986; Grantham et al., 1988; Groenewald et al., 1991; Jacobs et al., 1999, Jacobs et al., 2008a,b) (Fig. 1). These ages have contributed to hypotheses that this belt was part of the locus of the assembly of Rodinia (Dalziel, 1991), with the belt forming part of the Grenvillian belt described by McElhinney et al. (2003) and Evans (2009). Within the Namaqua-Natal-Maud-Mozambique (NNMM) belt, the initial magmatism is characterised by tonalitic gneisses with calc-alkaline signatures, interpreted as representing the accretion of mostly juvenile rocks in accretionary subduction settings onto the western, southern and eastern margins of the Kalahari Craton, involving continent-arc collision zones. The arc-related units include the Sinclair Group in Namibia (~1216 Ma; Brown and Wilson, 1986; Hoal and Heaman, 1995), the Areachap Group in eastern Namaqualand in the Areachap Terrane (~1280 Ma, Geringer et al., 1986; Eglington, 2006; Cornell and Petterson, 2007; Bailie et al., 2010), the Mzumbe Suite in Natal (~1210 Ma; Thomas, 1989; Thomas and Eglington, 1990; Spencer et al., 2015), Haag Nunataks (~1176 Ma; Millar and Pankhurst, 1987; Grantham et al., 1997), the Kvervelnaten Orthogneiss, Jutulrora Group in Kirwanveggan and Sverdrupfjella, WDML, Antarctica (~1140 Ma; Grantham et al., 1997, 2011; Jackson, 1999), the Chimoio Gneiss, Barue Complex, central Mozambique (~1140 Ma; Manhica et al., 2001; Grantham et al., 2011) and the Mocuba Suite, northern Mozambique (~1140 Ma; Macey et al., 2010).

Intruded into the arc-related belt, are voluminous megacrystic A-type granitoids which are inferred to have been emplaced during the terminal, late to post tectonic stages of the evolution of the NNMM belt. These granitoids include the Keimoes Suite in Areachap Terrane, eastern Namaqualand (Eglington, 2006; Bailie et al., 2011, 2017), the Spektakel and Rietberg Suites in the Garies and O'kiep Terranes of western Namaqualand (Robb et al., 1999; Clifford et al., 2004; Eglington, 2006; Duchesne et al., 2007; Macey et al., 2018), the Oribi Gorge Suite in Natal (Eglington et al., 1989; Thomas and Eglington, 1990; Jacobs and Thomas, 1994; Thomas et al., 1996; Spencer et al., 2015), the Kirwanveggan Megacrystic Orthogneiss and augen gneiss in Kirwanveggan and Heimefrontfjella, Antarctica (Arndt et al., 1991; Grantham et al., 1995; Harris, 1999; Jackson, 1999) and the Culicui Suite and Nhansipfe Gneiss in Mozambique (Manhica et al., 2001; Macey et al., 2010;

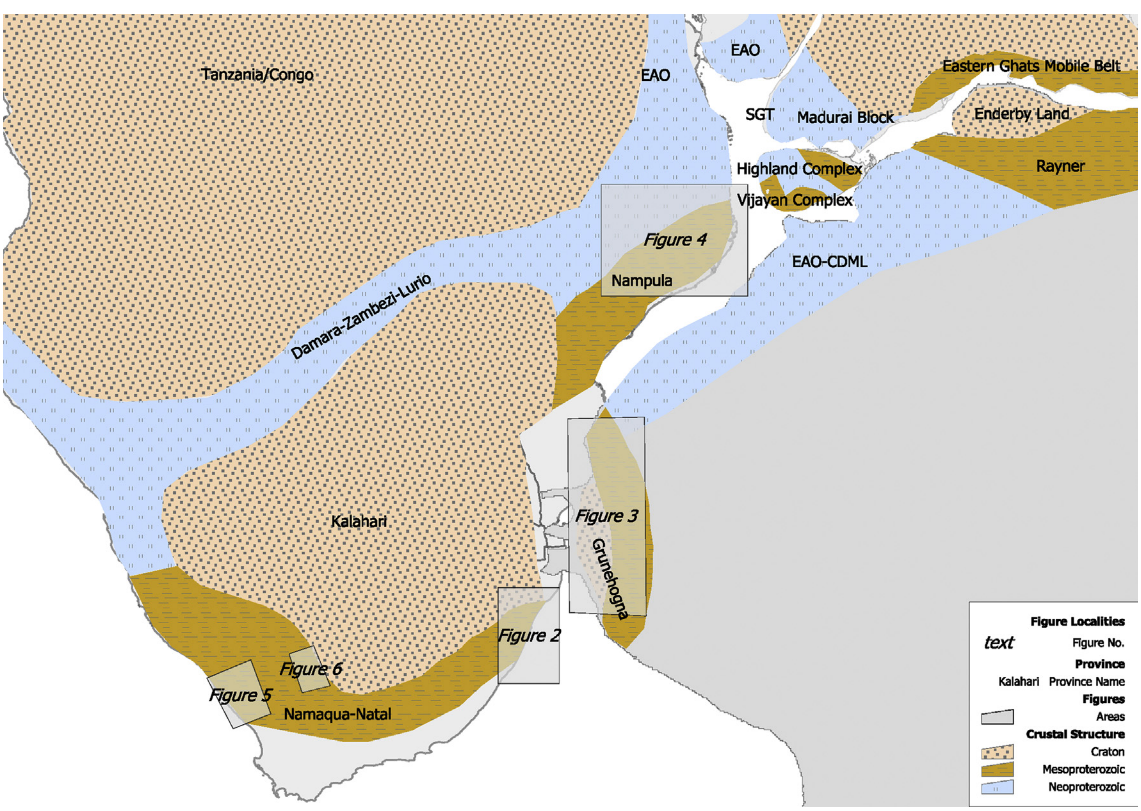

Fig. 1. Reconstruction of Gondwana showing the location of the study areas. Also show the approximate localities for Figs. 2–5.

Table 1
Table of data from various localities in Natal, Mozambique, Antarctica and Namaqualand providing data sources and reference to the figures reflecting the localities of the data.

	Sample Number/Locality Name	Area	Method	Age and error (Ma)	Figure No.	Locality/Pluton number	Reference
61	GGM201A	N. Mozambique	SHRIMP	1087 ± 13	Fig. 4	7	This study
60	GG604	N. Mozambique	SHRIMP	1091 ± 12	Fig. 4	5	This study
59	GG407	N. Mozambique	SHRIMP	1074 ± 13	Fig. 4	4	This study
58	PMM03062	N. Mozambique	SHRIMP	1077 ± 2.6	Fig. 4	1	Macey et al. (2010)
57	PMM03032	N. Mozambique	SHRIMP	1076 ± 8	Fig. 4	2	Macey et al. (2010)
56	PMM03002	N. Mozambique	SHRIMP	1073 ± 16	Fig. 4	3	Macey et al. (2010)
55	PMM03030	N. Mozambique	SHRIMP	1092 ± 42	Fig. 4	8	Macey et al. (2010)
54	701	N. Mozambique	SHRIMP	1082 ± 6	Fig. 4	6	This study
53	26879	N. Mozambique	SHRIMP	1060 ± 17	Fig. 4	9	Macey et al. (2010)
52	33566	N. Mozambique	SHRIMP	1072 ± 8	Fig. 4	10	Macey et al. (2010)
51	JJ110	N. Mozambique	SHRIMP	1087 ± 16	Fig. 4	12	Macey et al. (2010)
50	33296	N. Mozambique	SHRIMP	1057 ± 9	Fig. 4	11	Macey et al. (2010)
49	Nhansipfe	S. Mozambique	SHRIMP	1112 ± 18			Manhica et al. (2001)
48	Bowrakammen	Heimefrontfjella, WDML	SHRIMP	1091 ± 6	Fig. 3	5	Jacobs et al. (2003)
47	Bratsberghoten	Heimefrontfjella WDML	SHRIMP	1087 ± 9	Fig. 3	6	Jacobs et al. (2003)
46	Salknappen	Sverdrupfjella WDML	SHRIMP	1092 ± 7	Fig. 3	1	This study
45	Neumeyerskarvet	Kirwanveggan WDML	SHRIMP	1088 ± 10	Fig. 3	3	Harris (1999)
44	Hallgrenskarvet	Kirwanveggan WDML	SHRIMP	1074 ± 10	Fig. 3	4	Krynauw and Jackson (1996)
43	Mannefaulknasane	Heimefrontfjella WDML	SHRIMP	1073 ± 8	Fig. 3	7	Arndt et al. (1991)
42	Gjelsvikfjella	Gjelsvikfjella WDML	SHRIMP	1104 ± 8	Fig. 3	2	Bisnath et al. (2006)
41	Nthlimbitwa (10)	Mzumbe Terrane, Natal Province	SHRIMP	1089 ± 5	Fig. 2	Nthlimbitwa (10)	This study
40	Nthlimbitwa (10)	Mzumbe Terrane, Natal Province	SHRIMP	1088 ± 19	Fig. 2	Nthlimbitwa (10)	This study
39	Mvoti (9)	Mzumbe Terrane, Natal Province	SHRIMP	1055 ± 4	Fig. 2	Mvoti (9)	This study
38	Glendale (8)	Mzumbe Terrane, Natal Province	SHRIMP	1048 ± 14	Fig. 2	Glendale (8)	This study
37	Mgeni (7)	Mzumbe Terrane, Natal Province	TIMS	1030 ± 20	Fig. 2	Mgeni (7)	Eglington et al. (2003)
36	Kwalembe (6)	Mzumbe Terrane, Natal Province	SHRIMP	1041 ± 7	Fig. 2	Kwalembe (6)	This study
35	Fafa (5)	Mzumbe Terrane, Natal Province	SHRIMP	1037 ± 10	Fig. 2	Fafa (5)	Eglington et al. (2003)
34	Fafa (5)	Mzumbe Terrane, Natal Province	TIMS	1027.9	Fig. 2	Fafa (5)	Thomas et al. (1993)
33	Ntimbankulu (4)	Mzumbe Terrane, Natal Province	SHRIMP	1053 ± 19	Fig. 2	Ntimbankulu (4)	This study
32	Oribi Gorge (3)	Margate Terrane, Natal Province	SHRIMP	1063 ± 5	Fig. 2	Oribi Gorge (3)	Eglington et al. (2003)
31	Oribi Gorge (3)	Margate Terrane, Natal Province	TIMS	1068 ± 2	Fig. 2	Oribi Gorge (3)	Thomas et al. (1993)
30	Oribi Gorge (3)	Margate Terrane, Natal Province	TIMS	1046 +11/ −19	Fig. 2	Oribi Gorge (3)	Spencer et al. (2015)
29	Port Edward (1)	Margate Terrane, Natal Province	SHRIMP	1025 ± 8	Fig. 2	Port Edward (1)	Eglington et al. (2003)
28	Port Edward (1)	Margate Terrane, Natal Province	TIMS	1039 +9/ −18	Fig. 2	Port Edward (1)	Spencer et al. (2015)
27	Gems01	Keimoes Suite, E. Namaqua	SHRIMP	1104 ± 11	Fig. 6	Gems01	Bailie et al. (2011)
26	Klein 01	Keimoes Suite E. Namaqua	SHRIMP	1101 ± 10	Fig. 6	Klein 01	Bailie et al. (2011)
25	Klip 06-1	Keimoes Suite E. Namaqua	SHRIMP	1096 ± 10	Fig. 6	Klip 06-1	Bailie et al. (2011)
24	Kanoneiland	Keimoes Suite E. Namaqua	LA-ICPMS	1098 ± 26			Bailie et al. (2017)
23	Klipkraal	Keimoes Suite E. Namaqua	LA-ICPMS	1111 ± 7			Bailie et al. (2017)
22	Keboes	Keimoes Suite E. Namaqua	LA-ICPMS	1105 ± 27			Bailie et al. (2017)
21	Straussberg	Keimoes Suite E. Namaqua	SIMS	1090 ± 9	Fig. 6	Straussberg	Cornell et al. (2012)
20	Friersdale	Keimoes Suite E. Namaqua	SIMS	1078 ± 10	Fig. 6	Friersdale	Cornell et al. (2012)
19	Rietberg (NAM8)	Spektakel Suite, W. Namaqua	SHRIMP	1058 ± 30	Fig. 5	6	Robb et al. (1999)
18	Rietberg (NAM4)	Spektakel Suite, W. Namaqua	SHRIMP	1064 ± 31	Fig. 5	5	Robb et al. (1999)
17	Rietberg (107)	Spektakel Suite, W. Namaqua	SHRIMP	1035 ± 13	Fig. 5	3	Clifford et al. (2004)
16	Rietberg	Spektakel Suite, W. Namaqua	SHRIMP	1032 ± 11			Clifford et al. (2004)
15	Banke	Spektakel Suite, W. Namaqua	SHRIMP	1033 ± 17	Fig. 5	8	This study
14	Ibiquas	Spektakel Suite, W. Namaqua	LA-ICPMS	1074 ± 23	Fig. 5	10	Macey et al. (2018)
13	Klein Lieslap	Spektakel Suite, W. Namaqua	LA-ICPMS	1078 ± 4	Fig. 5	11	Macey et al. (2018)
12	Bloukop	Spektakel Suite, W. Namaqua	LA-ICPMS	1065 ± 2	Fig. 5	12	Macey et al. (2018)
11	Jakkalshoek	Spektakel Suite, W. Namaqua	LA-ICPMS	1060 ± 7	Fig. 5	13	Macey et al. (2018)
10	Kliphoek	Spektakel Suite, W. Namaqua	LA-ICPMS	1060 ± 9	Fig. 5	14	Macey et al. (2018)
9	Banke	Spektakel Suite, W. Namaqua	LA-ICPMS	1083 ± 12	Fig. 5	15	Macey et al. (2018)
8	Nuwerus	Spektakel Suite, W. Namaqua	LA-ICPMS	1098 ± 6	Fig. 5	16	Macey et al. (2018)
7	Uilklip	Spektakel Suite, W. Namaqua	LA-ICPMS	1090 ± 11	Fig. 5	17	Macey et al. (2018)
6	Strandfontein	Spektakel Suite, W. Namaqua	LA-ICPMS	1075 ± 4	Fig. 5	18	Macey et al. (2018)
5	Banke	Spektakel Suite, W. Namaqua	LA-ICPMS	1080 ± 6	Fig. 5	19	Macey et al. (2018)
4	Banke	Spektakel Suite, W. Namaqua	LA-ICPMS	1087 ± 11	Fig. 5	20	Macey et al. (2018)
3	Burtons Puts	Spektakel Suite, W. Namaqua	SHRIMP	1056	Fig. 5	21	Macey et al. (2018)
2	Kliphoek	Spektakel Suite, W. Namaqua	LA-ICPMS	1078 ± 5	Fig. 5	22	Macey et al. (2018)
1	Lepel se Kop	Spektakel Suite, W. Namaqua	LA-ICPMS	1097 ± 6	Fig. 5	23	Macey et al. (2018)

Grantham et al., 2011). The A-type granitic intrusions exposed in these areas are also commonly characterized by rapakivi textures preserved in low strain zones and also locally preserve charnockitic assemblages (Grantham et al., 2001, 2011; Duchesne et al., 2007; Macey et al., 2010, 2012). Available Sm–Nd data from the A-type intrusions indicate they have mostly juvenile characteristics with limited contributions from older rocks (Eglington et al., 1989; Grantham et al., 2001, 2011; Bailie et al., 2017). Radiogenic isotope data from samples from localized areas adjacent to the Zimbabwe-Grunehogna and Kaapvaal cratons indicate contributions from older sources, possibly reflecting extensions of these cratons at depth (Wareham et al., 1998; Duchesne et al., 2007; Bailie et al., 2011, 2017; Grantham et al., 2011). These granitic intrusions have uniform major and trace element geochemical characteristics typical of A-type rapakivi granites (Grantham et al., 2001, 2011; Macey et al., 2010, 2018; Bailie et al., 2017) as well as ferroan tholeiitic compositions (Grantham et al., 2001, 2011; Duchesne et al., 2007; Macey et al., 2010; Bailie et al., 2011, 2017). The

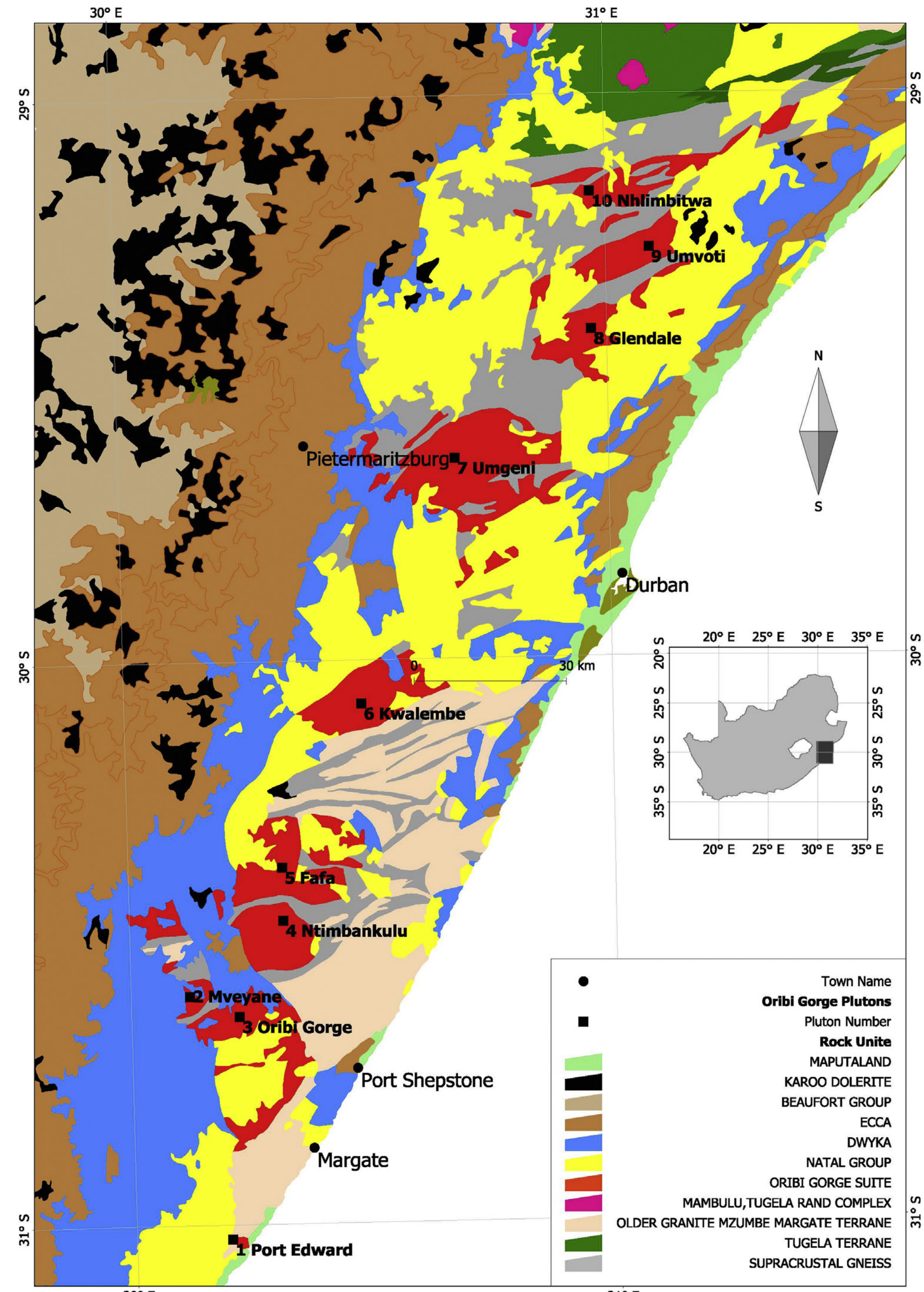

Fig. 2. Simplified geological map of the Natal Province, showing the distribution of the A-type granitoid intrusions and granitoid pluton names. The numbers and names on the map reflect the name of the respective pluton as shown in Table 1.

granites commonly plot in the within-plate granite fields of Pearce et al. (1984). The majority of the intrusions are interpreted as originating from fractionated mantle-derived magmas (Grantham et al., 2001, 2012) with their chemical signatures being further modified by assimilation of crust during ascent. High Zr, P and Ti contents in the rocks are indicative of high magmatic temperatures as high as ~1000 °C (Grantham et al., 2001, 2012), supported by textural evidence and pyroxene thermometry (Grantham et al., 2001, 2012).

The granites in Namaqualand and Natal were clearly emplaced toward the terminal stages of the Mesoproterozoic orogeny showing little to no evidence of deformation (Jacobs and Thomas, 1994; Macey et al., 2010). However, in Dronning Maud Land, Antarctica and northern Mozambique, field relations are less clear due to tectonic and metamorphic overprinting during the Kuunga Orogeny at ~530 Ma (Groenewald et al., 1991; Grantham et al., 1995; Manhica et al., 2001; Jacobs et al., 2003; Meert, 2003). Early interpretations in Natal viewed the intrusions as being post-tectonic (Thomas, 1988). The syntectonic emplacement of the

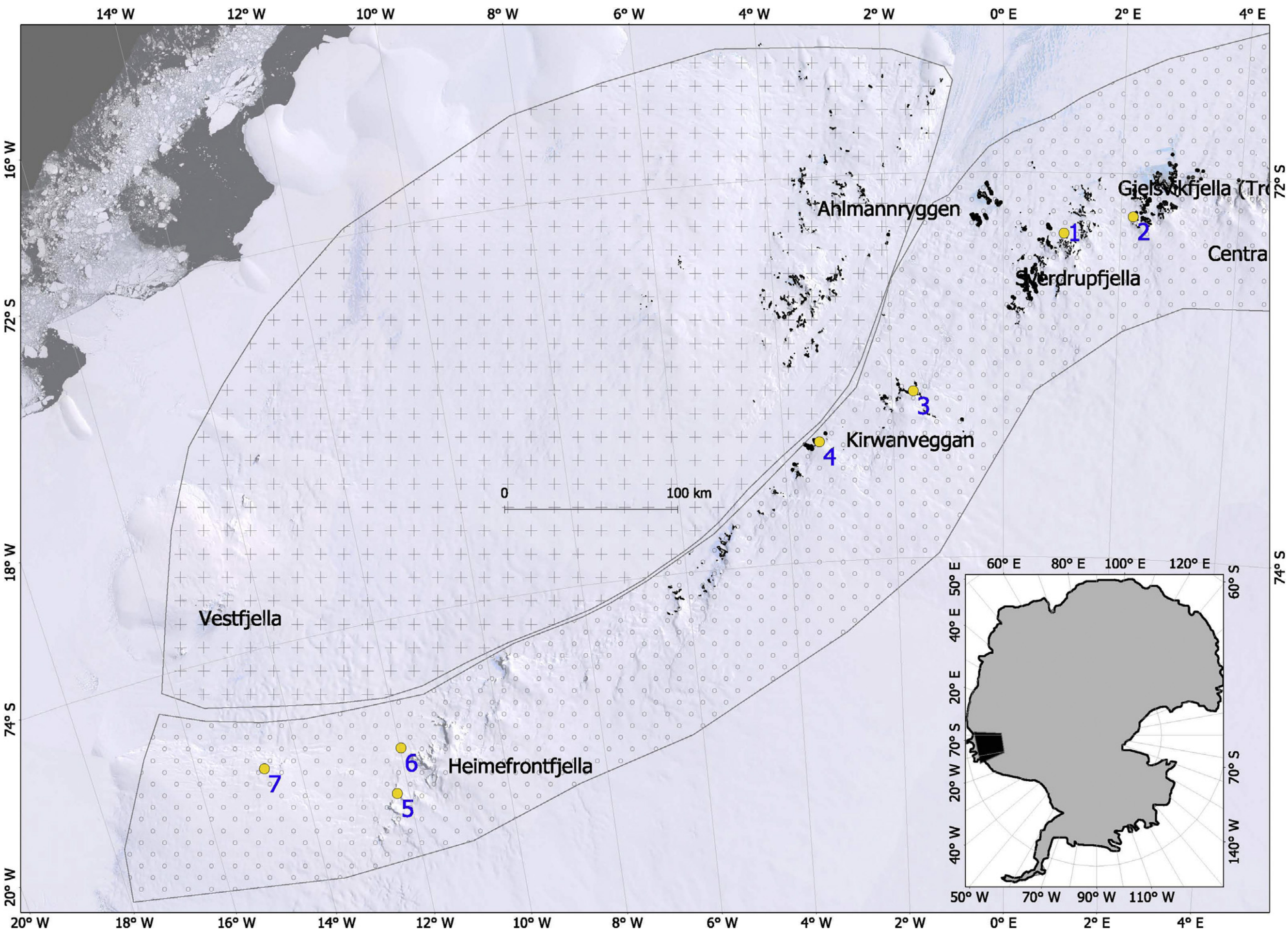

Fig. 3. Location map of western Dronning Maud Land Antarctica and sample localities numbered as per Table 1.

intrusions was later described by Jacobs et al. (1993) who interpreted accretion of the Natal-Namaqua Belt onto the southern boundary of the Kalahari Craton with sinistral and dextral shear systems along the Natal and Namaqua margins respectively, although subsequently the shear systems along the Natal and Namaqualand margins have been shown to not be coeval (Lambert, 2013; Mendonidis and Armstrong, 2016).

As more U-Pb single zircon data have become available from these intrusions, it has become apparent that there may be a progression in crystallization age along the eastern margin of the Kalahari Craton from the north in Mozambique, through Antarctica southward to Natal (Grantham et al., 2001; Manhica et al., 2001). Similarly, in Namaqualand, older ages are recorded at the western edge of the Kalahari craton in the Areachap Terrane of eastern Namaqualand (Eglington, 2006; Bailie et al., 2011, 2017) and in the Garies Terrane (Eglington, 2006) of western Namaqualand, with younger ages being recorded in the O'Kiep Terrane in the northwest (Robb et al., 1999; Clifford et al., 2004) (Table 1).

Natal Province comprises three tectonically bounded terranes namely the Tugela, Mzumbe and Margate Terranes (Thomas, 1989). Ten A-type granitic plutons are recognized and are restricted to the Mzumbe and Margate terranes. The significance of their absence from the Tugela Terrane is uncertain but may be related to the interpretation that the Tugela Terrane is underlain at depth by Archaean crust (Barkhuizen and Matthews, 1990) with the overlying Mesoproterozoic rocks having been obducted onto the southern margin of the Kaapvaal Craton (Matthews, 1972). Previous published SHRIMP zircon age data from the intrusions in Natal (Eglington et al., 2003; Spencer et al., 2015) suggested that there were two periods of emplacement at ~1070 Ma and 1030 Ma.

Similarly, in Sverdrupfjella, Antarctica, the A-type megacrystic gneisses, are not seen in western Sverdrupfjella, but are significant in Gjelsvikfjella, eastern Sverdrupfjella, Kirwanveggan, and Heimefrontfjella (Arndt et al., 1991; Grantham, 1992; Grantham et al., 1995; Jacobs et al., 1996; Bisnath et al., 2006). Preliminary data from western Sverdrupfjella suggest that it may similarly be underlain by Archaean crust (Wareham et al., 1998; Grantham and Jackson, unpubl data; Grantham et al., 2011; Marschall et al., 2013). Published data from WDML Antarctica include that of Arndt et al. (1991), Bauer et al. (2003a) and Bisnath et al. (2006) who reported ages of ~1073–1086 Ma from Heimefrontfjella, and ages of ~1074–1085 Ma from Kirwanveggen reported by Krynauw and Jackson (1996) and Harris (1999).

From central Mozambique the only reported age from megacrystic granitoids in the Barue Complex is that of Manhica et al. (2001) of 1112±18 Ma. Bingen et al. (2009) and Macey et al. (2010) have reported similar ages of ~1050–1090 My from the Culicui Suite in the Nampula Province of northern Mozambique.

The new SHRIMP zircon data presented (Suppl. Table) here from Natal, Sverdrupfjella, WDML, the Nampula province of northern Mozambique and western Namaqualand (Fig. 1) along with data from a number of sources (Table 1) permit a deeper examination of these observations.

2. Sample descriptions

Six samples were collected from plutons in Natal Province, South Africa (Fig. 2), one sample from Salknappen nunatak in Sverdrupfjella, western Dronning Maud Land, Antarctica (Fig. 3), four samples from plutons in the Nampula area of northern Mozambique (Fig. 4) and one sample from western Namqualand (Fig. 5).

2.1. Natal Province

Samples MA107B and MA106 (Nthlimbitwa Pluton): Major constituents are plagioclase, alkali feldspar, quartz, biotite, hornblende with minor clinopyroxene, titanite, apatite, opaque minerals, allanite and zircon (in decreasing order of abundance). Plagioclase occurs as idiomorphic phenocrysts up to 5 mm in diameter and sometimes has antiperthitic lamellae. Hornblende is 0.1–0.5 mm in diameter. Clinopyroxene is 0.5–2 mm in diameter, and is occasionally intergrown with or surrounded by hornblende. The rocks are locally sheared, and fine-grained biotite-quartz-rich mylonatized zones of less than 1 mm wide are developed (sample MA107B).

Sample MA202 (Mvoti Pluton): Rapakivi texture is conspicuous with alkali feldspar phenocrysts up to 1 cm in diameter surrounded by quartz, plagioclase, hornblende and biotite. Minor constituents are apatite, zircon and opaque minerals. Alkali feldspar phenocrysts commonly have perthite lamellae. Quartz grains are up to 5 mm in diameter, but plagioclase, hornblende and biotite are commonly less than 1 mm. Hornblende and biotite sometimes occur as poikilitic grains surrounding fine-grained (<100–200 μm) rounded quartz grains.

Sample MA204 (Glendale Pluton): Major constituents in this rock are alkali feldspar, quartz, plagioclase, biotite and garnet. Minor constituents include opaque minerals, allanite, zircon, and apatite. Garnet is coarse-grained (>5 mm) and sub-rounded and is typically inclusion-free with rare zircon inclusions and locally partially replaced by chlorite. Alkali feldspar is phenocrystic up to 1 cm, and commonly shows perthite texture. Plagioclase and quartz are less than 5 mm in diameter. Biotite occurs locally and is sometimes associated with garnet.

Sample MA301 (Kwalembe Pluton): The sample is composed of quartz, plagioclase, alkali feldspar, biotite partly replaced by chlorite with minor apatite, zircon and opaque minerals. Some of plagioclase grains are phenocrystic up to >1 cm in diameter and others are less than 1 mm. Quartz and alkali feldspar are commonly less than 5 mm.

Sample MA304 (Ntimbankulu Pluton): Major constituents are alkali feldspar, plagioclase, quartz, hornblende and biotite. Apatite, zircon and opaque minerals are minor. The rock is coarse-grained; alkali feldspar and quartz are up to >1 cm, and plagioclase and hornblende are 2–5 mm in diameter. Biotite, hornblende and plagioclase grains commonly occur around the phenocrystic quartz and alkali feldspar grains. Biotite is also associated with or surrounding hornblende.

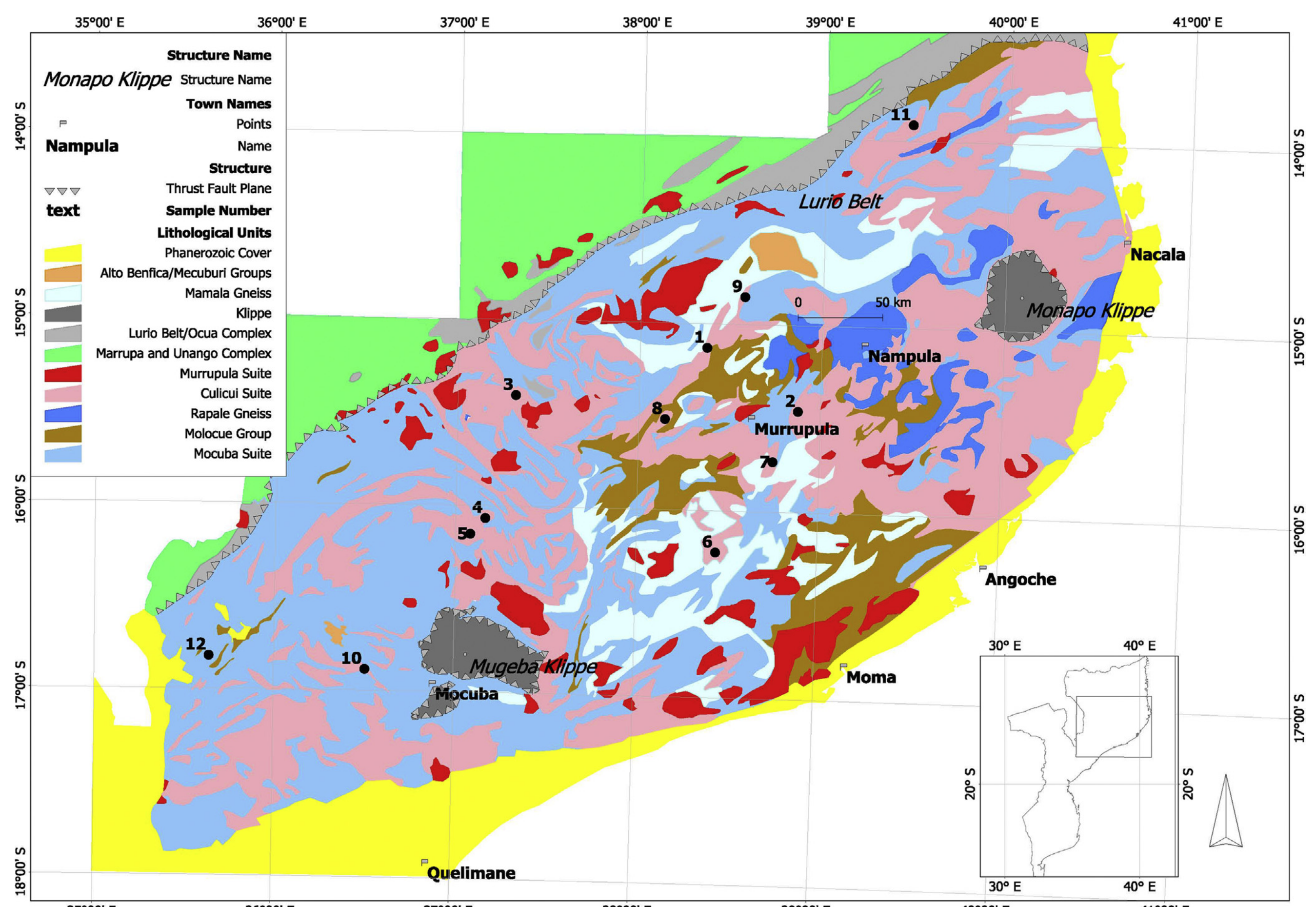

Fig. 4. Simplified geological map of the Nampula Province, northern Mozambique, showing the location of samples and distribution of the Culicui Suite as per Table 1 Locality/Pluton number.

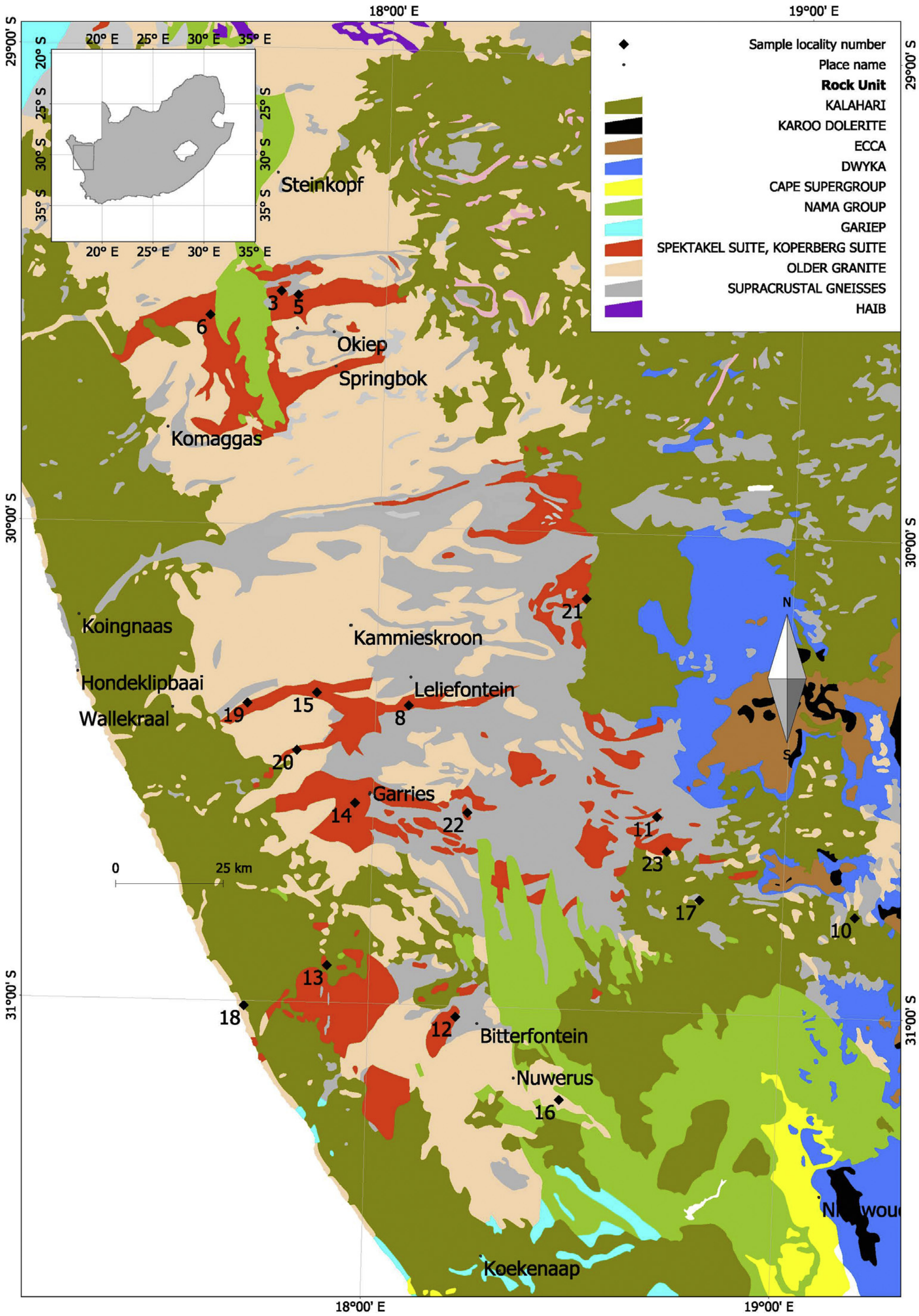

Fig. 5. Simplified geological map of the western Namaqualand, South Africa showing the location of samples and distribution of the A-type granites with locality numbers as per Table 1.

2.2. Sverdrupfjella, WDML, Antarctica

Sample SA 10 (Salknappen): The rock is medium- to coarse-grained (0.5–10 mm) and contains a strong planar foliation defined by biotite ± hornblende. The characteristic mineral assemblage of the granitic rocks is quartz + plagioclase + K-feldspar + garnet + biotite ± hornblende ± clinopyroxene. Garnet occurs as ragged poikiloblastic grains with inclusions of quartz. K-feldspar forms porphyroclasts up to ~10 mm in diameter with rims of myrmekite. Plagioclase in the groundmass commonly shows a trellis pattern antiperthite where K-feldspar exsolution lamellae commonly form up to 30% of the mineral. Clinopyroxene is partially rimmed by hornblende suggesting that the hornblende is replacing clinopyroxene.

2.3. Nampula Province, Mozambique

Sample 701: The rock is medium grained and has a weak foliation defined by oriented biotite grains. The biotite grains are set in a granoblastic mosaic of quartz + plagioclase + microcline. These

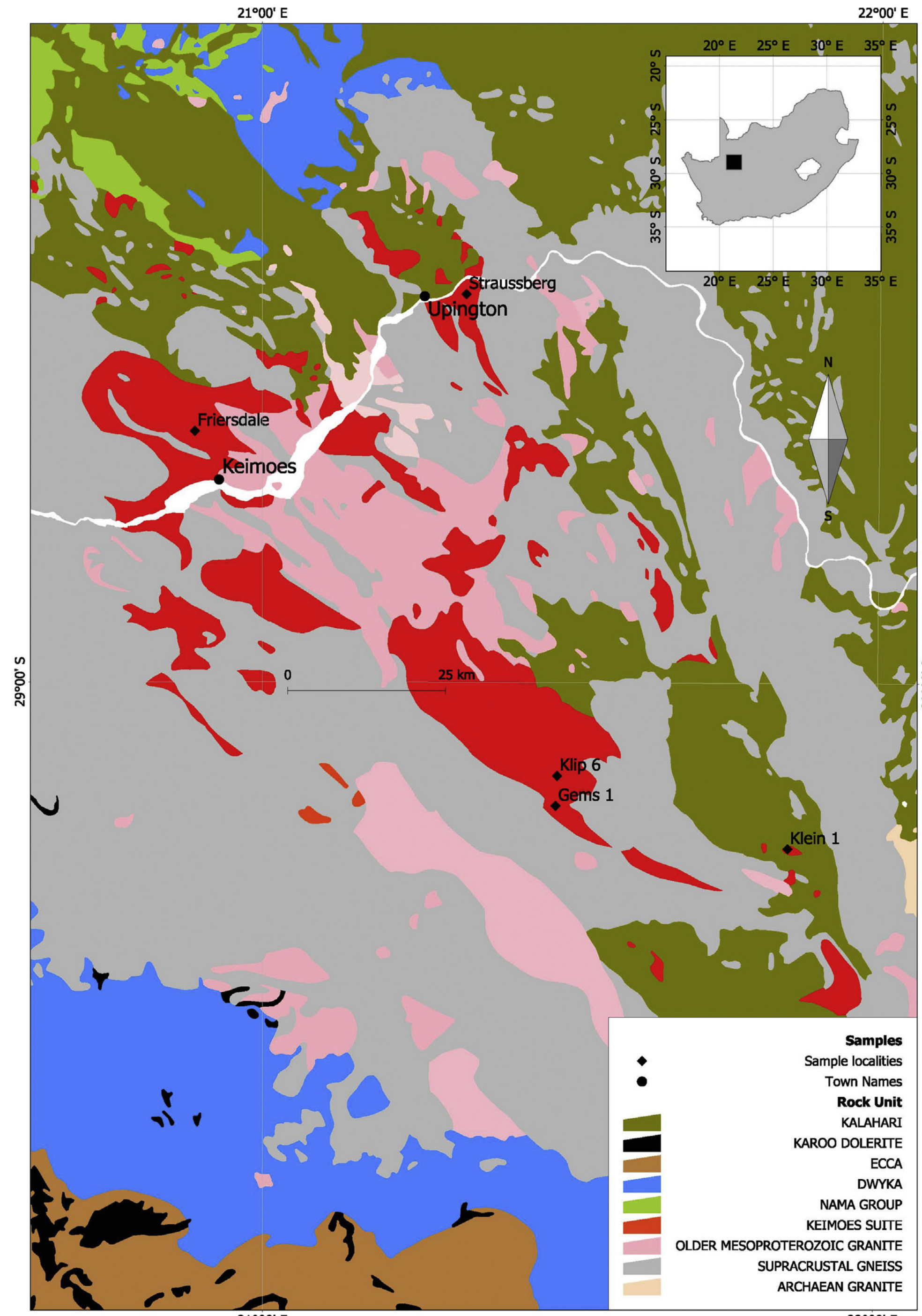

Fig. 6. Simplified geological map of the eastern Namaqualand, South Africa showing the location of samples and distribution of the A-type granites with locality numbers as per Table 1.

minerals are mostly equigranular except for local porphyroclastic grains of microcline containing inclusions of quartz and subordinate plagioclase.

Sample 407: The rock is medium to coarse grained with quartz + plagioclase + orthoclase defining a granoblastic mosaic. Plagioclase contains rectangular exsolution blobs of orthoclase forming antiperthitic textures whereas orthoclase is locally weakly perthitic. The dominant ferromagnesian phase is dark green hornblende which is locally transected by thin blades of red-brown biotite. Sparse orthopyroxene is partially replaced by red brown biotite and opaque minerals. Accessory phases include zircon and allanite.

Sample 604: The rock is medium grained and has a strong mylonitic planar fabric defined by oriented biotite grains and lenticular recrystallized plagioclase grains, the latter defining a porphyroclastic texture. The biotite grains are set in a granoblastic mosaic of quartz + plagioclase + microcline.

Sample 201: The rock is medium grained and has a weak foliation defined by oriented biotite grains. The biotite grains are set in a granoblastic mosaic of quartz + plagioclase + microcline. These

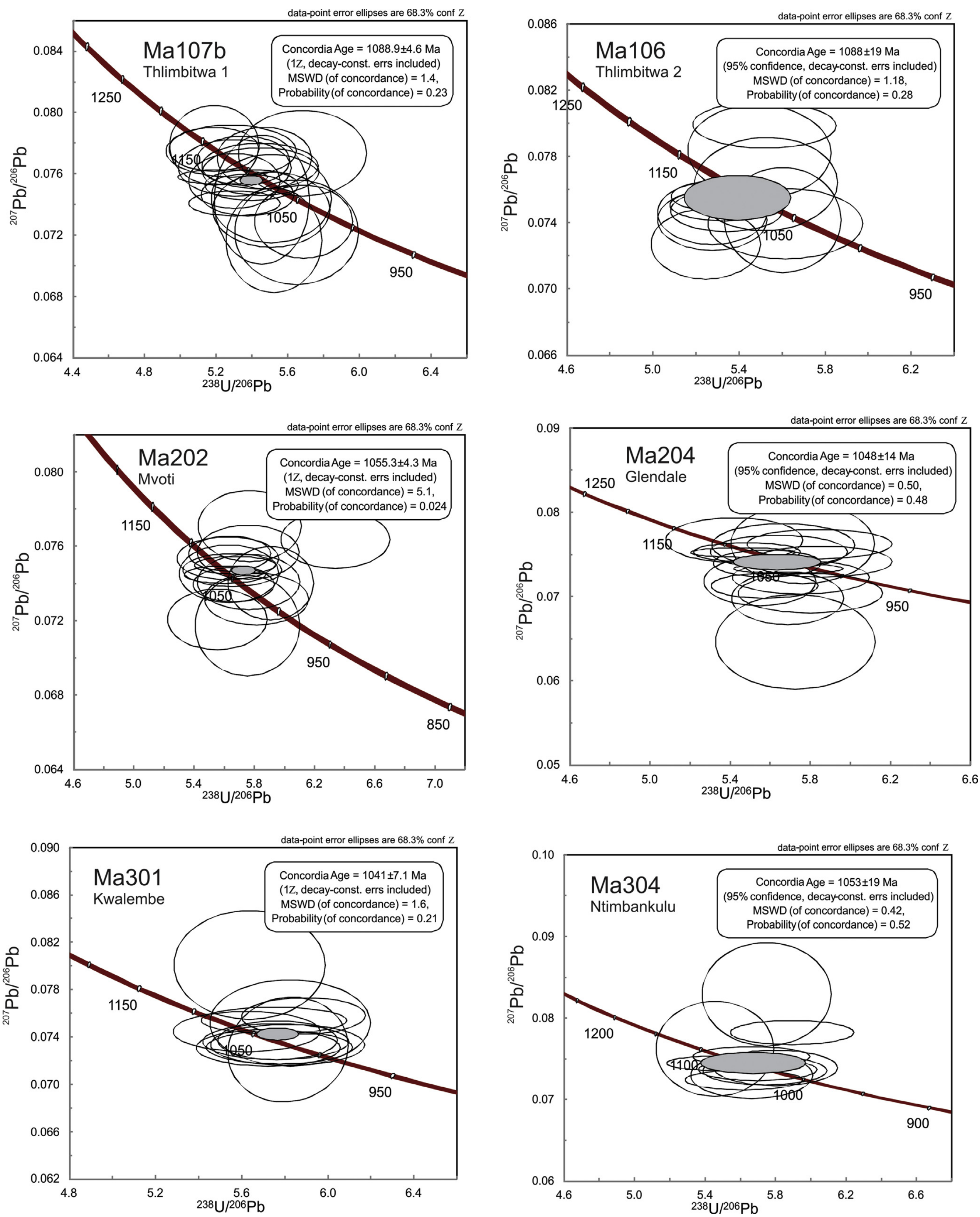

Fig. 7. $^{207}Pb/^{206}Pb-^{238}U/^{206}Pb$ concordia plots for zircons from granites in Natal. Error ellipses are reported with 1-σ uncertainties. Calculated average concordant ages are of 2-σ confidence.

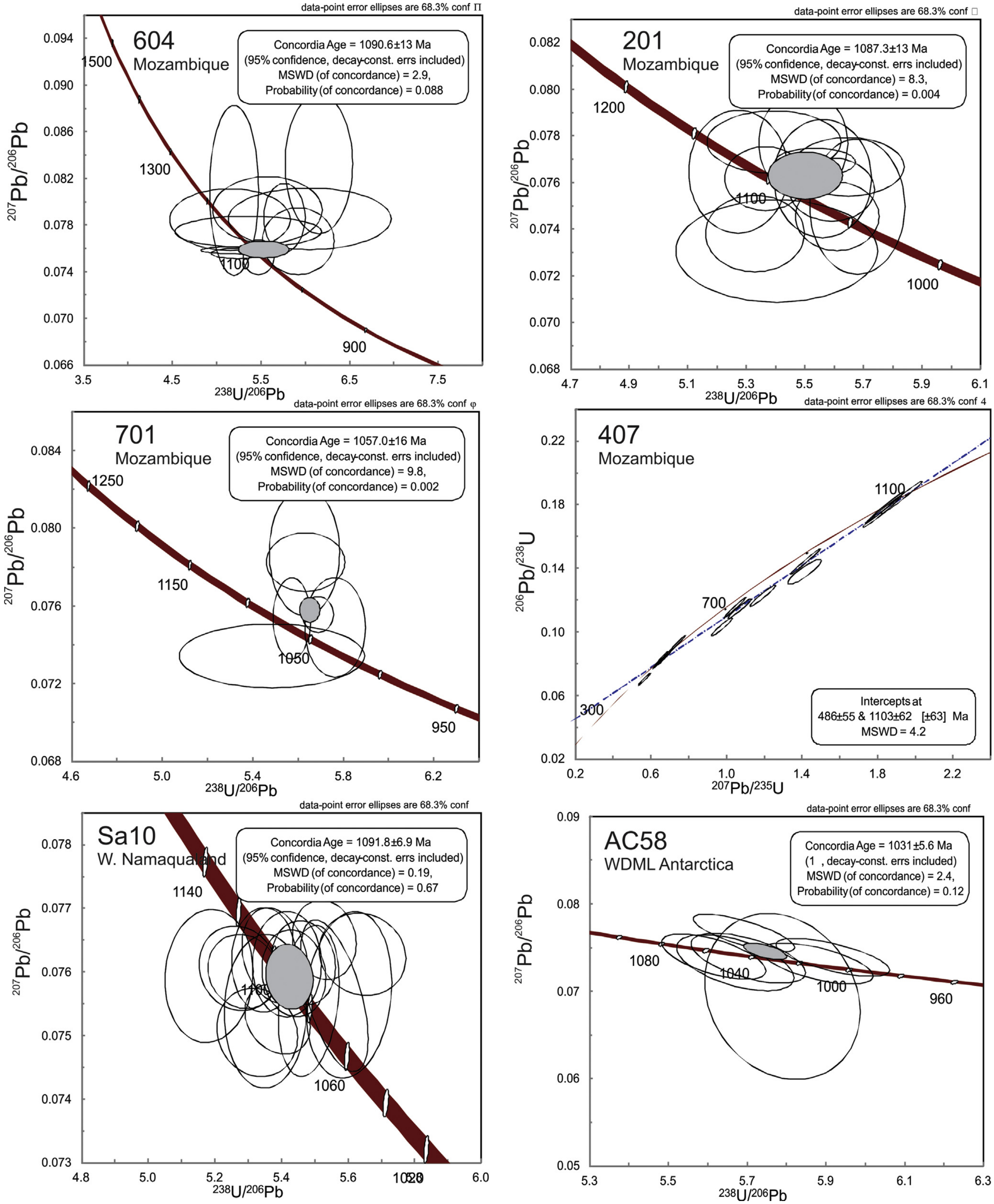

Fig. 8. $^{207}Pb/^{206}Pb$–$^{238}U/^{206}Pb$ concordia plots for zircons from the Salknappen Granite in Antarctica as well as samples from the Nampula Province of northern Mozambique. Error ellipses are reported with 1-σ uncertainties. Calculated average concordant ages are of 2-σ confidence.

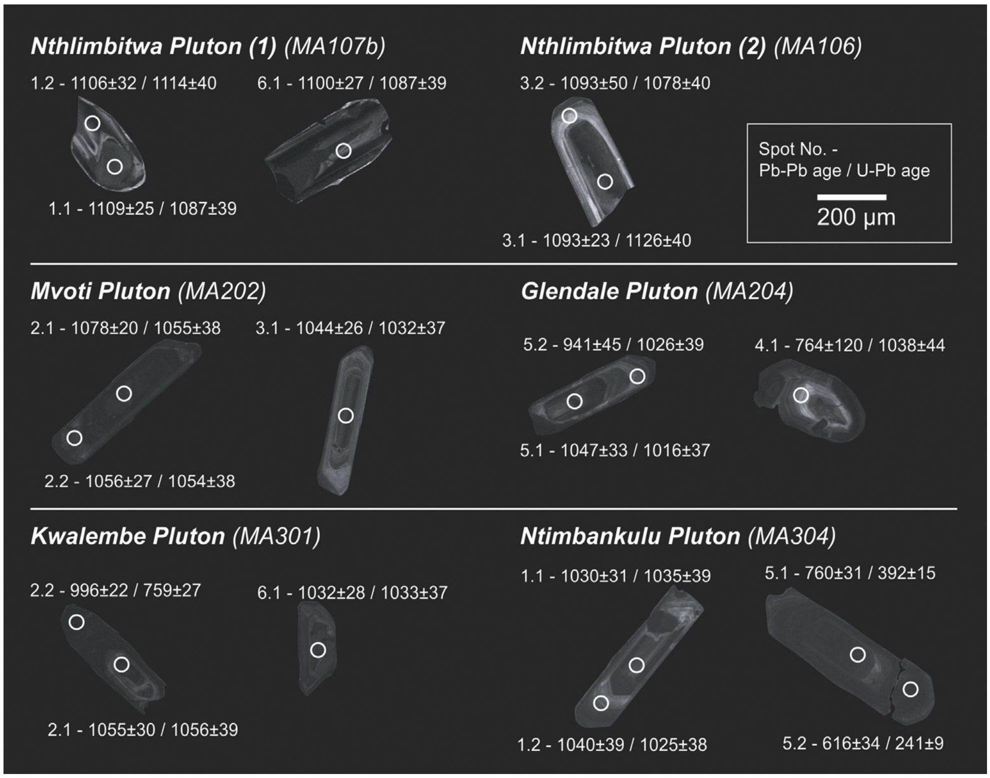

Fig. 9. Cathodoluminescence (CL) images and $^{207}Pb-^{206}Pb$ ages (in Ma) of selected zircon grains from the Natal granitoid samples analyzed by SHRIMP.

minerals are mostly equigranular except for local porphyroclastic grains of microcline containing inclusions of quartz and subordinate plagioclase.

2.4. Namaqualand

Sample AC58: Sample AC58 was collected from the megacrystic Banke Granodiorite (Fig. 5, locality 8) (Macey et al., 2011) and consists of quartz (~20%–30%), K-feldspar (~15%–25%), plagioclase (~35%–40%), biotite (~5%–10%) and, occasionally, orthopyroxene or hornblende (~5%). Zircon and opaques are the main accessory minerals. The feldspar megacrysts can be up to 5–7 cm long and show the development of an incipient rapakivi texture locally.

3. Analytical techniques

The rock specimens were ground in a tungsten-carbide mortar, and zircon grains were separated by using a sieve, heavy liquids and a magnetic separator. Zircon grains with small fragments of a standard zircon (SL13 and FC1) were mounted in epoxy, and the mount was polished and gold-coated. Zircon grains were imaged using cathodoluminescence (CL) to assess internal zircon structure prior to ion microprobe analysis.

The zircon grains from Natal and northern Mozambique were analyzed for U, Th and Pb using the sensitive high-resolution ion microprobe (SHRIMP II) at the National Institute of Polar Research, Tokyo, Japan whereas the samples from Sverdrupfjella and Namaqualand were analyzed on SHRIMP II at the Australian National University, Canberra, Australia. The analytical techniques for SHRIMP analysis essentially follow Williams (1998). A ~30 μm diameter analytical spot was used, and secondary ions were measured at a mass resolution of ~5500. Standard zircon SL13 (U = 238 ppm; $^{206}Pb/^{238}U$ age of 572 Ma) provided by the Australian National University was used for the reference value of U concentration in zircon. Pb/U ratios were corrected for instrumental mass fractionation using ratios measured on the standard zircon FC1 (1099 Ma; Paces and Miller, 1993). Common Pb corrections were based on the measured ^{204}Pb. Data reduction and processing were conducted using the computer programs SQUID ver.1 and ISOPLOT ver.4.1 provided by K.R. Ludwig at the Berkeley Geochronology Center of the University of California (Ludwig, 2001a, b). Analytical results are shown in Suppl. Table and Figs. 7 and 8. Errors of each analysis shown in Suppl. Table and Figs. 7 and 8 are at 1-σ (68% confidence level), whereas those for average concordant ages, which include U decay constant uncertainties, calculated by using ISOPLOT shown in Figs. 7 and 8 and in the text are at 2-σ (ca. 95% confidence level).

4. Results of SHRIMP zircon chronology

Zircons from eleven of the analyzed samples show elongated or sub-rounded shapes and oscillatory-zoned internal structures (Figs. 9 and 10), which are interpreted as typical of magmatic crystallization with minor modification (partial resorption?) after crystallization. Although the obtained ages from each spot include relatively large errors ranging from 10 Ma to 40 Ma due to the low U contents, most of the $^{206}Pb/^{238}U$ and $^{207}Pb/^{206}Pb$ ages that are <5% discordant are statistically identical and range from 1130 Ma to 1000 Ma (Suppl. Table). Most of the zircon analytical results from Natal and Namaqualand are concordant (Figs. 7 and 8), and each sample represents little age variation, whereas the samples from Dronning Maud Land and northern Mozambique show significant disturbance and lead loss (Figs. 7 and 8). Some of zircon grains display discontinuities in the internal zonal structure where two or three concentric domains can be seen (Figs. 9 and 10).

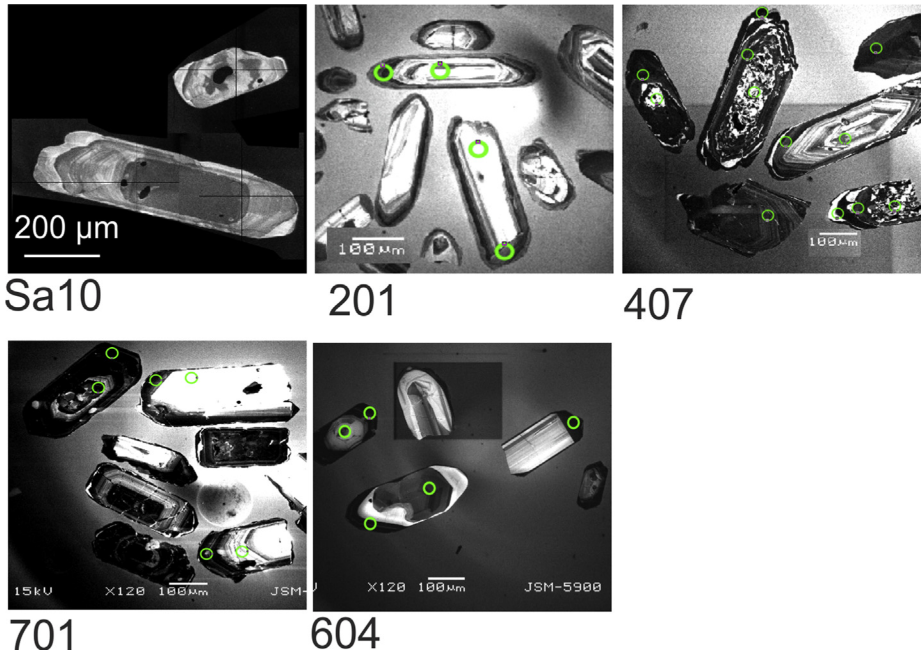

Fig. 10. CL images of zircon grains from the Salknappen Granite, Sverdrupfjella, Antarctica as well as samples from the Culicui Suite, Nampula Province, northern Mozambique. Thin metamorphic rims are occasionally developed in some grains. Many grains also show cracks and metamict cores.

The zoning in zircons from Natal (Fig. 9) are inferred to be magmatic with U-Pb ages being almost identical within error (e.g., grain 3 of MA106 in Fig. 9). Therefore, there exists no obvious reason for these different domains to have been formed during different events. They possibly reflect changes in f local-scale magma compositions in terms of Zr, Th, U and REEs rather than different events.

Two samples from Nthlimbitwa Pluton (MA107b, MA106) in the northern Natal Belt and one sample from Salknappen Pluton (SA10) in the Maud Belt have relatively older crystallization ages of 1089 ± 5 Ma (MA107b), 1088 ± 19 Ma (MA106) and 1092 ± 7 Ma (SA8) respectively. In contrast the other 4 samples from the Natal Belt (MA202, MA204, MA301, MA304) have $^{207}Pb/^{206}Pb$ crystallization ages of 1055 ± 4 Ma (Mvoti Pluton/MA202), 1048 ± 17 Ma (Glendale Pluton/MA204), 1041 ± 7 Ma (Kwalembe Pluton/MA301) and 1053 ± 19 Ma (Ntimbankulu Pluton/MA304). Zircon grains from the Natal samples show no younger overgrowths. However, two samples (MA301, MA304) from the Natal have younger discordant ages (spot 2.2 of MA301 and the spots 5.1 and 5.2 of MA304, resulting in imprecise lower intercept ages (180 ± 160 Ma for sample MA301, and 168 ± 79 Ma for sample MA304) with upper intercept ages (1046 ± 24 Ma for MA301 and 1034 ± 26 Ma for MA304) within error of the concordia ages calculated for these samples (Fig. 7).

In contrast, sample SA10 from Salknappen, Sverdrupfjella in WDML contains zircon grains with clear metamorphic rims (Fig. 10), with one spot from an overgrowth providing an age of 530 ± 8 Ma (spot 6.1, Suppl. Table). Most of the zircon core analyses from sample SA10 define a concordant age of 1092 ± 9 Ma (Fig. 7), but all the data define discordant array of data from a 1096 ± 14 Ma upper intercept to a 538 ± 25 Ma lower intercept (Discordia not shown). In contrast to Natal, the samples from Mozambique show varying degrees of disturbance, similar to Sample SA10 from western Dronning Maud Land. The majority of grains (11) from sample GG604 from Mozambique define a concordant age of 1090 ± 13 Ma (Fig. 8) with 6 grains being discordant. Similarly, most zircon grains from sample GG201 from Mozambique define a concordant age of 1087 ± 13 Ma (Fig. 8) with 6 grains defining a discordant array to a lower intercept of 664 ± 130 Ma (discordia not shown). Six of seventeen grains from sample 701 define a concordant age of 1057 ± 16 Ma (Fig. 8). The discordia trend in the data from sample 701 (not shown) defines an upper intercept of 1114 ± 60 Ma and a lower intercept of 536 ± 110 Ma. The CL images of most of the zircon grains from sample 701 (Fig. 10) preserve oscilliatory zoning, however, zones of recystallisation defined by cracks in the grains are evident (Fig. 10); these cracks presumably have facilitated extensive lead loss. Many zircon grains from sample 407 show extensive checkerboard alteration (Fig. 10) with some grains preserving oscillatory growth zoning. Consequently, it is not surprising that most grains from sample 407 are discordant with the data defining an upper intercept age of 1103 ± 62 Ma and a lower intercept age of 486 ± 55 Ma (Fig. 8). Four concordant grains from sample 407 define an age of 1074 ± 6 Ma (not shown). Seven of eight zircon grains from sample AC58 from western Namaqualand define a concordant age of 1031 ± 6 Ma.

5. Discussion

5.1. Timing of A-type granitic magmatism around the Kalahari Craton

Besides the broadly similar ages, the granitic intrusions in Namaqua, Natal, Maud and Mozambique Belts have common features such as A-type tholeiitic granitic geochemical characteristics, common rapakivi textures in undeformed examples, megacrystic, porphyritic (porphyroclastic in deformed varieties) textures and locally preserve charnockitic mineralogy. Outcrop patterns, where not significantly altered by deformation comprise large plutons (e.g. Natal), or sheet like bodies (e.g. Banke, Namaqualand). In the relatively undeformed areas (Natal, Namaqualand) the granites appear to have postdated, but were emplaced temporally close to, the major Grenvillian granulite events in these areas (Spencer et al., 2015). Therefore, the age of these plutons constrain the terminal

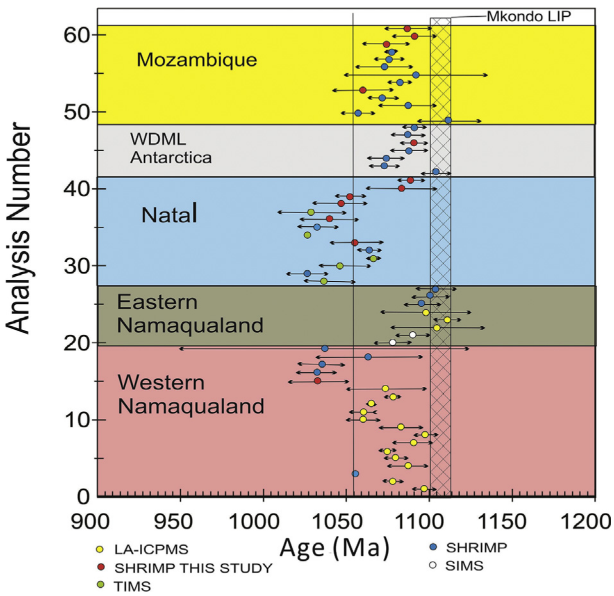

Fig. 11. Summary of U-Pb ages reported for A-type granitoid in Mozambique (Mz)-Maud-Natal-Namaqua belt. Data sources: Arndt et al. (1991), Thomas et al. (1993), Krynauw and Jackson (1996), Harris (1999), Robb et al. (1999), Grantham et al., (2001, unpublished data), Manhica et al. (2001), Eglington et al. (2003), Jacobs et al. (2003), Clifford et al. (2004), Cornell et al. (2012). See Table 1 for detail. The line number of the age in Table 1 correlates to the Y axis in Fig. 11.

stage of the convergent Mesoproterozoic orogenesis around the Kaapvaal Craton (Spencer et al., 2015).

The ages of the intrusions from this study and others are summarized in Table 1 and show that the ages vary between ~1025 Ma and 1110 Ma based on single zircon chronology from a variety of methods. These ages are more reliable than the younger 950–890 Ma dates obtained by Rb-Sr whole rock and biotite studies (Thomas et al., 1993; Eglington et al., 2003). The data in Table 1 and Fig. 11 show that two age groups can be defined namely between ~1055–1110 Ma (most of the samples) and ~1025–1050 Ma. Formerly, it had been considered that these granitoids formed as a results of two episodes of intrusion at ~1.0 Ma and 0.89 Ma, respectively, based on Rb/Sr chronology. Eglington et al. (2003) reported SHRIMP U-Pb zircon ages from the Fafa, Oribi Gorge and Port Edward Plutons from Natal, and suggested at least two generations of A-type granitoid intrusions at ~1070 Ma and 1030 Ma. Thomas et al. (1993) suggested based on TIMS U-Pb zircon data that the Oribi Gorge Suite of A-type granites in Natal Province intruded between 1070 Ma and 1030 Ma, and that the younger 950–890 Ma dates obtained by Rb-Sr whole rock and biotite to represent the time when the various plutons or the entire terrane cooled through the relevant blocking temperatures. Similarly, on a broader scale, the geochronological data presented here, along with all the available data from the NNMM belt are within two age brackets of 1110–1055 Ma and 1050–1025 Ma (Fig. 11, Suppl. Table and Table 1).

In those areas unaffected by significant discernible Pan African overprints (Natal, Namaqualand), structural studies show that the megacrystic A-type intrusions were emplaced relatively late in the tectonic history (Jacobs et al., 1993). For example the ~1025 Ma Port Edward Pluton (Eglington et al., 2003), the youngest and most southerly of the A-type intrusions in the areas of consideration, only has a S2 planar fabric which is axial planar to F2 folds in adjacent supracrustal rocks (Talbot and Grantham, 1987). The most northerly of the plutons in Natal, the Nthlimbitwa Pluton, that also has a strong penetrative planar fabric, has a ~1095 Ma age, which is significantly younger than the older tonalitic magmatism of ~1210 Ma reported from the thrust-nappe stack of the Tugela Terrane (Johnston et al., 2001) immediately to the north. Jacobs and Thomas (1994) recognized that the shape of the plutons in Natal also became more flattened from south to north in Natal with the Nthlimbitwa pluton being the most elliptical and consequently the most deformed. These observations may imply early deformation in the north, younging to the south in Natal supporting previous studies which suggested that the A-type magmatism took place diachronously showing southward younging (Grantham et al., 2001; Manhica et al., 2001).

On an intercontinental scale, the available SHRIMP zircon data, including that presented here (Arndt et al., 1991; Krynauw and Jackson, 1996; Harris, 1999; Manhica et al., 2001; Bauer et al., 2003a; Eglington et al., 2003) range in age from ~1110 Ma in Mozambique in the north to ~1025 Ma in southern Natal. Although there is a crude reduction in age from north to south, the ages appear to form two broad groups (Fig. 11). The first has ages between ~1110 Ma and 1055 Ma with these samples being collected in eastern Namaqualand, the Nampula Province of Mozambique, WDML Antarctica and northern Natal. The second younger group has ages of ~1050–1025 Ma and is restricted to Natal and western Namaqualand. These data can therefore be interpreted to suggest a two stage process. The initial emplacement of the older plutons occurred along the transpressional eastern and western margins of the Kalahari Craton (Jacobs and Thomas, 1994). The second phase of plutons was emplaced, marginally later, only along the southern margin of the Kalahari Craton in Natal and Namaqualand.

It is noteworthy that the ages of the older group of intrusions overlap partially with the age of the intracratonic Umkondo Large Igneous Province (LIP) of ~1100–1110 My (Hanson et al., 2006) centered on the Kalahari Craton. Recognising that the A-type magmatism described here was preceded by two subduction related magmatic belts in a reconstructed Gondwana; the first stretching from Namibia via Namaqualand to Natal with an age of ~1225–1240 Ma (Sinclair Group, Namibia ~1216 Ma, Hoal and Heamann, 1995; Areachap Group in E. Namaqualand, 1280 Ma, Geringer et al., 1986, Eglington, 2006, Cornell and Pettersson, 2007, Bailie et al., 2010; Mzumbe Suite in Natal, ~1210 Ma, Thomas, 1989, Thomas and Eglington, 1990, Spencer et al., 2015) and the second stretching at least from WDML, Antarctica (Haag Nunataks, Heimefrontfjella) through to central and northern Mozambique with an age of ~1140–1110 Ma (Haag Nunataks ~1176 Ma, Millar and Pankhurst, 1987; Grantham et al., 1997; the Kvervelnaten Orthogneiss, in Kirwanveggan and Sverdrupfjella, WDML, Antarctica, ~1140 Ma, Grantham et al., 1997, 2011; Jackson, 1999; the Chimoio Gneiss, central Mozambique, ~1140 Ma, Manhica et al., 2001; Grantham et al., 2011; the Mocuba Suite, northern Mozambique, ~1140 Ma, Macey et al., 2010), it is possible that following the second subduction processes described here, the Kalahari Craton migrated over a sub-continental plate margin spreading centre, contributing to the almost synchronous Umkondo LIP and A-type magmatism at the periphery of the Kalahari Craton. The younger subduction setting is recognized along the eastern margin of the Kalahari Craton (Frimmel, 2004; Grantham et al., 2011; Marschall et al., 2013) and is marginally older at ~1140–1110 Ma than the oldest A-type granites recognized here. The Mkondo LIP is also exposed more on the eastern half of the Kalahari Craton (Hanson et al., 2006). The Mkondo LIP is dominantly tholeiitic in character but along its eastern margin, basaltic andesites correlated with the Mkondo LIP have calc-alkaline signatures (Moabi et al., 2015, 2017). In southern Natal, the calc-alkaline, porphyritic Munster Suite with appearance similar to the A-type granites described here, has a SHRIMP zircon age of ~1092 Ma (Mendonidis et al., 2008), is charnockitic and may also represent a lower crustal lithological unit correlatable with the older A-type granites described here. The calc-alkaline signature of the Munster Suite may similarly reflect emplacement in the vicinity of the margin of the Kalahari Craton, south of the accreted ~1210 Ma old Umzumbe Terrane (Thomas, 1989).

Geophysical data suggest that the metamorphic terranes along the eastern margin of the Kalahari Craton swing around along the southern margin of the craton (Mieth and Jokat, 2014; Mueller and Jokat, 2019) and hence it is uncertain, but probable, that the younger subduction zone also swings around the southern margin, probable seaward of the older subduction zone of ~1200 Ma.

The length of the NNMM belt described here can potentially be extended into the Vijayan Complex of Sri Lanka where the dominant rock types are described as comprising (a) strongly foliated granitic augen gneisses (Mathavan et al., 1999), similar in appearance to exposures of the Culicui Suite in the Nampula Terrane of Northern Mozambique (Grantham et al., 2007) and (b) biotite hornblende tonalitic gneisses (Mathavan et al., 1999), similar in appearance to the Mocuba Suite of northern Mozambique (Grantham et al., 2007). Ages from the granitic rocks in the Vijayan Complex are ~1060–1100 Ma with the rocks showing a strong ~500 Ma overprint (Kroner et al., 2015; Wai-Pan Ng et al., 2017), comparable to that recognized in Mozambique and Dronning Maud Land, Antarctica. No further correlatives eastward of the Vijayan Complex in the Lutzhow-Holm Bay area of Antarctica have been recognized.

5.2. *Implications for Gondwana/Rodinia reconstructions*

The definition of a continuous ~1050–1100 Ma A-type granitic belt from Namaqualand to Sri Lanka has implications for various Gondwana reconstructions (Dalziel et al., 2000; Bauer et al., 2003b; Jacobs et al., 2003; Collins and Pizarevsky, 2005). Dalziel et al. (2000) proposed a position for an isolated separate Kalahari Craton, away from an envisaged Rodinia Supercontinent of ~1000 Ma to 750 Ma. The reconstruction of Dalziel et al. (2000) was constrained by geochronological and paleomagntic similarities between Grenvillian assemblages in North America (Llano Orogenic Belt = Namaqua-Natal and Keeweenawan = Umkondo) and envisaged the accretion of a Coates Land-Maud-Grunehogna Block. Subsequent work demonstrates that the extent of the Kalahari Craton is greater than that envisaged by Dalziel et al. (2000), as reflected in Collins and Pizarevsky (2005).

Reconstructions of Gondwana by Bauer et al. (2003b) and Jacobs et al. (2003) proposed a continuation of the East African Orogen (EAO), extending from North Africa to Heimefrontfjella, Antartica, involving orogenic amalgamation of East and West Gondwana. The EAO proposed by Stern (1994, 2002) was recognized as involving a Wilson cycle of ~900–850 Ma rifting followed by arc-related collisional closure from ~750 Ma to 700 Ma, typically generating magmatic rocks with juvenile Nd signatures in the north, but involving reworking of older crust in the south, in northern Mozambique and Tanzania. The southern limit of the EAO as defined by Stern (1994) was not defined, with reconstructions by Bauer et al. (2003b) and Jacobs et al. (2003) proposing its extension into western Dronning Maud Land, Antarctica. Meert (2003) recognized a separate east west oriented Kuunga Orogeny (KO) transecting and overprinting the southern end of the EAO and inferred that the EAO terminated in N. Mozambique. Collins and Pizarevsky (2005) defined a Lurio-Vijayan Peninsular (LVP) as part of the Kalahari Craton, effectively defining a southern limit to the EAO along the Lurio Belt. It is important to recognize that many lithologies north of the Lurio Belt with ages typical of the EAO (~700–900 Ma), did not exist when the dominant ~1000–1140 Ma old lithologies underlying the Nampula Terrane, including the A-type granites describe here, were generated. The LVP of Collins and Pizarevsky (2005) included western and central Dronning Maud Land, up to the Lutzhow-Holm Bay area in Antarctica, adjacent to the Vijayan Complex of Sri Lanka, in a reconstructed Gondwana. Data from Bingen et al. (2009) and Macey et al. (2010) and summarized in Grantham et al., (2008) demonstrated that no crystallisation ages typical of the EAO (~900–600 Ma) were recognized south of the Lurio Belt in North Mozambique, except in granulite grade enclaves interpreted as EAO klippen overlying the ~1000–1150 Ma Nampula Terrane (Grantham et al., 2008, 2013). Grantham et al., (2008) demonstrated that the Neoproterozoic rocks in central Dronning Maud Land (CDML), including the Sor Rondane area, were similar to those from the Cabo Delgado Nappe Complex (CDNC) (Viola et al., 2008; Bingen et al., 2009), north of the Lurio Belt in northern Mozambique, but dissimilar to the Nampula terrane, which separates CDNC from CDML in a Gondwana framework. A mega-nappe structure was inferred to explain the lithological, geochronological and metamorphic differences between northern Mozambique and DML, Antarctica (Grantham et al., 2008, 2013).

This paper supports the recognition and definition of the Lurio Belt as a Mesoproterozoic-age continental margin along which North and South Gondwana were amalgamated in a continent-continent collisional setting within the Kuunga Orogeny. The Kuunga Orogeny is also recognized further east in Antarctica, continuing from east of Enderby Land, eventually terminating along the west coast of Australia (Daczko et al., 2018).

6. Conclusions

SHRIMP U-Pb zircon chronology indicates that A-type granitic and locally charnockitic magmatism with similar characteristics took place at ~1110–1025 Ma in the Namaqua-Natal Belt (South Africa), Maud Belt (WDML, Antarctica), Barue and Nampula Complexes (Mozambique) and Vijayan Complex (Sri Lanka) with the magmatism constraining the termination of the Mesoproterozoic orogeny in the belt. Granitoids with older and similar ages are recognized in the belt, however the lithological units correlated in this study have, besides age, similar whole rock major and trace element characteristics and field appearances. Whole rock radiogenic isotope data are available from a few plutons and further work in that direction will either enhance or question the correlations inferred here. The zircon ages obtained in this study are consistent with those of previous studies, but more clearly demonstrate the restricted duration closeness but distinct bimodal age distribution as well as the regional age variation along the eastern and southern margins of the Kalahari Craton. The older ages of granitic magmatism defined here partially overlap with the age of the Mkondo Large Igneous Province in the Kalahari-Grunehogna cratons possibly suggesting the subduction of a spreading centre under the Kalahari Craton at ~1100 My. A similar tectonic setting scenario has been inferred by Meijer (2016) who recognized spreading ridge subduction contributing to the genesis of Paleoproterozoic granitoid plutons and metavolcanic complexes in Arizona, USA.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gsf.2019.04.003.

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