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Detrital zircon U–Pb ages of the Palaeozoic Natal Group and Msikaba Formation, Kwazulu-Natal, South Africa: provenance areas in context of Gondwana

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Abstract – The Natal Group and Msikaba Formation remain relatively poorly understood with regards to their provenance and relative age of deposition; a much-needed geochronological study of the detrital zircons from these two units was therefore undertaken. Five samples of the Durban and Mariannhill Formations (Natal Group) and the Msikaba Formation (Cape Supergroup) were obtained. A total of 882 concordant U–Pb ages of detrital zircon populations from these units were determined by means of laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). Major Neoproterozoic and secondary Mesoproterozoic detrital zircon age populations are present in the detrital zircon content of all the samples. Smaller contributions from Archean-, Palaeoproterozoic-, Cambrian- and Ordovician-aged grains are also present. Due to the presence of a prominent major population of 800–1000 Ma zircons in all the samples, late Stenian – Tonian ancient volcanic arc complexes overprinted by Pan-African metamorphism of Mozambique, Malawi and Zambia, along with areas of similar age within Antarctica, India and Sri Lanka, are suggested as major sources of detritus. The Namaqua–Natal Metamorphic Complex is suggested as a possible source of minor late Mesoproterozoic-aged detritus. Minor populations of Archean and Palaeoproterozoic zircons were likely sourced from the Kaapvaal and Grunehogna Cratons. Post-orogenic Cambrian – Lower Ordovician granitoids of the Mozambique Belt (Mozambique) and the Maud Belt (Antarctica) made lesser contributions. In view of the apparent broad similarity of source areas for the Natal Group and Msikaba Formation, their sedimentation occurred in parts of the same large and evolving basin rather than localized in small continental basins, and the current exposures merely represent small erosional relicts.

Keywords: Natal Group, Msikaba Formation, Provenance, U–Pb ages, detrital zircon.

1. Introduction

The pre-Karoo early Palaeozoic siliciclastic sedimentary strata of the Natal Group and Msikaba Formation, overlying mainly basement rocks of the *c.* 1.1 Ga Namaqua–Natal Metamorphic Complex (NNMC) along the SE coastal margin of South Africa in Kwazulu–Natal and the far NE part of the Eastern Cape Province, remain somewhat controversial with regard to their stratigraphic relationship to each other and to that of the Cape Supergroup further to the south (Fig. 1).

The Msikaba Formation, characterized by abundant, well-sorted quartz arenite, was historically classified as part of the Natal Group. Numerous researchers (Du Toit, 1946; Hobday & Mathew, 1974; Visser, 1974; Kingsley, 1975; Hobday & Von Brunn, 1979) considered outcrops of the Natal Group rocks to occur as far south as Port St Johns, thereby implying the Msikaba Formation to be a southern lateral facies equivalent of the mixed argillaceous-arenaceous red beds and quartz arenites of the Durban and Mariannhill formations. The latter rocks would then comprise the group north of the so-called Dweshula palaeographic high between Port Shepstone and Hibberdene on the Kwazulu–Natal south coast (Fig. 1; Visser, 1974; Kingsley, 1975; Hobday & Von Brunn, 1979). Furthermore, the Natal Group was considered part of the Cape Supergroup, with the Msikaba Formation correlative to the Ordovician Table Mountain Group (Visser, 1974; Kingsley, 1975). However, upon identifying two distinct facies to the north and south of Port Shepstone, Schwarz (1916) had earlier suggested that the grey quartz arenites (Msikaba Formation) of the southern facies are younger than the rocks of the northern facies. The Msikaba Formation is currently considered to be Devonian in age, possibly correlative to the Witteberg Group of the Cape Supergroup, and not part of the red-bed succession of the Natal Group. The latter is thought to be Ordovician in age, deposited in a basin separate from that of the Ordovician Table Mountain Group and therefore not classified as part of the Cape Supergroup (Fig. 2) (Marshall, 2006; Kingsley & Marshall, 2009).

These changes in original concepts came about through (1) the discovery of Devonian *lycopod* fossils in the Msikaba Formation (Lock, 1973; SACS, 1980; Anderson & Anderson, 1985); (2) the realization that there is no physical field evidence for lateral interfingering

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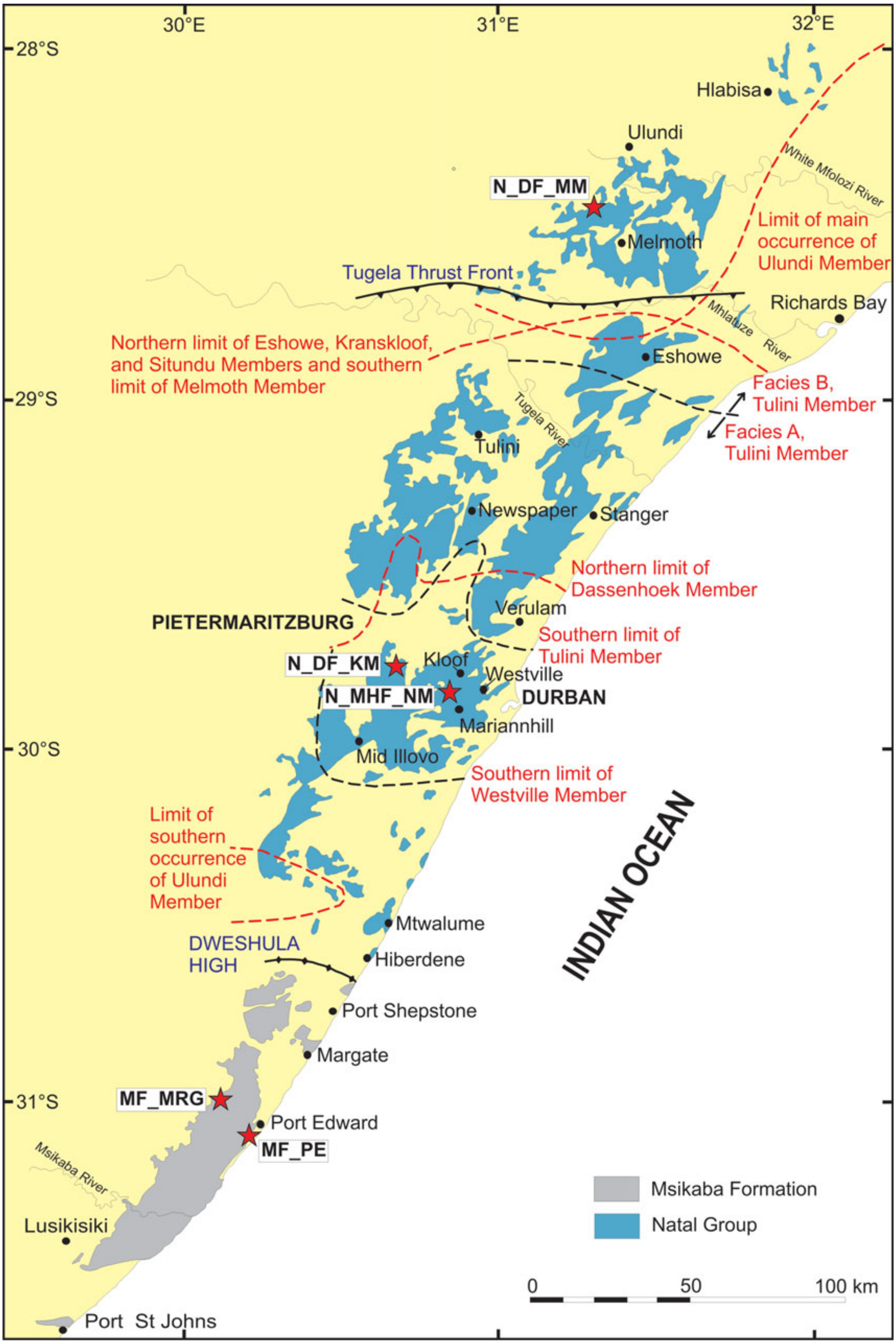

Figure 1. (Colour online) The location of the Natal Group and Msikaba Formation along the eastern margin of South Africa, showing the distribution and extent of the various units. The approximate locations for each sample have been indicated (redrawn and modified after Marshall & Von Brunn, 1999; Kingsley & Marshall, 2009).

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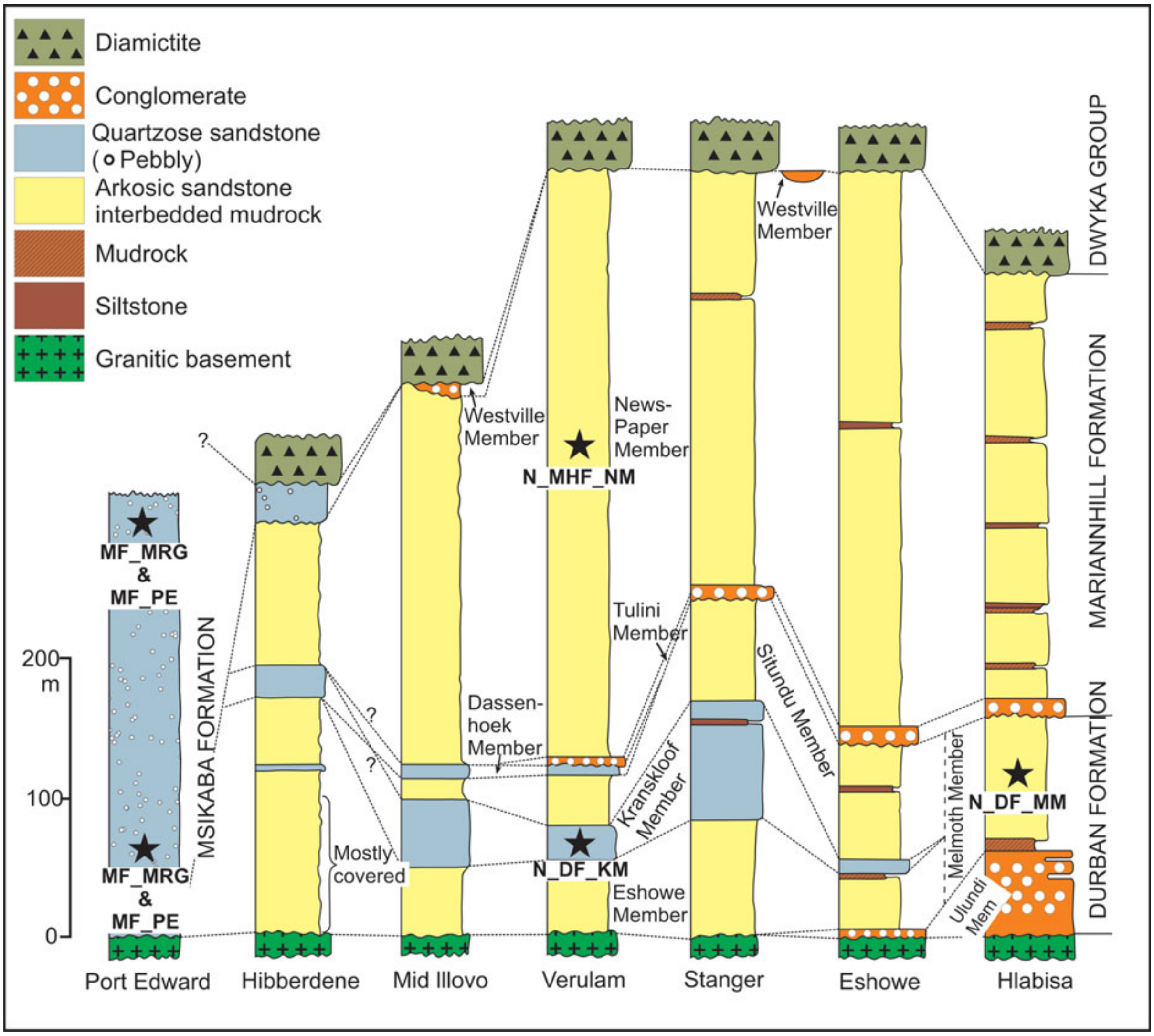

Figure 2. (Colour online) Cross-sections of Natal Group and Msikaba Formation strata at various locations along the eastern margin of South Africa, indicating the units sampled for detrital zircon provenance evaluation (redrawn and modified from Marshall, 2006).

of Msikaba Formation quartz arenites with red beds of the Durban and Mariannhill formations across the Dweshula palaeographic high (first noted by Schwarz, 1916); (3) the presence of apparently diagenetic illite with Early Ordovician Ar–Ar and K–Ar ages of *c.* 485 Ma in the lower part of the Durban Formation (Thomas *et al*. 1992*b*); and (4) an assumption that the Dweshula palaeographic high represented the southern limit of the Natal Group depository (C.G.A. Marshall, unpub. M.Sc. thesis, Univ. of Natal, South Africa, 1994; Marshall & Von Brunn, 1999).

Recently it was shown that the latter assumption has to be modified because relicts of the lowermost strata of the Natal Group are preserved below a marked unconformity at the base of the Msikaba Formation to the south of the Dweshula palaeographic high (Hicks, 2010). Although not considered by Hicks (2010), this finding opens up the possibility that the Natal basin linked up southwards with the Cape Basin and that the Natal Group may in fact have correlatives in the lowermost fluvial and paralic red beds of the Ordovician Table Mountain Group. The major erosional unconformity at the base of the Msikaba Formation (Hicks, 2010) also proves unequivocally for the first time that the quartz arenites of this formation are not laterally equivalent to red beds of the Natal Group to the north.

The lithology and stratigraphy of both the Natal Group and overlying Msikaba Formation have been well documented (Marshall, 2003*a*, *b*, 2006; Thamm & Johnson, 2006; Kingsley & Marshall, 2009). However, some uncertainty still persists about their depositional age, provenance areas of sediments and the nature of the depository. The only depositional age data available is that of ^{40}Ar–^{39}Ar analyses of two authigenic mica samples from the Durban Formation that yielded a poorly constrained age of *c.* 490 Ma indicating that deposition of the Natal Group may already have been in progress during very late Cambrian – very Early Ordovician times (Thomas *et al*. 1992*b*). No radiometric age constraints are available for the deposition of the Msikaba Formation.

Some deductions regarding the nature of the basin of the Natal Group and potential sources of sediment

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supply have been made in the past (Marshall & Von Brunn, 1999; Marshall 2003*a*, 2006) on the basis of palaeocurrent directions and possible syndepositional tectonic activity. The only radiometric age data on possible source rocks of the Natal Group are K–Ar ages of detrital muscovites from the southern outcrop areas, which revealed Pan-African ages of *c.* 580 Ma (Thomas *et al.* 1992*a*, *b*). Since there was no record of a Pan-African metamorphic overprint for the KwaZulu–Natal basement rocks at the time, it was concluded that the detrital muscovite must have originated from a source area outside the basin (Thomas, Eglington & Kerr, 1990; Thomas *et al*. 1992*b*; Jacobs & Thomas, 1996; Marshall & Von Brunn, 1999). The Mozambique Belt or the Maudheim Province of Antarctica have subsequently been suggested as possible source regions for the sediments of the Natal Group (Thomas *et al.* 1992*a*, *b*). However, this proposal as well as the possibility that local sources from the 1.1–1.2 Ga NNMC and Archean–Palaeoproterozoic rocks of the Kaapvaal Craton could have supplied sediments to the depository (Marshall, 2006; Hicks, 2010) have not been thoroughly tested. This highlights the need for adequate detrital zircon age data for the Natal Group in order to test such hypotheses on the source regions of detritus and to better constrain the maximum age of deposition of the unit. The same applies to the Msikaba Formation for which no detrital provenance age data are available, while the nature of the depositional basin and possible source terrains also remain essentially unconstrained. In a broad sense, the only information available is that the quartz arenites represent deposition on a stable shelf as a result of a marine transgression from the south coupled with sediment dispersal offshore to the southwest (Shone & Booth, 2005; Kingsley & Marshall, 2009).

The objective of this study is therefore to determine the U–Pb age distribution of detrital zircons in the sediments of the Natal Group and Msikaba Formation by means of laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). The dataset obtained allows testing of the hypotheses on source regions of sediments for the Natal Group and also reveals subtle differences in provenance areas between the Natal Group and Msikaba Formation.

2. Geological setting

2.a. Natal Group

Relatively flat-lying strata of the Natal Group, that unconformably overlie rocks of the Archean Kaapvaal Craton in the far north and of the 1.1–1.2 Ga NNMC in the south, crop out intermittently from below a cover of Karoo strata in a narrow strip from Hlabisa in the north to Hibberdene in the south, extending inland as far as Pietermaritzburg (Fig. 1; Shone & Booth, 2005; Marshall, 2006). The succession, with a maximum known preserved thickness of *c.* 530 m, is characterized by dominant lithologies of reddish-brown arkosic sandstone, siltstone, micaceous mudrock and reddish-grey conglomerate (Marshall, 2006). The two formations of the group, namely the Durban and Mariannhill formations, have rather similar lithological composition, the main difference being that quartz arenite beds are present in the first and absent from the second (Fig. 2; Table 1).

The older Durban Formation nonconformably overlies the Precambrian basement and has been subdivided into six members as summarized in Table 1 (Marshall & Von Brunn, 1999). The Ulundi Member at the base of the succession is conformably overlain by the Eshowe Member (Fig. 2). This conglomerate unit pinches out to the south so that the Eshowe Member forms the base of the succession. The Kranskloof Member conformably overlies the Eshowe Member and is, in turn, overlain by the Situndu Member (Fig. 2). North of the contact between basement rocks of the NNMC and those of the Kaapvaal Craton in the vicinity of Eshowe, the Kranskloof Member pinches out. This results in the Eshowe and Situndu Members becoming lithologically indistinguishable, and the lateral equivalents of these units are therefore referred to as the Melmoth Member (Fig. 2; Marshall, 2003*a*, 2006). Within the southern outcrop area the Dassenhoek Member overlies the Situndu Member (Marshall, 2003*a*).

The Mariannhill Formation paraconformably overlies the Durban Formation and comprises the basal Tulini, Newspaper and Westville members (Marshall & Von Brunn, 1999; Marshall, 2003*b*). The Tulini Member occurs mostly within the northern and central parts of the Natal basin (Fig. 2) where it overlies the Melmoth, Situndu and Dassenhoek members, respectively (Shone & Booth, 2005; Marshall, 2006). The Newspaper Member occurs throughout the outcrop region of the Natal Group and conformably overlies the Tulini Member or, in the absence of the latter, paraconformably overlies the Durban Formation (Marshall & Von Brunn, 1999; Marshall 2003*b*, 2006). The Westville Member, preserved sporadically throughout the region below the erosional unconformity at the base of the Dwyka diamictite of the Karoo Supergroup, is regarded as the uppermost unit of the Natal Group (Marshall & Von Brunn, 1999; Marshall, 2003*b*).

Deposition of the Natal Group is considered by some to have occurred within the so-called 'Natal Trough', interpreted as a foreland graben with a SSW-sloping axial gradient oriented parallel to the present KwaZulu–Natal coastline and related to a late stage of the Pan-African (*c.* 550 Ma) orogeny (Hobday & Von Brunn, 1979; Thomas *et al*. 1992*b*). However, Hicks (2010) suggests interplay between a passive margin setting along the southern edge of the Kaapvaal Craton, combined with a rifted margin to the west (Fig. 3). In both models, the present western outcrop margin of the Natal Group rocks is considered to coincide approximately with the original western normal-fault-margin of the depositional basin (Hobday & Von Brunn, 1979; Thomas *et al*. 1992*b*; Marshall, 2006; Hicks, 2010). The eastward extent of the basin remains unknown

Table 1. Lithostratigraphy of the Natal Group and Msikaba Formation. The relative thickness (in metres) of the units are given in brackets (Marshall 2003*a*, *b*, 2006; Thamm & Johnson, 2006).

Group	Formation	Member		Rock type		Depositional environment	
	Msikaba (1200)	~		Coarse-grained quartz arenite		Shallow marine	
Natal	Mariannhill	Westville (30)		Conglomerate		Fluvial braidplain	
		Newspaper (400)		Arkosic sandstone, shale		Braided river	
		Tulini (28)		Conglomerate		Fluvial braidplain	
	Durban	**Northern area**	**Southern area**	**Northern area**	**Southern area**	**Northern area**	**Southern area**
		Melmoth (168)	Dassenhoek (42)	Arkosic sandstone, interbedded shale	Silicified quartz arenite	Braided river	Fluvial
			Situndu (84)		Coarse arkosic sandstone		Fluvial
			Kranskloof (51)		Silicified quartz arenite		Fluvial
			Eshowe (142)		Arkosic sandstone, shale		Braided river
		Ulindi (60)		Conglomerate		Alluvial fan	

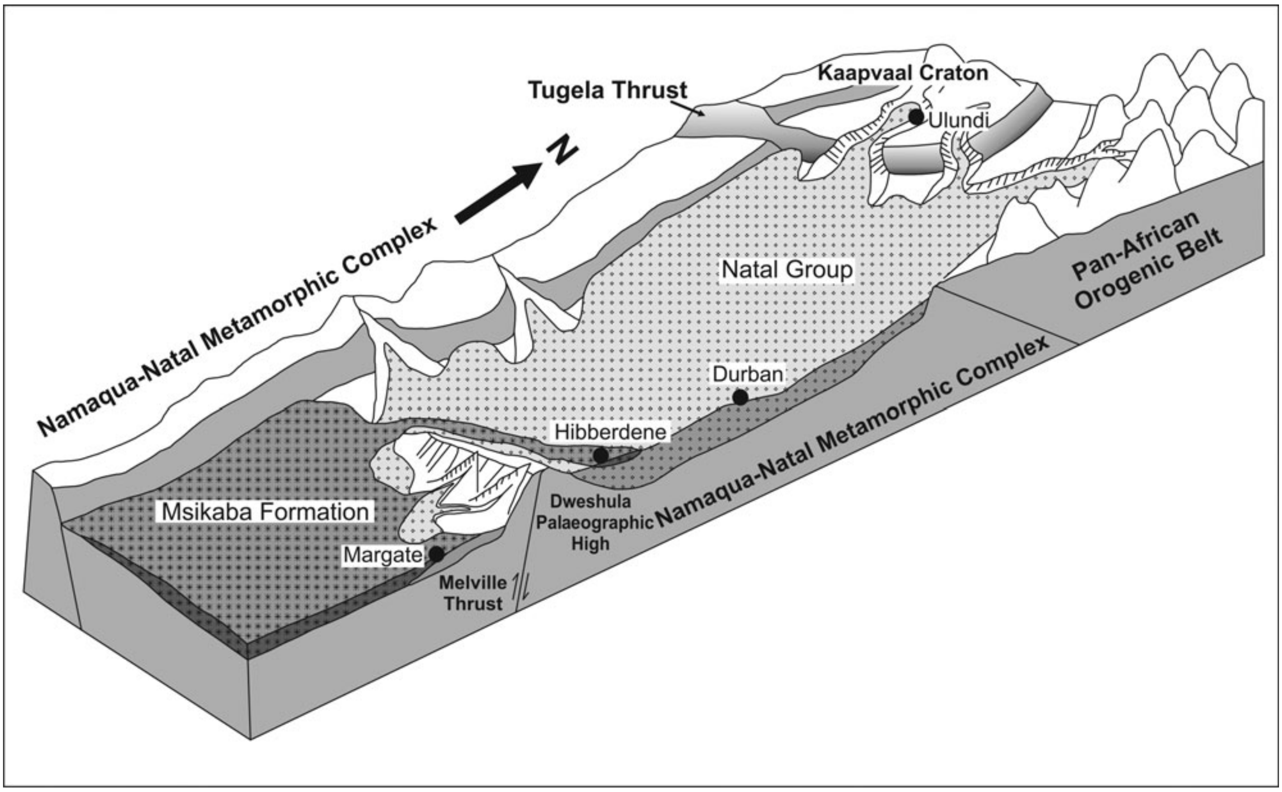

Figure 3. Depositional model for the Natal Group and Msikaba Formation. The deposition of the Natal Group occurred in a passive margin setting south of the Kaapvaal Craton and a rifted margin setting along the eastern margin of the NNMC, with deposition of the Msikaba Formation upon a stable platform within a high-energy shallow-marine environment. More recently, the Natal Basin is considered to have extended south of the Dweshula palaeographic high which was previously regarded as the southern margin of this basin. Some localized deposition of the Msikaba Formation also occurred towards the north of this feature (redrawn and modified after Hicks, 2010).

because it was cut off by the Falkland–Agulhas Fracture Zone during the break-up of Gondwana (Thomas *et al*. 1992*b*; Marshall & Von Brunn, 1999; Marshall, 2006). Although the southern margin of the Natal basin was formerly considered to coincide with the Dweshula palaeographic high (Marshall, 2006), it is now known that it extended much further to the south (Fig. 3; Hicks, 2010).

The deposition of the conglomeratic Ulundi, Tulini and Westville members has been ascribed to fluvial activity and debris-flow processes, whereas braided river depositional environments have been proposed for the argillaceous or arenaceous units (Marshall & Von Brunn, 1999; Shone & Booth, 2005; Marshall, 2006). A prevailing NE–SW-directed palaeocurrent has been reported for the Eshowe and Melmoth members, which supports the proposal of a provenance area to the northeast. Palaeocurrents measured along the western margin of the basin suggest a small, localized input of detritus from the west, or may be interpreted as eddy currents caused by the steep basin margin (Fig. 3; Marshall & Von Brunn, 1999; Hicks, 2010).

2.b. Msikaba Formation

Outcrops of the Msikaba Formation occur sporadically below Karoo cover between Margate in the north to Port St Johns in the south (Thamm & Johnson, 2006; Kingsley & Marshall, 2009). Lycopod fossils constrain its age of deposition as Middle–Late Devonian (Lock, 1973; Anderson & Anderson, 1985) but it may be as young as middle Carboniferous in age (Marshall & Von Brunn, 1999; Shone & Booth, 2005; Marshall, 2006). The unit mostly rests on a basement of rocks of the NNMC, but immediately north and south of the Dweshula palaeographic high it overlies the Eshowe Member of the Durban Formation (Natal Group) with an apparent sharp erosional contact (Hicks, 2010). It is essentially composed of grey quartz arenite with minor interbeds of quartz pebble conglomerate (Thamm & Johnson, 2006; Kingsley & Marshall, 2009). The base of the Msikaba Formation is found only in a few localities, as recently described by Hicks (2010), where the contact relationship between the Natal Group and Msikaba Formation is clearly exposed. A granitic-boulder conglomerate and reworked granitic veneers have been identified within some of these exposures, located in the vicinity of the Dweshula palaeographic high. This conglomerate at the base of the Msikaba Formation near the Dweshula palaeographic high has been interpreted as a fluvial channel fill that preceded deposition of overlying transgressive marine quartz arenite (Hicks, 2010).

It has been proposed that the deposition of the Msikaba Formation occurred within the vast Cape Basin (Kingsley, 1975; Shone & Booth, 2005; Thamm & Johnson, 2006). *Rusophycus*, *Scolicia and Planolites* trace fossils (Hobday, Brauteseth & Mathew, 1971; Hobday & Mathew, 1974) together with the maturity of the quartz arenite and quartz pebble conglomerate support a shallow-marine shelf depositional setting (Visser, 1974; Kingsley, 1975; Shone & Booth, 2005; Thamm & Johnson, 2006; Hicks, 2010). This depositional setting is very similar to that of the Witpoort Formation of the Witteberg Group (Cape Supergroup) that also contains abundant *lycopod* plant stem remains thought to have floated into the marine environment from river run-off (J.N. Theron, unpub. M.Sc. thesis, University of Stellenbosch, South Africa, 1960). A dominantly SW-directed palaeocurrent has been recorded (Shone & Booth, 2005; Thamm & Johnson, 2006).

3. Sample description and analytical methods

Samples were collected from both formations of the Natal Group, as well as from the Msikaba Formation. Ideally, both successions should have been sampled at the same location. Only a few localities have been described where the Msikaba Formation overlies the Natal Group however, and at these localities the contact relationships are mostly poorly exposed. For example, at Woodgrange near Hibberdene the contact is obscured by beach sand (C.G.A. Marshall, unpub. M.Sc. thesis, University of Natal, South Africa), making sampling at this locality rather problematic. Alternative sampling sites have therefore been selected. In general, sampling sites were selected to allow sample collection at the least weathered and most accessible sites. The red arkosic-sandstone Melmoth Member (N_DF_MM) of the lower Durban Formation was sampled near the town of Melmoth (28° 27′ 34.2″ S, 31° 20′ 05.8″ E; Fig. 1) in the northern outcrop region of the Natal Group, with a sample of the quartz-arenitic Kranskloof Member (N_DF_KM) collected near Kloof (29° 44′ 57.7″ S, 30° 39′ 54.2″ E). A sample of red arkosic sandstone of the Newspaper Member (N_MHF_NM), in the upper part of the Mariannhill Formation of the Natal Group, was obtained near Mariannhill (29° 49′ 24.8″ S, 30° 48′ 34.2″ E). Quartz arenite samples of the Msikaba Formation were obtained within the Mthamvuna River Gorge (MF_MRG) near Port Edward (31° 00′ 37.5″ S, 30° 10′ 17.8″ E) as well as at a beach outcrop of the formation at Port Edward itself (MF_PE) (31° 03′ 24.5″ S, 30° 13′ 38.5″ E). At every location, samples were collected as numerous chips closely spaced throughout the immediate outcrop area of a given unit. In the Mthamvuna River Gorge three sets of chip samples were collected in the lower, middle and upper part of the several-hundred-metre-thick exposed profile of the Msikaba Formation. These sets were separately treated and analysed before being combined into a single population. The sample collected on the beach at Port Edward represents the lower few tens of metres of the Msikaba Formation, where it disconformably overlies magmatic charnockites of the NNMC.

Sample preparation and extraction of zircons followed a standard procedure as described in Belyanin *et al.* (2014). Mostly *c.* 100 (but never less than 70) detrital zircon grains were selected from each sample on the basis of random and non-random grain selection (Košler, 2012) in order to ensure that the various grain sizes and morphologies within a population would be well represented.

The U–Pb age determination of the detrital zircon grains was conducted by means of LA-ICP-MS at SPECTRUM (the central analytical facility of the Faculty of Science, University of Johannesburg) equipped with a New Wave 213 nm Nd:YAG laser coupled to a Thermo Electron X-Series II Quadrupole-based ICP-MS with dual mode detection system. A standard-sample-standard bracketing analysis procedure was followed for U–Pb age determination of unknown detrital zircon grains using two well-characterized zircon standards: GJ1 (608.5 ± 0.4 Ma, Jackson *et al.* 2004) and 91500 (1065 ± 0.4 Ma, Wiedenbeck *et al.* 1995). Both standards and unknowns were analysed using a 30 μm spot size and 4 Hz repetition rate, resulting in a pulse energy of 0.045–0.050 mJ. Helium was used as the carrier gas. Each analysis involved the 30 s measurement of the gas blank for background corrections followed by an 80 s analysis of the sample. A time-resolved analysis data acquisition protocol was used to

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record analyte signals for ^{202}Hg, ^{204}(Hg + Pb), ^{206}Pb, ^{207}Pb, ^{208}Pb, ^{232}Th, ^{235}U and ^{238}U. In the ablation of all detrital zircon grains care was taken to avoid the sampling of distinct cores, as well as areas of metamorphic overgrowth or within fractures, where possible.

The reduction of acquired detrital zircon data was conducted using in-house data reduction software. The software utilizes the data from measurements of both zircon standard reference materials, GJ1 and 91500, in order to yield approximate U, Th and Pb concentrations and conduct a precise external correction for elemental fractionation and mass discrimination. For samples that indicated a significant contribution of common Pb, the software allows for the data to be corrected by applying a common Pb correction based on the model Pb composition proposed by Stacey & Kramers (1975).

Concordia ages were calculated and results plotted using the Excel® integrated Isoplot/Ex 3.00 software (Ludwig, 2003). Following that, probability density diagrams were constructed for each studied unit using detrital zircon age data that are less than 10 % discordant. Circular percentage charts, which illustrate the percentage of the zircon population assigned to the different geological periods (in accordance with the International Commision on Stratigraphy chronostratigraphic chart; see Cohen *et al.* 2013), were constructed to accompany each probability density diagram.

4. Results

4.a. Morphology and cathode luminescence data

The detrital zircons extracted from the samples representing the Natal Group (N_DF_MM, D_DF_KM and N_MHF_NM, Fig. 4) are mostly euhedral, rounded and elongate. In general, the grains range in length from *c.* 80 μm to 250 μm, although grains of up to *c.* 300 μm in length were present in sample N_DF_KM. The overall majority of the zircon grains are oscillatory zoned with clearly distinguishable cores. A few grains with no zoning are also present. Some of the grains appear to have thin metamorphic rims partially surrounding them. Numerous grain fragments are present, which could in part be ascribed to the sample preparation procedure. However, some of the fragmented grains show secondary rounding, indicating that these grains were broken and again rounded during natural sediment transport processes.

The Msikaba Formation detrital zircon population (MF_MRG and MF_PE, Fig. 4) also contains mostly euhedral, elongated grains that have been rounded by sedimentary transport processes. The grains vary between *c.* 80 μm and 270 μm in length, with some significantly larger grains (*c.* 330 μm) present in sample MF_MRG. Grain fragments of between *c.* 60 μm and 370 μm are common among both samples. As in the case of the Natal Group samples, these grain fragments are often again rounded. Most of the grains have oscillatory zoned interiors, and some have thin metamorphic overgrowths.

4.b. Zircon age populations

4.b.1. Durban Formation (Natal Group)

Sample N_DF_MM, representing the Melmoth Member of the Durban Formation, yielded 99 concordant zircon ages (online Supplementary Table S1, available at http://journals.cambridge.org/geo). Only grains with ages that are more than 90 % concordant were included (Fig. 5a). From their age probability density diagram, it is evident that there is a large Neoproterozoic age component comprising two main peaks centred at 564 and 944 Ma (Fig. 6a). A barely resolved population of Ordovician- and Cambrian-aged grains accounts for 2 and 3 % of the population, respectively (Fig. 6b). The peak centred at 564 Ma could therefore be considered to represent the youngest detrital age cluster ranging from 452 ± 19 to 686 ± 25 Ma (26 grains in total). A smaller input from Mesoproterozoic-aged sources (9 % Stenian, 4 % Ectasian and 1 % Calymmian) and some grains of Palaeoproterozoic (5 %), Neoarchean (1 %), Mesoarchean (2 %) and Palaeoarchean (2 %) age are also present. It is unlikely that the older populations represent inherited zircon cores, as the analysis of cores was avoided.

The individual Th/U ratios range from 0.014 to 2.082 (online Supplementary Table S1, available at http://journals.cambridge.org/geo) with an average Th/U ratio of 0.532 (standard deviation 0.342). While there is no definite cut-off value for zircon Th/U ratios, (Rubatto, 2002; Hoskin & Schaltegger, 2003; Möller *et al.* 2003), values of *c.* 0.1 or lower are generally regarded to indicate a metamorphic origin. Using this value, the vast majority of the grains (*c.* 97 %) of sample N_DF_MM can be considered as magmatic zircons rather than metamorphic zircons.

The sample preparation and analysis of sample N_DF_KM, representing the Kranskloof Member, was performed in triplicate and 229 concordant dates on detrital zircons were obtained (Fig. 5b and online Supplementary Table S2, available at http://journals.cambridge.org/geo). The age probability distribution is dominated by one broad peak centred at 990 Ma and ranging from Neo- to Mesoproterozoic (Fig. 6c). The Neoproterozoic-aged component comprises 1 % Ediacaran-, 4 % Cryogenian- and 34 % Tonian-aged grains, while the Mesoproterozoic-aged component is made up of 36 % Stenian-, 5 % Ectasian- and 2 % Calymmian-aged grains. Grains originating from Palaeoproterozoic (7 %), Neoarchean (5 %), Mesoarchean (7 %) and Palaeoarchean (1 %) sources are present to a lesser, yet significant extent (Fig. 6d).

The small peak centred at 692 Ma (Fig. 6c) represents the youngest cluster of grains ranging from 570 ± 55 to 691 ± 43 Ma and comprises only three grains. The youngest grain analysed therefore has a Neoproterozoic age and is interpreted as the age of the

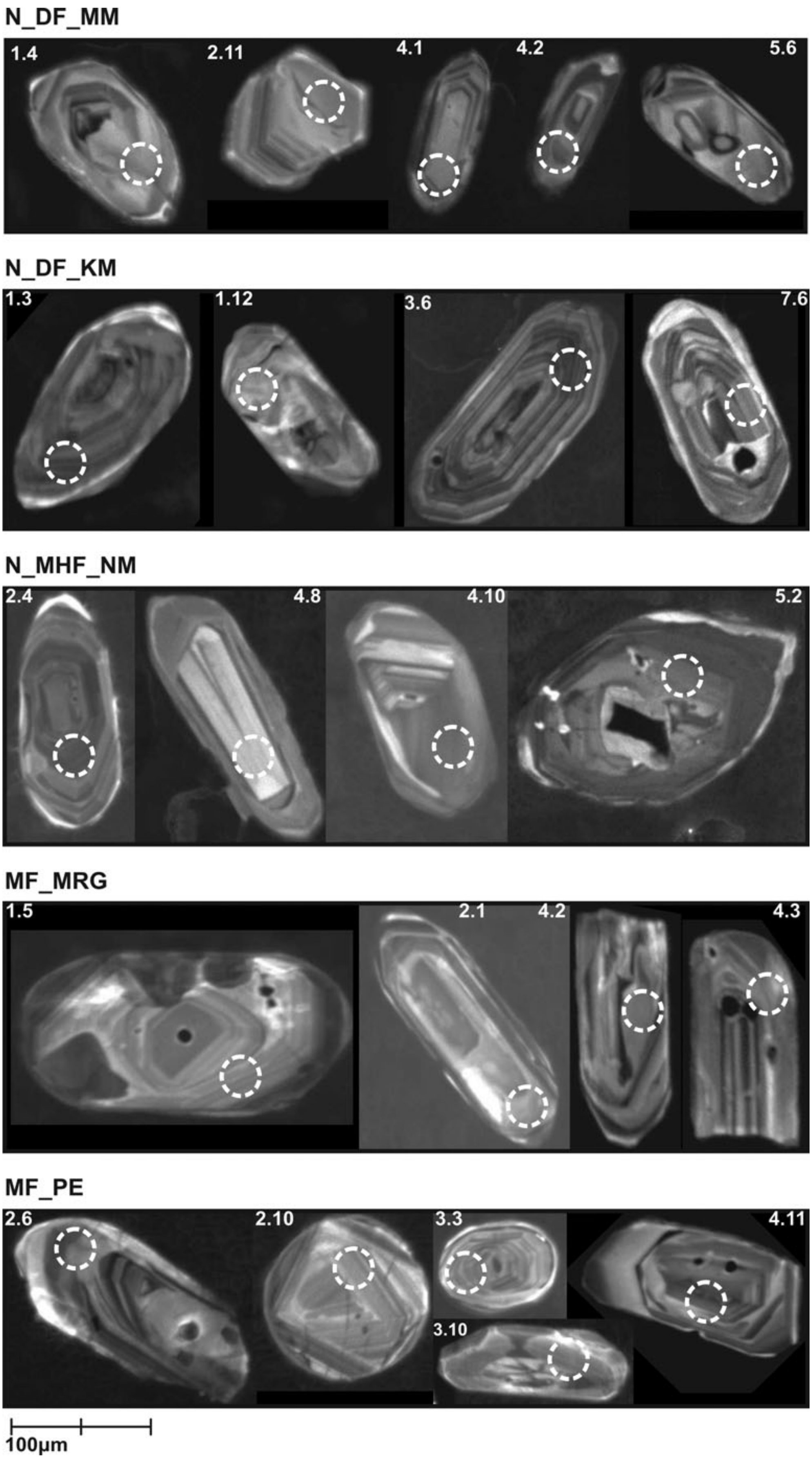

Figure 4. CL-images of selected zircon grains of the Natal Group (N_DF_MM, N_DF_KM and N_MHF_NM) and the Msikaba Formation (MF_MRG and MF_PE), with the location of the ablation pit for detrital zircon age determination by LA-ICP-MS.

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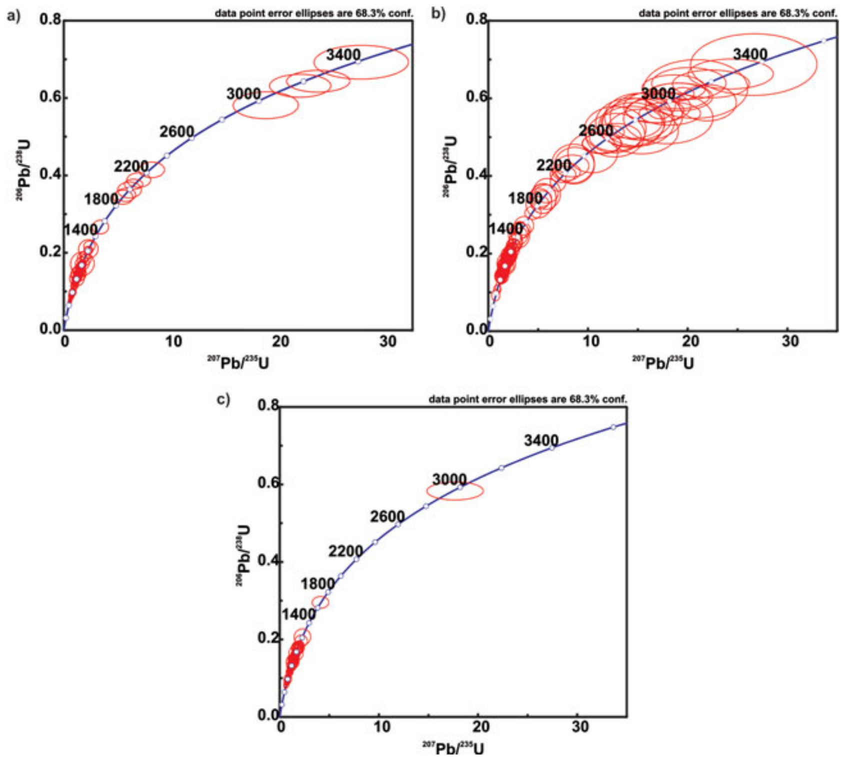

Figure 5. (Colour online) Concordia diagrams for the Durban and Mariannhill formations, Natal Group. All U–Pb ages of grains are more than 90 % concordant: (a) N_DF_MM; (b) N_DF_KM; and (c) N_MHF_NM.

youngest source of detrital material available during the deposition of the Kranskloof Member. The majority of the zircon grains (*c.* 99 %) are again considered to be of magmatic origin, based on the values of their Th/U ratio. Here, Th/U ratios ranging from 0.045 to 3.889 (online Supplementary Table S2, available at http://journals.cambridge.org/geo) were obtained with an average value of 0.910 (standard deviation 0.459).

4.b.2. Mariannhill Formation (Natal Group)

Zircons from sample N_MHF_NM of the Newspaper Member of the Mariannhill Formation yielded 94 concordant ages (Fig. 5c; online Supplementary Table S3, available at http://journals.cambridge.org/geo). The probability density diagram (Fig. 6e) reveals a dominant Neoproterozoic zircon age component, constituting 80 % of the zircon age population (13 % Ediacaran, 33 % Cryogenian and 34 % Tonian ages, Fig. 6f) which is distributed over three abundance peaks centred at 565, 780 and 897 Ma. Furthermore, there is a significant input of zircon grains from Mesoproterozoic sources (15 %), most of which is in the tail of the oldest Neoproterozoic probability peak (14 % Stenian ages, Fig. 6e). A minor contribution from Cambrian-aged grains (3 %) is present, as well as Palaeoproterozoic- and Mesoarchean-aged components contributing 1 % to the zircon population (Fig. 6f).

The youngest detrital zircon age cluster is centred at *c.* 565 Ma. This cluster encompass 21 grains with ages ranging from 493 ± 23 to 669 ± 16 Ma. The Cambrian age obtained for the youngest grain within the zircon population dates the youngest detrital material sourced during deposition of the Newspaper Member. Since Th/U ratios of between 0.100 and 1.799 were measured for the grains from the Newspaper Member, they can all be considered to be of magmatic origin.

4.b.3. Msikaba Formation

The samples from the Mthamvuna River Gorge (MF_MRG) and Port Edward (MF_PE) locality, representing the Msikaba Formation, yielded 279 (Fig. 7a) and 181 (Fig. 7b) concordant zircon dates (>90 % concordance), respectively (online Supplementary Tables S4, S5, available at http://journals.cambridge.org/geo). The probability density diagrams for these two samples are provided in Figures 8a and c. Both samples contain large Neoproterozoic-aged zircon populations (65 % of all data for sample MF_MRG and 75 % for sample MF_PE, Fig. 8b, d) with main abundance peaks centred at 634–647 and 922–927 Ma and a minor peak at 810–858 Ma. A significant input of Mesoproterozoic-aged grains is also apparent, which appears to be slightly larger for the sample collected at Port Edward (18 %) in the lower part of the succession compared to the Mthamvuna River Gorge sample that spanned the entire preserved succession (11 %). No significant differences in the detrital zircon age distribution were found for the lower, middle and upper part of the Msikaba Formation sampled in the Mthamvuna River (MF_MRG), thereby suggesting a uniform distribution of detritus for the formation at this locality.

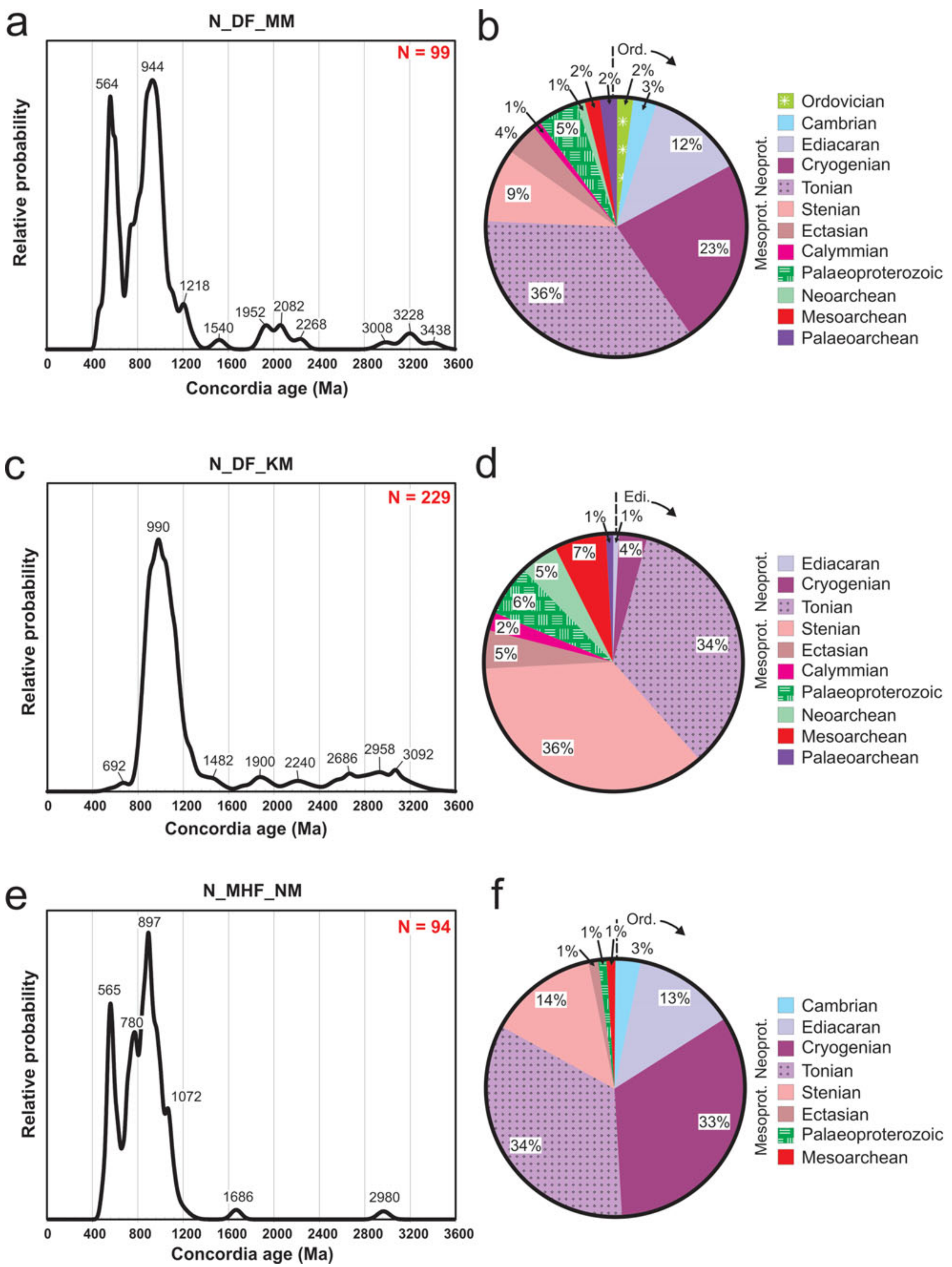

Figure 6. (Colour online) Probability density diagrams and circular percentage plots for members of the Natal Group. Only detrital zircon ages that are more than 90 % concordant were incorporated in these diagrams: (a, b) Melmoth Member, Durban Formation (sample N_DF_MM); (c, d) Kranskloof Member, Durban Formation (sample N_DF_KM); and (e, f) Newspaper Member, Mariannhill Formation (N_MHF_NM).

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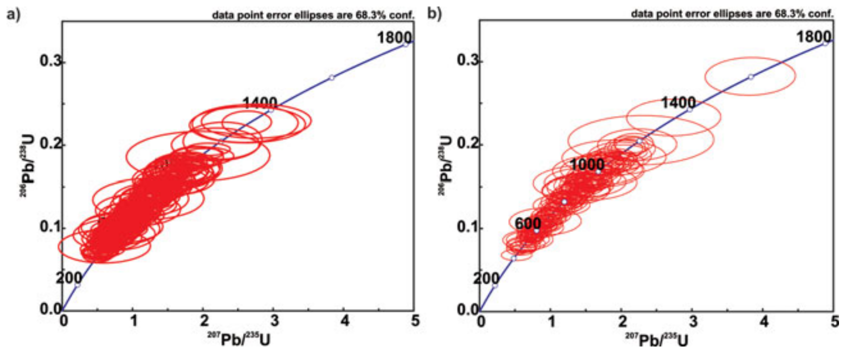

Figure 7. (Colour online) Concordia diagrams for the two samples collected from the Msikaba Formation. All U–Pb ages of grains are more than 90 % concordant: (a) MF_MRG and (b) MF_PE.

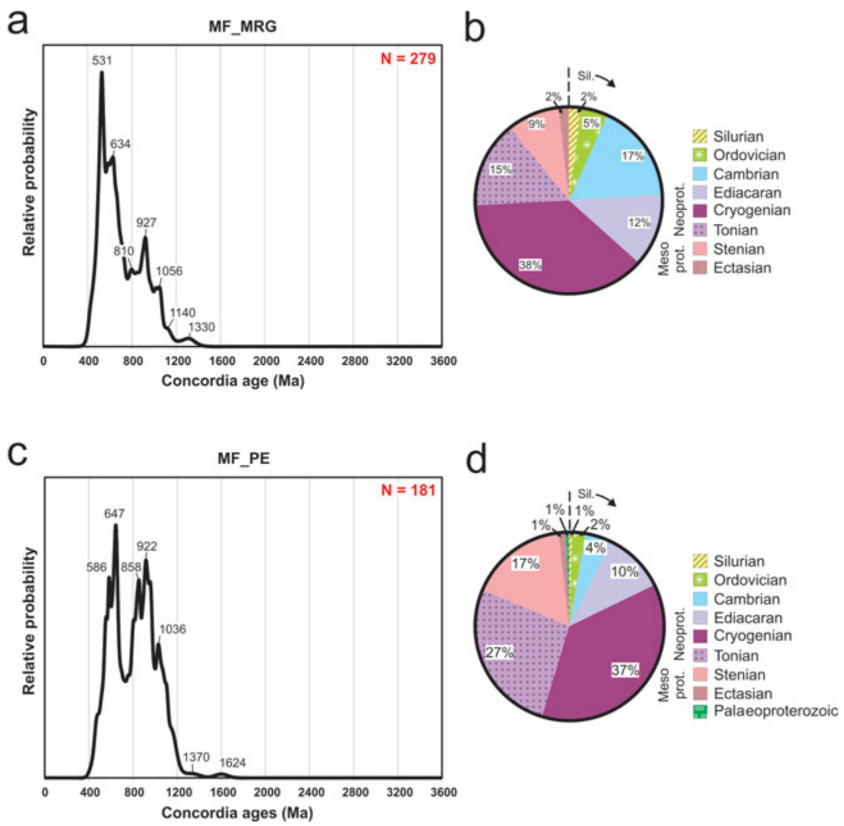

Figure 8. (Colour online) Probability density diagrams and circular percentage plots for the Msikaba Formation. Only detrital zircon ages that are more than 90 % concordant were incorporated in these diagrams. (a, b) Msikaba Formation sampled at Mthamvuna River Gorge (MF_MRG). (c, d) Msikaba Formation sampled at Port Edward (MF_PE).

It is also interesting to note that Cambrian-aged grains appear to be more abundant in the sample collected over the entire succession in the Mthamvuna River Gorge (17 % in sample MF_MRG, Fig. 8a), compared to the sample at Port Edward (4 % in sample MF_PE, Fig. 8c). Minor Silurian- (1–2 %) and Ordovician- (2 to 5 %) aged components were also noted for both samples, along with the presence of a few grains of Palaeoproterozoic age (1 % of the population) within the zircon population of the sample MF_PE (Fig. 8b, d).

The youngest age cluster for sample MF-MRG is represented by the peak centred at *c.* 531 Ma (Fig. 8a) ranging from 424 ± 14 to 564 ± 28 Ma (81 zircons in total). The small peak shoulder at *c.* 450 Ma represents the youngest age cluster for sample MF_PE (Fig. 8c). Here, five detrital grains range in age from 425 ± 26 to 483 ± 27 Ma. The youngest grains within the overall Msikaba Formation zircon population are therefore of Silurian age.

The detrital zircon grains of both samples from the Msikaba Formation have an average Th/U ratio of 0.533 (standard deviation 0.305) and majority of the grains (*c.* 97 %) could be considered to be of magmatic origin, although the individual values range from 0.003 to 2.044.

5. Discussion

5.a. Depositional age

The youngest zircon populations present in the Natal Group and Msikaba Formation appear to be clearly

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distinct. Although these populations constitute only a minor portion of the overall zircon populations in both successions, the ages associated with the youngest grains are significant. The youngest age cluster of the Durban Formation is that of sample N_DF_MM (452 ± 19 to 686 ± 25 Ma), whereas the sample from the Mariannhill Formation contains a population of young zircons ranging from 493 ± 23 to 669 ± 16 Ma. In addition, the youngest clusters of detrital zircon ages of the Msikaba Formation, 424 ± 14 to 564 ± 28 Ma and 425 ± 26 to 483 ± 27 Ma for samples MF_MRG and MF_PE, respectively, are slightly younger than those of the Natal Group. This observation is in accordance with the observation that a major erosional hiatus is present between red beds of the Natal Group and the quartz arenite of the Msikaba Formation (Hicks, 2010).

The youngest zircon observed in the Durban Formation, present among the detrital zircon population of the Melmoth Member (N_DF_MM), has an age of 452 ± 19 Ma. A maximum Early Ordovician depositional age for the Durban Formation is therefore inferred by this age. This age is also comparable with, but younger than, the depositional age of *c.* 480 Ma suggested by Thomas *et al.* (1992*b*) for deposition of the Natal succession based on K–Ar age data on mixed detrital and authigenic illite and biotite in the matrix of the sandstones. The age of the youngest detrital zircon within the overlying Mariannhill Formation (493 ± 23 Ma) is older than the youngest detrital zircon grain analysed for the Durban Formation. The age of this grain has been interpreted as the age associated with the youngest available source area during the deposition of the Mariannhill Formation. It therefore does not imply that the Mariannhill Formation is older than the Durban Formation. The ages of the youngest cluster of detrital zircon grains for all the samples analysed of the Natal Group confirms that the deposition of the group was already in progress during Early Ordovician time, with the possibility that it could be as young in age as Late Ordovician. The new zircon age constraints make the Natal Group in chronostratigraphic terms correlative to the Table Mountain Group of the Cape Supergroup.

In contrast to the Natal Group, the youngest zircon observed in the Msikaba Formation has an age of 424 ± 14 Ma. We interpret this age as that of the youngest available source area during the deposition of the Msikaba Formation, and a maximum age of deposition during middle–late Silurian time is inferred. This is in accordance with the finding that the Msikaba Formation was deposited during Devonian time, as indicated by the *lycopod* fossil remains (Anderson & Anderson, 1985), although an age as young as Carboniferous is not excluded by the data. It should be noted that there is a lack of potential source areas of early Palaeozoic age that are in accordance with the prevailing SW-directed palaeocurrent reported for the Msikaba Formation.

The difference (*c.* 28 Ma) between the absolute age of the youngest detrital zircon of the Natal Group and that of the Msikaba Formation might not be very significant. However, the youngest age clusters associated with both units consistently indicate that progressively younger source areas were eroded during the deposition of the Msikaba Formation compared to the units of the Natal Group, thereby suggesting that the Msikaba Formation is younger than the Natal Group.

5.b. Provenance

The detrital zircon age populations for the members representing the Durban and Mariannhill formations of the Natal Group show remarkable similarities, but also some differences. All three samples indicate a major input of detrital zircon grains in age abundance peaks centred at 900–990 Ma and ranging from *c.* 800 to 1200 Ma. The Melmoth and Newspaper Member samples (N_DF_MM and N_MHF_NM) both have a significant Neoproterozoic abundance peak centred at 565 Ma, which is absent from the Kranskloof Member sample. Further, both Durban Formation samples (N_DF_MM and N_DF_KM) have more significant Palaeoproterozoic and Archean input than the Mariannhill Formation (N_MHF_NM; Fig. 6).

The determination of possible provenance areas for the detrital zircon populations requires that the Natal and Msikaba successions be placed in the context of a geochronological reconstruction of the geology of Gondwana at time of their deposition (Fig. 9). The first aspect that becomes clear from such a reconstruction is that the present-day known distribution of the two units represents a minute area in relation to even just part of Western and Eastern Gondwana (Fig. 9). Based on dominantly SW-directed palaeocurrents in both successions, it is logical to consider possible source terrains situated to the northeast of the present outcrop area. From such a reconstruction it is evident that the minor populations of Archean and Palaeoproterozoic zircons present in the Melmoth and Kranskloof members of the Natal Group could have been sourced from immediately adjacent rocks of the Kaapvaal (southern Africa) and Grunehogna (East Antarctica) Cratons.

Zircons with Stenian ages (1000–1200 Ma), that is, the dominant age range of known arc magmatism in the Natal Sector of the NNMC (Table 2; Fig. 10), are present in all sampled units. The probability density diagram for the Melmoth Member (Fig. 6a) clearly shows a zircon population in this age group. However, this unit was sampled in a location on the Kaapvaal Craton that renders the NNMC rather unlikely as a source, except if it extended further onto the craton in the hanging wall of the Tugela thrust at the time. Although not obvious at first glance, detrital zircons of this age range also make up a considerable portion of the detrital zircon population of the more basal Kranskloof Member (36 % of the population; Fig. 7d). These could at least have been partly sourced directly from the NNMC basement rocks. In addition, the Late Mesoproterozoic Cape Meredith Complex of West Falkland (Jacobs *et al.* 1999*b*) should be considered as a possible

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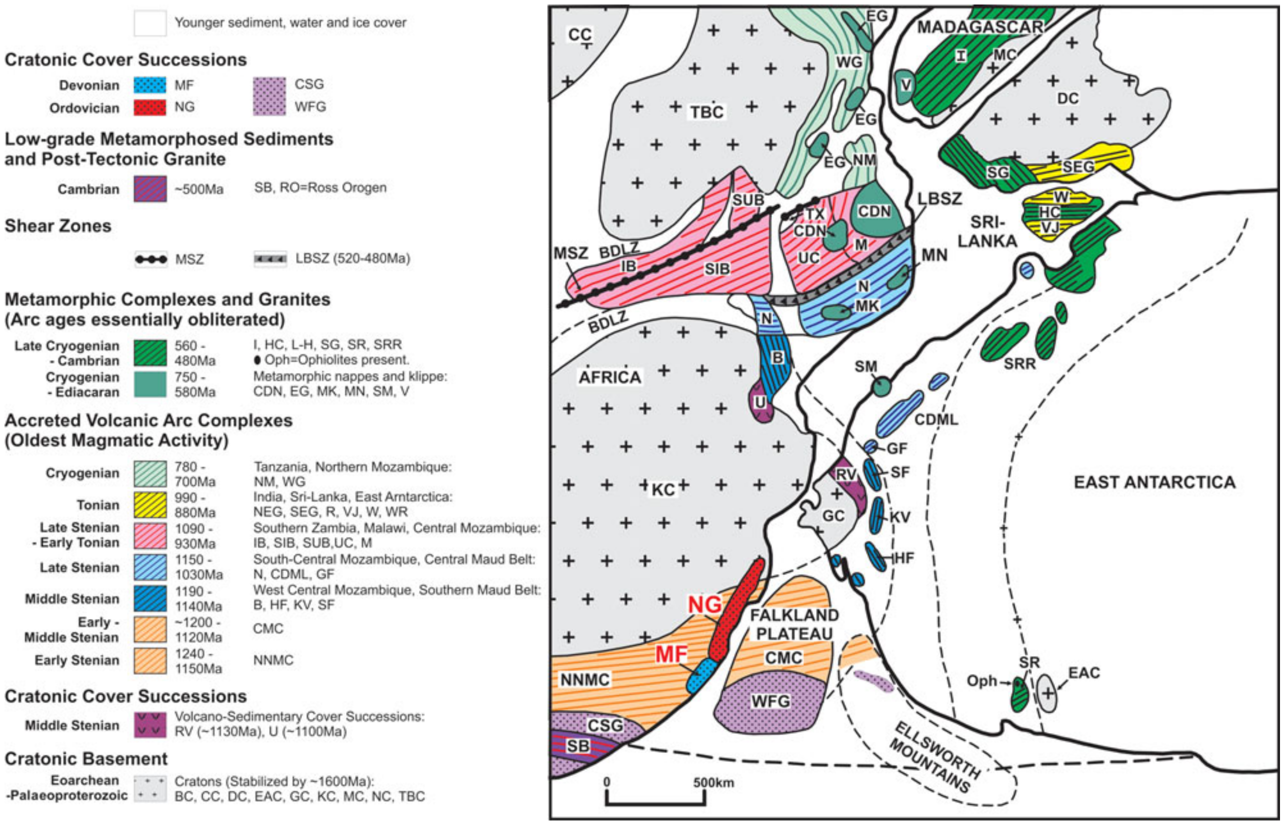

Figure 9. (Colour online) Geochronological reconstruction of the geology of east Gondwana at the time of the deposition of the Natal Group and Msikaba Formation (geochronological information from Eby *et al*. 1998; Burke *et al*. 2003; Meert, 2003; Bisnath *et al*. 2006; Bingen *et al*. 2009; Sajeev, Williams & Osanai, 2010; Grantham *et al*. 2011; Elliot, 2013). Abbreviations: B – Báruè Complex; BC – Bastar Craton; BDLZ – Basal Damaran Lufilian Zambezi succession; CC – Congo Craton; CDML – Central Dronning Maud Land; CDN – Cabo Dellgado Nappes; CMC – Cape Meredith Complex; CSG – Cape Supergroup; DC – Dharwar Craton; EAC – East Antarctica Craton; EG – Eastern Granulites; GC – Grunehogna Craton; GF – Gjelsvikfjella; HC – Highland Complex; HF – Heimefrontfjella; I – Itremo (Madagascar); IB – Irumide Belt; K – Kemp Land; KC – Kalahari Craton; KV – Kirwanveggen; LBSZ – Lurio Shear Zone; L-H – Lützow Holm Complex; M – Marrupa Complex; MC – Madagascar Craton; MF – Msikaba Formation; MK – Mugeba Klippe; MN – Monapo Klippe; MSZ – Mwembeschi Shear Zone; N – Nampula Complex; NC – Napier Complex; NEG – North Eastern Ghats; NG – Natal Group; NM – North Marrupa Complex; NNMC – Namaqua–Natal Metamorphic Complex; Oph – Ophiolites; R – Rayner Complex; RO – Ross Orogen; RV – Ritscherflya Supergroup; SB – Saldania Belt; SEG – South Eastern Ghats; SF – Sverdrupfjella; SG – Southern Ghats; SIB – Southern Irumide Belt; SM – Schirmacher; SR – Shackleton Range; SRR – Sør Rondane Range; SUB – Southern Usagaran Belt; TBC – Tanzania–Bangweulu Craton; TX – Txitonga Group; U – Umkondo Group; UC – Unango Complex; V – Vohitory; VJ – Vijayan Complex; W – Wanni Complex; WFG – West Falkland Group; WG – Western Granulites; WR – Western Rainier Complex.

provenance region. It has become widely accepted that the Falkland Microplate was positioned between SE South Africa and Antarctica within the Gondwana Supercontinent, therefore placing the unit close to the Natal Basin during the deposition of the Melmoth and Kranskloof Members.

An alternative source of detritus should also be considered to account for the minor Stenian age population (14 %) obtained for the Newspaper Member (upper Mariannhill Formation). By the time of deposition of the upper Mariannhill Formation, the greatest part of the NNMC basement was likely already covered by the sediments of the lower Durban Formation. Any such possible alternative source areas of Stenian-aged detritus are located much further towards the north-east. They include the *c.* 1.1 Ga felsic igneous rocks associated with the Báruè Complex (Fig. 9) in west-central Mozambique (Manttarri, 2008; Grantham *et al.* 2011) or Stenian gneisses of western and central Dronning Maud Land, Antarctica (Harris *et al*. 1995; Jacobs *et al*. 1998, 1999*a*; Bauer *et al*. 2003; Jacobs, Bauer & Fanning, 2003*b*; Board, Frimmel & Armstrong, 2005; Bisnath *et al*. 2006; Grantham *et al*. 2011).

The prominent major population of 800–1000 Ma aged zircons observed in all the members of the Natal Group poses a problem, especially for models in which the Durban Formation red beds are envisaged to have been deposited in a small, possibly half-graben, continental basin with sediment influx from local sources (Fig. 6). From the Gondwana geochronological map (Fig. 9), it is evident that with present knowledge there is no nearby source for the 800–1000 Ma zircon population. The same applies to 565 Ma peaks in the Melmoth and Newspaper Member samples (N_DF_MM and N_MHF_NM). The only area in Gondwana where geological units with these two ages were possibly

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Table 2. Late Mesoproterozoic, Neoproterozoic and early Palaeozoic ages associated with selective present-day outcrops in Mozambique, Zambia, Southern Tanzania, Malawi, India, Sri Lanka, South Africa (NNMC) and Antarctica.

Geological entity	Unit/Locality	Rock type	Method	Age (Ma)	Reference
Mozambique					
Barue Complex	Chimoio	Granite	U–Pb Zircon	1119 ± 21	Manttari, 2008
		Granodiorite	U–Pb Zircon	1079 ± 7	Manttari, 2008
		Granodiorite gneiss	U–Pb Zircon	1139 ± 7	Manhica *et al*. 2001
		Granitic gneiss (Nhansipfe)	U–Pb Zircon	1112 ± 18	Manhica *et al*. 2001
Marrupa Complex	Mecula	Granitic gneiss	U–Pb Zircon	1026 ± 9	Bingen *et al*. 2009
	Majune	Granitic gneiss	U–Pb Zircon	1025 ± 12	Bingen *et al*. 2009
	Marrupa	Granitic gneiss	U–Pb Zircon	1016 ± 10; 1011 ± 16; 1005 ± 19	Bingen *et al*. 2009
	Cuamba	Leucogneiss	U–Pb Zircon	968 ± 10	Bingen *et al*. 2009
		Granitic gneiss	U–Pb Zircon	946 ± 11	Bingen *et al*. 2009
		Mangeritic gneiss	U–Pb Zircon	753 ± 13	Bingen *et al*. 2009
	Mecula	Leucogranite	U–Pb Zircon	547 ± 14	Bingen *et al*. 2009
	Ribaue	Granitic gneiss	U–Pb Zircon	521 ± 15	Bingen *et al*. 2009
	Malema	Syenitic gneiss	U–Pb Zircon	504 ± 11	Bingen *et al*. 2009
		Granodioritic gneiss	U–Pb Zircon	486 ± 27	Bingen *et al*. 2009
Unango Complex	Majune	Quartz monzonotic gneiss	U–Pb Zircon	1062 ± 13	Bingen *et al*. 2009
	Macaloge	Leucogneiss	U–Pb Zircon	1047 ± 8	Bingen *et al*. 2009
		Granodioritic gneiss	U–Pb Zircon	1040 ± 8	Bingen *et al*. 2009
	Cuamba	Quartz mangerite gneiss	U–Pb Zircon	1039 ± 11	Bingen *et al*. 2009
	Lichinga	Banded granulite	U–Pb Zircon	1037 ± 10	Bingen *et al*. 2009
		Quartz monzonotic gneiss	U–Pb Zircon	1034 ± 14	Bingen *et al*. 2009
		Granitic gneiss	U–Pb Zircon	1013 ± 10	Bingen *et al*. 2009
	Metangula	Leucogneiss	U–Pb Zircon	1008 ± 9	Bingen *et al*. 2009
		Granitic gneiss	U–Pb Zircon	975 ± 31	Bingen *et al*. 2009
	Mandimba	Charnockite	U–Pb Zircon	949 ± 13	Bingen *et al*. 2009
	Milange	Banded granulite	U–Pb Zircon	827 ± 20	Bingen *et al*. 2009
	Macaloge	Syenitic gneis	U–Pb Zircon	799 ± 8	Bingen *et al*. 2009
	Gurue	Leucogneiss	U–Pb Zircon	519 ± 6	Bingen *et al*. 2009
		Quartz mangerite	U–Pb Zircon	512 ± 4	Jacobs *et al*. 2008
	Cuamba	Granite	U–Pb Zircon	517 ± 12	Bingen *et al*. 2009
		Quartz mangerite	U–Pb Zircon	512 ± 36	Bingen *et al*. 2009
	Lichinga	Granite	U–Pb Zircon	501 ± 29	Bingen *et al*. 2009
	Milange	Augen gneiss	U–Pb Zircon	493 ± 35	Bingen *et al*. 2009
Nampula Complex		Migmatitic tonalitic gneiss	U–Pb Zircon	1128 ± 9	Macey *et al*. 2010
	Milange	Leucogneiss	U–Pb Zircon	1123 ± 9	Bingen *et al*. 2009
		Quartz-feldspar gneiss	U–Pb Zircon	1092 ± 13; 1090 ± 22	Macey *et al*. 2010
	Milange	Quartz diorite gneiss	U–Pb Zircon	1087 ± 16	Bingen *et al*. 2009
		Augen gneiss	U–Pb Zircon	1077 ± 26; 1073 ± 16	Macey *et al*. 2010
	Mocube	Granitic gneiss	U–Pb Zircon	1072 ± 8	Bingen *et al*. 2009
	Ribaue	Granitic gneiss	U–Pb Zircon	1060 ± 17	Bingen *et al*. 2009
	Montepuez	Augen gneiss	U–Pb Zircon	1057 ± 9	Bingen *et al*. 2009
	Mocuba	Granitic gneiss	Pb–Pb Zircon	1048 ± 1	Kröner *et al*. 1997
	Mecufi	Granitic-syenitic gneiss	U–Pb Zircon	1042 ± 9	Bingen *et al*. 2009
		Granitic gneiss	U–Pb Zircon	511 ± 12	Bingen *et al*. 2009
Nampula Complex	Montepuez	Phenocryst granite	U–Pb Zircon	511 ± 12	Bingen *et al*. 2009
	Ribaue	Phenocryst granite	U–Pb Zircon	508 ± 2	Jacobs *et al*. 2008
	Gurue	Phenocryst granite	U–Pb Zircon	508 ± 4	Jacobs *et al*. 2008
		Granitic gneiss	U–Pb Zircon	507 ± 3	Jacobs *et al*. 2008
Ocua Complex	Ribaue	Mylonitic leucogneiss	U–Pb Zircon	538 ± 10	Bingen *et al*. 2009
	Mecufi	Boudin-neck pegmatite	U–Pb Zircon	532 ± 13	Viola *et al*. 2008
North Nyasa Alkaline Province	Meponda	Nepheline syenite	U–Pb Zircon	538 ± 6/12	Lulin *et al*. 1985
Zambia					
Irumide Belt	Lukamfwa Hill granite gneiss	Granite gneiss	U–Pb Zircon	1664 ± 9, 1653 ± 7 and 1639 ± 14	DeWaele *et al*. 2003
	Mutangoshi gneissic granite	Gneissic granite	U–Pb Zircon	1592 ± 43	DeWaele *et al*. 2003

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Table 2. Continued.

Geological entity	Unit/Locality	Rock type	Method	Age (Ma)	Reference
			U–Pb Zircon	1046 ± 77; 1028 ± 8 and 953 ± 19	DeWaele *et al.* 2003
	~	Porphyritic granite	U–Pb Zircon	1034 ± 5; 1033 ± 16 and 1024 ± 9 1021 ± 6; 1022 ± 8 and 1005 ± 21	DeWaele *et al.* 2003
North Nyasa Alkaline Province	Nkombwa	Carbonatite	K–Ar phlogopite	679 ± 25	Snelling, 1962
	Mivula	Sodalite syenite	K–Ar biotite	550 ± 20	Snelling, Johnson & Drysdall, 1972
Southern Tanzania					
Mozambique Belt	Wami River	Charnockite gneiss	U–Pb Zircon	841 ± 14	Muhongo, Kröner & Nemchin, 2001
	Morogoro, Uluguru mountains	Intermediate granulite	U–Pb Zircon	725 ± 14	Muhongo, Kröner & Nemchin, 2001
	Amani, Eastern Usambara mountains	Intermediate granulite	U–Pb Zircon	753.6 ± 0.9	Muhongo, Kröner & Nemchin, 2001
		Charnockite	U–Pb Zircon	656.4 ± 0.9	Muhongo, Kröner & Nemchin, 2001
	Masasi	Migmatic granite gneiss	U–Pb Zircon	1094 ± 13	Kröner, unpub. data, 2001
		Leucocratic granite	U–Pb Zircon	1009 ± 13	Kröner, unpub. data, 2001
		Granite gneiss	U–Pb Zircon	955.6 ± 0.7	Kröner, unpub. data, 2001
		Migmatic granite gneiss	U–Pb Zircon	792.7 ± 5.6	Kröner, unpub. data, 2001
		Granite gneiss	U–Pb Zircon	767.1 ± 0.8	Kröner, unpub. data, 2001
		Porphyritic granite gneiss	U–Pb Zircon	739.4 ± 0.9	Kröner, unpub. data, 2001
		Granite gneiss	U–Pb Zircon	702 ± 0.9	Kröner, unpub. data, 2001
		Pink granite	U–Pb Zircon	687.9 ± 0.9	Kröner, unpub. data, 2001
		Granodiorite gneiss	U–Pb Zircon	676.1 ± 0.9	Kröner, unpub. data, 2001
		Tonalitic gneiss	U–Pb Zircon	665.3 ± 0.9	Kröner, unpub. data, 2001
		Pink granite gneiss	U–Pb Zircon	658.4 ± 0.9	Kröner, unpub. data, 2001
		Porphyritic granite gneiss	U–Pb Zircon	631.5 ± 0.9	Kröner, unpub. data, 2001
Malawi					
	Near Kwewza	Biotite gneiss	U–Pb Zircon	1040.6 ± 0.7	Kröner *et al.* 2001
	Near Blantyre	Charnoenderbitic gneiss	U–Pb Zircon	1012.5 ± 0.8	Kröner *et al.* 2001
	Near Mwanza	Migmatic biotite gneiss	U–Pb Zircon	998.9 ± 0.8	Kröner *et al.* 2001
Mozambique Belt	Near Dezda	Charnockite gneiss	U–Pb Zircon	928.9 ± 0.8	Kröner *et al.* 2001
	Near Lilongwe	Mafic granulite	U–Pb Zircon	644.9 ± 0.9	Kröner *et al.* 2001
		Leucocratic granite	U–Pb Zircon	602.7 ± 1	Kröner *et al.* 2001
		Biotite gneiss	U–Pb Zircon	590.5 ± 1	Kröner *et al.* 2001
		Biotite gneiss	U–Pb Zircon	582.9 ± 1	Kröner *et al.* 2001
		Leucocratic granite	U–Pb Zircon	577.5 ± 1	Kröner *et al.* 2001
	Near Ntcheu	Migmatic paragneiss	U–Pb Zircon	576.7 ± 1	Kröner *et al.* 2001
	Near Thyolo	Biotite hornblende gneiss	U–Pb Zircon	576.7 ± 1	Kröner *et al.* 2001
	Near Zomba	Granitic gneiss	U–Pb Zircon	667.5 ± 0.9	Kröner *et al.* 2001
	Near Blantyre	Enderbitic gneiss	U–Pb Zircon	554.7 ± 1	Kröner *et al.* 2001
North Nyasa Alkaline Province	Ilomba	Nepheline syenite	Rb–Sr WR isochron	685 ± 62	Ray, 1974
			K–Ar biotite	508 ± 12 ; 490 ± 12	Bloomfield, Deans & Wells, 1981

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Table 2. Continued.

Geological entity	Unit/Locality	Rock type	Method	Age (Ma)	Reference
	Chikangawa	Nepheline syenite	Rb–Sr WR isochron	650 ± 40	Bloomfield, Deans & Wells, 1981
			K–Ar biotite	410 ± 16	Snelling, 1965
India					
Eastern Ghats	Salur-Pachipenta-Sunki	Migmatic gneiss	U–Pb Zircon	1005 ± 22 to 874 ± 20∗	Korhonen *et al.* 2013
			U–Pb Monazite	980 ± 15 to 921 ± 15∗	Korhonen *et al.* 2013
				633 ± 16 and 533 ± 12∗	Korhonen *et al.* 2013
		Enderbite	U–Pb Zircon	954 ± 14 ∗	Korhonen *et al.* 2013
		Migmatic gneiss	U–Pb Monazite	966 ± 6∗	Korhonen *et al.* 2013
			U–Pb Zircon	950 ± 17∗	Korhonen *et al.* 2013
	Anantagiri-Sunkarametta	Sapphirine-bearing granulite	U–Pb Zircon	970 ± 28∗	Korhonen *et al.* 2013
		Granulite	U–Pb Monazite	953 ± 7∗	Korhonen *et al.* 2013
				948 ± 5∗	Korhonen *et al.* 2013
	Paderu-Gangaraja-Madugula	Migmatic gneiss	U–Pb Zircon	929 ± 17∗	Korhonen *et al.* 2013
			U–Pb Monazite	968 ± 20 and 822 ± 31∗	Korhonen *et al.* 2013
Sri Lanka					
Vijayan Complex	Near Hulanuge	Tonalitic gneiss	U–Pb Zircon	1084.4 ± 1.4	Kröner *et al.* 2013
	Near Kandahind-agama	Granodiorite gneiss	U–Pb Zircon	1083.4 ± 1.4	Kröner *et al.* 2013
	Ussangoda beach	Dioritic gneiss	U–Pb Zircon	1049 ± 2	Kröner *et al.* 2013
	Welikanda	Granodiorite gneiss	U–Pb Zircon	1012.9 ± 0.7	Kröner *et al.* 2013
	Arugam Bay	Granodiorite gneiss	U–Pb Zircon	1000 ± 1.2	Kröner *et al.* 2013
	Near Lahugala	Charnockite gneiss	U–Pb Zircon	999 ± 3	Kröner *et al.* 2013
	Potuvil	Charnockite gneiss	U–Pb Zircon	923.2 ± 0.8 and 891.3 ± 0.8	Kröner *et al.* 2013
	Vijepura	Pegmatitic gneiss	U–Pb Zircon	821 ± 10	Kröner *et al.* 2013
	Nimalawa	Monzonitic gneiss	U–Pb Zircon	766 ± 8	Kröner *et al.* 2013
	Nimalawa	Porphyritic granite-gneiss	U–Pb Zircon	766 ± 8	Kröner *et al.* 2013
	Near Tangalla	Migmatitic granitic gneiss	U–Pb Zircon	746 ± 3	Kröner *et al.* 2013
	Near Suriyawewa	Gabbroic dyke	U–Pb Zircon	590 ± 2	Kröner *et al.* 2013
Wanni Complex	Near Victoria	Tonalitic gneiss	Pb–Pb Zircon	1005.8 ± 1.1	Kröner, Kehelpannala & Hegner, 2003
	Near Hirassagala	Tonalitic gneiss	Pb–Pb Zircon	983.8 ± 1.1	Kröner, Kehelpannala & Hegner, 2003
		Leucotonalite vein	Pb–Pb Zircon	918.0 ± 0.8	Kröner, Kehelpannala & Hegner, 2003
	Getambe Synform	Tonalitic gneiss	Pb–Pb Zircon	969.3 ± 0.8	Kröner, Kehelpannala & Hegner, 2003
		Leucocratic metagranite	Pb–Pb Zircon	923.6 ± 0.8	Kröner, Kehelpannala & Hegner, 2003
	Balagolla	Tonalitic gneiss	Pb–Pb Zircon	937.8 ± 0.8	Kröner, Kehelpannala & Hegner, 2003
	Gadaladeniya Synform	Granodiorite gneiss	Pb–Pb Zircon	916.9 ± 0.8	Kröner, Kehelpannala & Hegner, 2003
		Tonalitic gneiss	Pb–Pb Zircon	902.8 ± 0.8 and 881.5 ± 0.8	Kröner, Kehelpannala & Hegner, 2003
	Dumbara Synform	Tonalitic gneiss	Pb–Pb Zircon	916.9 ± 0.8	Kröner, Kehelpannala & Hegner, 2003
	Near Kadugannawa	Tonalitic gneiss	Pb–Pb Zircon	914.2 ± 0.8	Kröner, Kehelpannala & Hegner, 2003

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Table 2. Continued.

Geological entity	Unit/Locality	Rock type	Method	Age (Ma)	Reference
Wanni Complex	Walala	Tonalitic gneiss	Pb–Pb Zircon	906.1 ± 1.3	Kröner, Kehelpannala & Hegner, 2003
	Near Perdeniya	Dioritic gneiss	Pb–Pb Zircon	893.8 ± 1.0	Kröner, Kehelpannala & Hegner, 2003
	Near Kurogoda	Enderbitic gneiss	Pb–Pb Zircon	893.5 ± 0.9	Kröner, Kehelpannala & Hegner, 2003
	~	Siliminite bearing gneiss	U–Pb Zircon	793 ± 4	Hölzl *et al*. 1994
	Kurunegala	Charnockite	U–Pb Zircon	771 +17/-14	Baur *et al*. 1991
South Africa (NNMC)					
Tugela Terrane	Kotongweni intrusion	Tonalite gneiss	U–Pb Zircon	1209 ± 5	Johnston *et al*. 2001
			U–Pb Zircon	1208 ± 5	McCourt *et al*. 2006, unpub. data
	Dondwana gneiss		Pb–Pb Zircon	1175 ± 9	McCourt *et al*. 2006, unpub. data
	Mkondene intrusion	Biotite diorite	U–Pb Zircon	1161 ± 9	Johnston *et al*. 2001
	Mtungweni granitoids		U–Pb Zircon	1155 ± 6	McCourt *et al*. 2006, unpub. data
	Wosi granitoid suite	Leucocratic quartz monzite	U–Pb Zircon	1145 ± 1	Johnston *et al*. 2001
Mzumbe Terrane	Quha Formation, Mapumulo Group	Metagreywacke	U–Pb Zircon	1235 ± 9	Thomas, Cornell & Armstrong, 1999
		Biotite gneiss	U–Pb Zircon	1163 ± 12	Cornell *et al*. 1996
	Mzumbe Suite	Tonalitic orthogneiss	U–Pb Zircon	1207 ± 10	Thomas & Eglington, 1990
	Mzimlilo Granite	Granitic orthogneiss	U–Pb Zircon	1147 ± 8	Eglington, Thomas & Armstrong, 2010
	Mahlongwa Granite	Granitic gneiss	Rb–Sr	1083 ± 14	Eglington, Harmer & Kerr, 1989*a*
	Equeefa Suite	Melanorite	U–Pb Zircon	1083 ± 6	Eglington, Thomas & Armstrong, 2010
Margate Terrane	Sikombe Granite	Granite	U–Pb Zircon	1181 ± 15	Thomas, Armstrong & Eglington, 2003
	Mbizana Microgranite		U–Pb Zircon	1026 ± 3	Thomas, Eglington & Bowring, 1993
			Rb–Sr	960 ± 32	Grantham & Eglington, 1992
	Glenmore Granite		U–Pb Zircon	1091 ± 9	Mendonidis *et al*. 2002
			Rb–Sr	946 ± 31	Eglington, Harmer & Kerr, 1986
	Portobello Granite, Margate Suite	Charnockite	U–Pb Zircon	1093 ± 7	Mendonidis & Armstrong, 2009
	Munster Suite	Mafic Granulites	U–Pb Zircon	1093 ± 5	Mendonidis, Armstrong & Grantham, 2009
		Quartz monzonorites	U–Pb Zircon	1091 ± 7	Mendonidis, Armstrong & Grantham, 2009
	Banana Beach Tonalite, Margate Suite	Tonalite	U–Pb Zircon	1065 ± 10	Cornell & Thomas, 2006
Oribi Gorge Suite	Oribi Gorge Pluton		U–Pb Zircon	1092 ± 2	Thomas *et al*. 1993
			U–Pb Zircon	1070 ± 4	Eglington *et al*. 2003
	Port Edward Pluton	Enderbite	U–Pb Zircon	1025 ± 8	Eglington *et al*. 2003
			Rb–Sr	987 ± 19	Eglington, Harmer & Kerr, 1986
	Fafa Pluton	Granite	U–Pb Zircon	1032 ± 7	Eglington *et al*. 2003
			U–Pb Zircon	1029 ± 1 0	Thomas *et al*. 1993
			Rb–Sr	915 ± 19	Thomas *et al*. 1993
	Mvenyane granite pluton		Rb–Sr	992 ± 39	Thomas, 1988
	Mgeni pluton	Granite	U–Pb Zircon	1030 ± 20	Eglington, Harmer & Kerr, 1989*b*
			Rb–Sr	1001 ± 35	Eglington, Harmer & Kerr, 1989*b*

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Table 2. Continued.

Geological entity	Unit/Locality	Rock type	Method	Age (Ma)	Reference
Antarctica					
Maud Belt	Central Dronning Maud Land	Granite Gneiss	U–Pb Zircon	1130 ± 12	Jacobs *et al.* 1998
		Orthogneiss	U–Pb Zircon	1086 ± 20 and 1087 ± 28	Jacobs *et al.* 1998
		Charnockite	U–Pb Zircon	608 ± 9	Jacobs *et al.* 1998
		Anorthosite	U–Pb Zircon	600 ± 12	Jacobs *et al.* 1998
		Leucogranite	U–Pb Zircon	527 ± 6	Jacobs *et al.* 1998
		Syenite	U–Pb Zircon	512 ± 2	Mikhalsky *et al.* 1995
	Gjelsvikfjella	Migmatic gneiss	U–Pb Zircon	1115 ± 12	Jacobs, Bauer & Fanning, 2003*b*
				1130 ± 9 and 1133 ± 16	Bisnath *et al.* 2006
		Migmatic augen gneiss	U–Pb Zircon	1137 ± 14; 1123 ± 21 and 1096 ± 8	Jacobs, Bauer & Fanning, 2003*b*
				1104 ± 8.3 and 1124 ± 11	Bisnath *et al.* 2006
		Migmatite	U–Pb Zircon	1163 ± 6	Paulsson & Austrheim, 2003
		Banded gneiss	U–Pb Zircon	1091 ± 16	Bisnath *et al.* 2006
		Lamprophyre dyke	Pb–Pb Zircon	508 ± 7	Jacobs, Bauer & Fanning, 2003*a*
		Syenite	U–Pb Zircon	500 ± 8	Paulsson & Austrheim, 2003
		Aplitic dykes	Pb–Pb Zircon	495 ± 14	Paulsson & Austrheim, 2003
			U–Pb Zircon	498 ± 5	Bisnath *et al.* 2006
		Granite sheet	Pb–Pb Zircon	486 ± 3.8	Jacobs, Bauer & Fanning, 2003*a*
		Stabben Gabbro	U–Pb Zircon	487.3 ± 4.4	Bisnath *et al.* 2006
	Muhlig-Hofmanfjella	Migmatic gneiss	U–Pb Zircon	1142 ± 12	Jacobs, Bauer & Fanning, 2003*b*
		Leucosome	Pb–Pb Zircon	558.4 ± 5.6 and 557 ± 13	Jacobs, Bauer & Fanning, 2003*a*
		Charnockitic gneiss	Pb–Pb Zircon	521 ± 3.4	Jacobs, Bauer & Fanning, 2003*a*
	Sverdrupfjella	Granodiorite gneiss	U–Pb Zircon	1134 ± 4	Grantham *et al.* 2011
		Granitic gneiss	U–Pb Zircon	1132 ± 16	Board, Frimmel & Armstrong, 2005
		Gneissic granite	U–Pb Zircon	1072 ± 10	Board, Frimmel & Armstrong, 2005
	Kirwanveggen	Granite gneiss	U–Pb Zircon	1131 ± 25	Harris *et al.* 1995
		Augen gneiss	U–Pb Zircon	1127 ± 12	Harris *et al.* 1995
		Migmatite augen gneiss	U–Pb Zircon	1103 ± 13	Harris *et al.* 1995
		Granite	U–Pb Zircon	475 ± 10	Harris *et al.* 1995
	Heimefrontfjella	Felsic metavolcanic	U–Pb Zircon	1161.2 ± 9.5 and 1129 ± 31	Bauer *et al.* 2003
		Tonalitic gneiss	U–Pb Zircon	1130 ± 17	Jacobs *et al.* 1999*b*
		Metagranitiods	U–Pb Zircon	1088 ± 10	Arndt *et al.* 1991
		Pegmatite	U–Pb Zircon	1060 ± 8	Arndt *et al.* 1991
	Midbresrabben	Granodiorite	U–Pb Zircon	1142 ± 4	Grantham *et al.* 2011
Rayner Complex	North Prince Charles Mountains	Granodiorite	U–Pb Zircon	1293 ± 28	Kinny, Black & Sheraton, 1997
		Biotite granite	U–Pb Zircon	1020 ± 48	Kinny, Black & Sheraton, 1997
		Leucogneiss	U–Pb Zircon	990 ± 30 and 994 ± 39	Kinny, Black & Sheraton, 1997
		Granite	U–Pb Zircon	990 ± 18	Boger *et al.* 2000
		Syenite	U–Pb Zircon	984 ± 12	Kinny, Black & Sheraton, 1997
		Granite	U–Pb Zircon	984 ± 7 and 976 ± 24	Kinny, Black & Sheraton, 1997
		Granite	U–Pb Zircon	936 ± 14	Boger *et al.* 2000
		Leucosome	U–Pb Zircon	900 ± 28	Boger *et al.* 2000

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Table 2. Continued.

Geological entity	Unit/Locality	Rock type	Method	Age (Ma)	Reference
Rayner Complex	Mawson coast	Biotite-orthopyroxene orthogneiss	U–Pb Zircon	992 ± 10	Dunkley, Clarke & White, 2002
		Felsic dyke	U–Pb Zircon	937 ± 19	Dunkley, Clarke & White, 2002
	Fold Island, Kemp Land	Pegmatite	U–Pb Zircon	940 ± 80	Grew, Manton & James, 1988
	Oygarden Islands, Kemp Land	Pegmatite	U–Pb Zircon	931 ± 14	Kelly, Clarke & Fanning, 2002
		Felsic othogneiss	U–Pb Zircon	929 ± 12 and 924 ± 17	Kelly, Clarke & Fanning, 2002
Trans Antarctic Mountains	Deep Freeze Range, North Victoria Land	Phorphyritic biotite monzogranite	U–Pb Zircon	506 ± 7; 499 ± 2.4 and 493 ± 3.8	Bomparola *et al.* 2007
		Biotite monzogranite	U–Pb Zircon	481 ± 2.3	Bomparola *et al.* 2007
		Micro-monzodiorite	U–Pb Zircon	489 ± 3.8	Bomparola *et al.* 2007
	Wilson Terrane, North Victoria Land	Gabbro-diorite	U–Pb Zircon	489 ± 4	Bomparola *et al.* 2007
	Mulock Glaciers, South Victoria Land	Granite	U–Pb Zircon	546 ± 3	Cottle & Cooper, 2006
	Dry Valleys region, South Victoria Land	Granite	U–Pb Zircon	551 ± 4	Encarnacion & Grunow, 1996
		Quartz syenite	U–Pb Zircon	551 ± 4	Rowell *et al.* 1993
		Quartz monzodiorite	U–Pb Zircon	531 ± 10, 505 ± 9 and 502 ± 9	Allibone & Wysoczanski, 2002
		Granite orthogneiss	U–Pb Zircon	516 ± 10	Allibone & Wysoczanski, 2002
		Quartz Monzodiorite	U–Pb Zircon	505 ± 2	Encarnacion & Grunow, 1996
		Granodiorite	U–Pb Zircon	502 ± 2	Cox *et al.* 2000
		Granodiorite	U–Pb Zircon	499 ± 6	Allibone & Wysoczanski, 2002
	Miller Range	Tonalite	U–Pb Zircon	542 ± 1	Goodge *et al.* 1993
		Granite	U–Pb Zircon	539 ± 1	Goodge *et al.* 1993
			U–Pb Zircon	533 ± 3	Goodge *et al.* 1993
	Scott Glacier area	Granite	U–Pb Zircon	521 ± 2	Encarnacion & Grunow, 1996
		Granodiorite	U–Pb Zircon	521 ± 9 and 527 ± 6	Encarnacion & Grunow, 1996
Antarctic Peninsula	Palmer Land	Orthogeneiss	Rb–Sr	440 ± 57 and 399 ± 57	Harrison & Piercy, 1992
		Gneiss	U–Pb Zircon	438 ± 5	Millar, Pankhurst & Fanning, 2002
		Orthogeneiss	U–Pb Zircon	422 ± 18	Millar *et al.* 2002
	Graham Land	Orthogeneiss	Rb–Sr	426 ± 12 and 410 ± 15	Milne & Millar, 1989
	Horseshoe Island	Granite cobbles	U–Pb Zircon	431 ± 12	Tangeman, Mukasa & Grunow, 1996

*Age of crystallization

present at that time and combined are the late Stenian (<1090 Ma) – Tonian (990–880 Ma) ancient volcanic arc complexes, overprinted by Pan-African (*c.* 550 Ma) metamorphism in the Irumide Belt and Unango and Maruppa Complexes of central Mozambique, Malawi and Southern Zambia (Kröner, 2001; Kröner *et al.* 2001; De Waele *et al.* 2003; Meert, 2003; Bingen *et al.* 2009), combined perhaps with Rayner, eastern Ghats and Vijayan–Wanni complexes in Antarctica, India and Sri Lanka, respectively (Figs 9, 10; Table 2) (Baur *et al.* 1991; Hölzl *et al.* 1994; Kelly, Clarke & Fanning, 2002; Kröner, Kehelpannala & Hegner, 2003; Korhonen *et al.* 2013; Kröner *et al.* 2013).

The Maud Belt of East Antarctica together with the contiguous Nampula and Báruè complexes of west-central Mozambique are largely ruled out as major source terrains for this 800–1000 Ma zircon population, because of the dominance of Stenian (1150–1050 Ma) combined with Pan-African (*c.* 550 Ma) old rocks in some of these units (Figs 9, 10). They could have contributed sediment but to a lesser degree than the younger volcanic arc terrains and metamorphic

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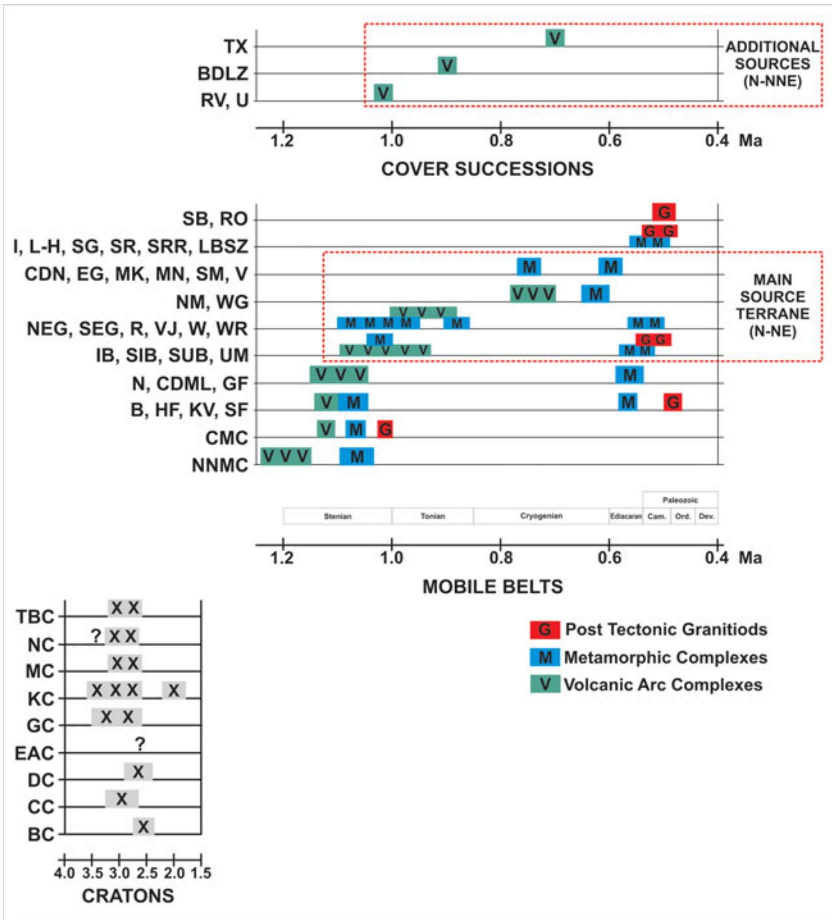

Figure 10. (Colour online) Ages associated with cratonic basements, volcanic arc and metamorphic complexes and post-tectonic granitoids of selected regions within east Gondwana. Abbreviations for units as in Figure 9. (Geochronological information from Eby *et al*. 1998; Burke *et al*. 2003; Meert, 2003; Bisnath *et al*. 2006; Bingen *et al*. 2009; Sajeev, Williams & Osanai, 2010; Grantham *et al*. 2011; Elliot, 2013).

complexes further to the north. It is also interesting to note that some of these metamorphic complexes, especially Unango and Nampula complexes and Gjelsvikfjella (Maud Belt), are commonly intruded by post-orogenic Cambrian – Early Ordovician granitoids (Eby *et al.* 1998; Burke, Ashwal & Webb, 2003; Jacobs, Bauer & Fanning, 2003*a*; Paulsson & Austrheim, 2003; Bisnath *et al*. 2006; Bingen *et al.* 2009; Fig. 10; Table 2). The latter could have sourced the minor population of Ordovician-aged zircons contained in the Melmoth Member of the Natal Group.

Proposing these source terrains means that some sediment would have been transported over distances of 1500–2000 km, which implies the presence of large fluvial systems at the time especially across central Mozambique, Malawi and southern Zambia. This would be in accordance with the well-rounded nature of most of the zircons. Marshall (2003*a*, 2006) also proposed that the detritus of the Kranskloof and Dassenhoek Members of the Durban Formation had been sourced from unconsolidated sediments of the Eshowe Member during a period of sediment shortage as a result of lowering or depletion of the primary source area. This proposed reworking of sediments could account for the rounded and fragmented appearance of the detrital zircon grains in the sample from the Kranskloof Member (N_DF_KM) analysed during this study. The proposed derivation of sediments from both distal and proximal source areas is also in agreement with suggestions made by Hicks (2010).

In the two samples from the Msikaba Formation (samples MF_MRG and MF_PE), the detrital zircon population ranging in age between 800 and 1200 Ma (particularly for MF_MRG) is less significant than in the Natal Group samples, while the abundance peak at *c.* 640 Ma is more prominent, and a conspicuous Cambrian peak exists in MF_MRG. Archean grains are absent. The SW-directed palaeocurrents reported for cross-bedding within the Msikaba Formation (Marshall, 2006) imply that the same regions that acted as source areas for the sediments of the Natal Group could also have provided detritus to the Msikaba Formation (Figs 9, 10; Table 2). The greater importance of the zircon population of Pan-African age in the Msikaba Formation than in the Natal Group could reflect progressive unroofing of these relatively young plutons from Ordovician to Devonian–Carboniferous times. Further, the Cambrian zircon populations in both samples (prominent in MF_MRG) could also have been sourced from either the Mozambique Belt or the Maud

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Belt, where plutons of this age exist (Eby *et al*. 1998; Burke, Ashwal & Webb, 2003; Jacobs, Bauer & Fanning, 2003*a*; Paulsson & Austrheim, 2003; Bisnath *et al*. 2006; Bingen *et al*. 2009; Table 2). These proposed Mesoproterozoic–Cambrian source regions are also in accordance with the finding that the great majority of the detrital zircon grains in the Msikaba Formation are of magmatic origin, based on their Th/U ratios.

The single zircon grain dated to be of Palaeoproterozoic age within sample MF_PE, given the age of 1601 ± 58 Ma, most likely originated from Kemp Land in East Antarctica. Magmatic and metamorphic activity was interpreted to have occurred during *c*. 1650–1600 Ma in the Oygarden Group in Kemp Land, although no distinct evidence was found for *c*. 1600 Ma plutonic rocks in the area (Kelly, Clarke & Fanning, 2002).

The origin of the minor populations of Ordovician- and Silurian-aged detrital zircon grains present in the Msikaba Formation are even more difficult to account for. Because the quartz arenites of the Msikaba Formation were deposited in a shallow-platform marine setting, longshore currents could have been important in the dispersal of sediments. It is therefore possible that the Cambro-Ordovian and Silurian zircons present in this formation could have been sourced from granitoid plutons of this age range within an active continental margin that started to develop in the eastern part of the southern trailing margin of Gondwana. At present this is located in the middle to eastern reaches of the Trans-Antarctic Mountain Range, incorporating the *c*. 500 Ma Ross Orogeny (Table 2; Bomparola *et al*. 2007; Giacomini *et al*. 2007; Federico, Capponi & Crispini, 2009; Elliot, 2013).

Detrital zircons of Silurian age could possibly also have been derived from the late Silurian – early Carboniferous granitoids of the Deseado Massif (DM), which form part of present-day southern Patagonia (Pankhurst *et al*. 2003, 2006). This southern part of Patagonia, where the rocks of the DM are contained, is considered to have belonged to an allochthonous terrane with a different geological history from the rest of the South American continent (Pankhurst *et al.* 2003, 2006; Ramos, 2008; Chernicoff *et al*. 2013). In most of the recent reconstructions of Gondwana, the DM continental block is placed in close proximity to the southern tip of South Africa (Pankhurst *et al*. 2006). Complex sediment dispersal patterns in shallow-marine shelf settings could have introduced sands from this massif. However, the tectonic origin and amalgamation of the parts of DM as well as its accretion onto the Gondwana Supercontinent remain controversial (Pankhurst *et al.* 2003; Chernicoff *et al*. 2013).

5.c. Nature of depositional basin

The detrital-zircon-aged populations observed in both the Natal Group and Msikaba Formation do not generally indicate local nearby source areas, as could be expected from deposition in a small continental basin. Rather, they argue in favour of both the Natal and Msikaba successions being emplaced in part of much larger basin and depositional systems. The current exposures in this case would then merely represent small erosional relicts.

In the case of the Natal Group it can be argued that the conglomeratic basal Ulundi Member in the north and the laterally equivalent lower part of the Eshowe Member were initially deposited in a rather localized NE–SW-aligned depositional trough, which derived detritus in part from the adjacent Kaapvaal and Grunehogna Cratonic basement (Fig. 11). However, these cratons quickly became covered by younger fluvial sediment derived from source areas much further north: the Irumide Belt (south Zambia); and Unango, Maruppa (central Mozambique and Malawi), Rayner (east Antarctica), eastern Ghats (India) and Vijayan–Wanni (Sri Lanka) complexes (Fig. 11). It is also highly probable that the succession built up to at least 1300–1500 m during this time as indicated by the presence of load-fragmented quartz grains and secondary authigenic clay and mica minerals (Thomas *et al*. 1992*b*; Marshall & Von Brunn, 1999). Maximum burial diagenesis most probably took place during Early Devonian time at *c*. 398 Ma as suggested by the K–Ar ages of diagenetic illite-biotite assemblages (Thomas *et al.* 1992*b*). This thick red-bed succession could have represented the northern fluvial facies of the Ordovician – Early Devonian Table Mountain to Bokkeveld Groups of the Cape Supergroup further to the south along the trailing margin of Gondwana at that time (Fig. 9).

Uplift and erosion in the northern part of the basin must have followed, resulting in the marked erosional unconformity at the base of the Msikaba Formation for which the fossil evidence defines a Devonian age (Lock, 1973; Anderson & Anderson, 1985), while the youngest (Silurian) detrital zircon grains merely reflect the age of the youngest source area. This erosion of the Natal Group could possibly have removed much of the upper Durban Formation in the north (and all of it in the far north) in an arch that extended from south of the Dweshula palaeographic high towards the present-day Cape Fold Belt in the south (Fig. 11).

It is important to note that a similar major erosional unconformity (the Kukri erosion surface) is developed at the base of the time-correlative quartz arenites of the Devonian Taylor Group in the Trans-Antarctic Mountain Range. These overlie low-grade metamorphic folded late Neoproterozoic strata of the Ross Orogeny (Elliot, 2013) that are coeval with the Saldania Orogeny along the south coast of South Africa. These Devonian successions that would also include the Witteberg Group of the Cape Supergroup are all linked by the presence of *lycopod* plant remains (Elliot, 2013). At this time the southern trailing margin of Gondwana must have been flooded by a vast shallow shelf sea on which quartz sands were dispersed and deposited. Sourcing of sediment from the Tonian to the late Palaeoproterozoic – early Cambrian metamorphic complexes of northern Mozambique and Kemp Land of

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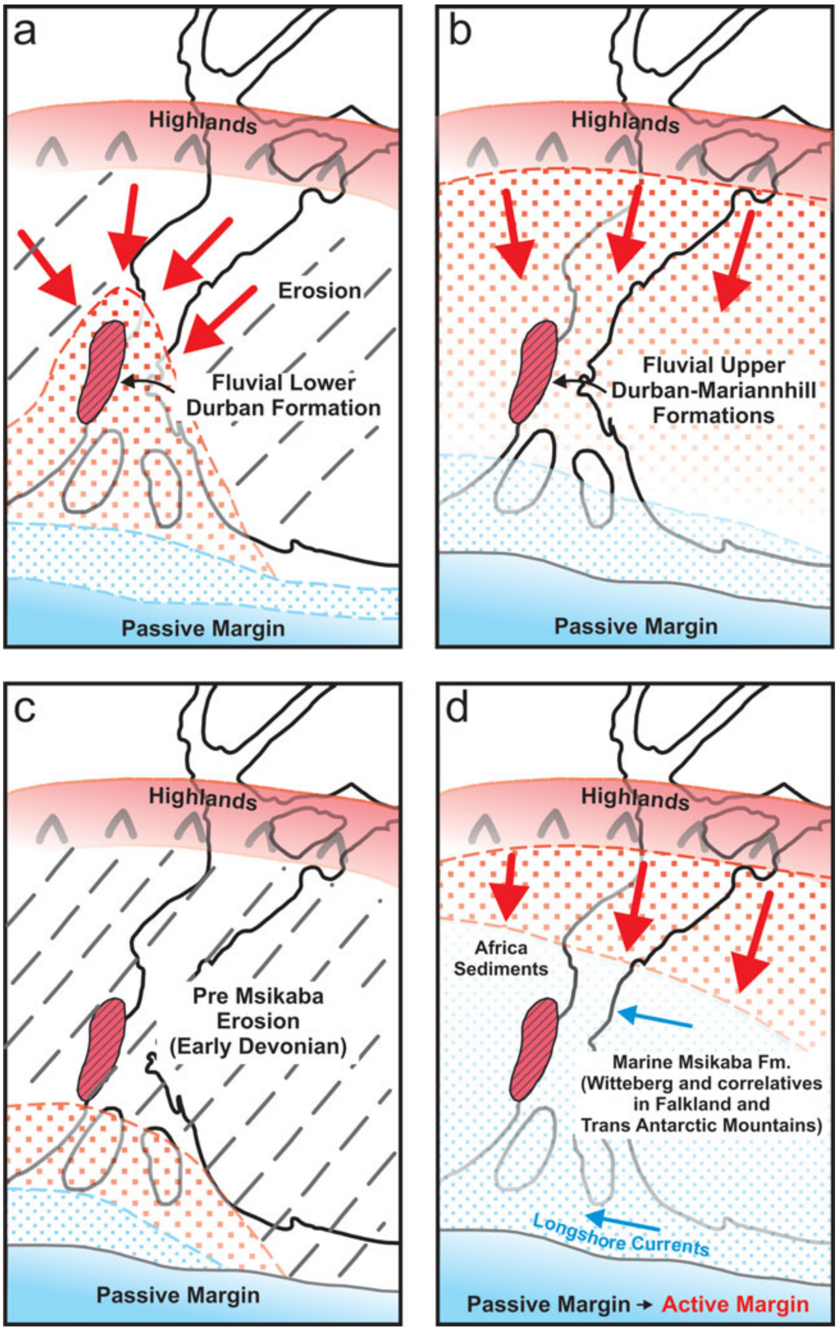

Figure 11. (Colour online) Proposed depositional model for the Natal Group and Msikaba Formation. (a) Localized deposition of the basal Durban Formation during Early Ordovician time within a fluvial depositional environment (Thomas *et al*. 1992*b*). Sediments are derived, in part, from the Kaapvaal and Grunehogna cratons and deposited in a NE–SW-aligned depositional trough. (b) Deposition of the upper Durban and Mariannhill formations during Ordovician – Early Devonian time. Cratons rapidly become covered with younger fluvial sediment derived from source areas much further north (Irumide Belt, Unango, Maruppa and Rayner complexes, Eastern Ghats and Vijayan–Wanni complexes of north-central Mozambique, East Antarctica, India and Sri Lanka) resulting in the very thick accumulation of sediment (Thomas *et al*. 1992*b*; Marshall & Von Brunn, 1999). (c) The deposition of the Msikaba Formation is preceded by major uplift and erosion of the thick Natal Group succession during Early Devonian time. (d) Deposition of the Msikaba Formation during Late Devonian – early Carboniferous time within a marine depositional environment. Sediments are derived mainly from the north as for the Natal Group succession. Longshore currents transport detritus from potential Ordovician–Silurian source regions located in the Trans-Antarctic Mountain Range (Shone & Booth, 2005; Thamm & Johnson, 2006; Kingsley & Marshall, 2009; Elliot, 2013).

eastern Antarctica (Fig. 11) is in accordance with this scenario, as is the transport of Ordovician–Silurian zircons by the action of longshore currents, as discussed in Section 5.b.

The Msikaba Formation has a maximum known preserved thickness of *c*. 900–1000 m below the overlying glacial Dwyka Group. It is most unlikely that this thick succession of marine shelf sands just pinched out over a short distance from south to north of the Dweshula palaeographic high. More likely, it extended much further north over the red beds of the Natal Group prior to being removed by erosion at the base of the continental

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glacial ice cap that resulted in the deposition of the glacial diamictites of the late Carboniferous – very early Permian Dwyka Group of the Karoo Supergroup. This conclusion is supported by K–Ar and Ar–Ar results on authigenic clay assemblages (Thomas *et al*. 1992*b*) in red beds of the Natal Group that indicate a second episode of load diagenesis at *c.* 354 Ma. In the above scenario of the depositional history of the area, this process could have resulted from a thick cover of Msikaba Formation during early Cambrian time.

6. Summary and concluding remarks

The Early Ordovician age obtained for the youngest detrital zircon in the Durban Formation constrains the maximum age of deposition of the Natal Group, with deposition probably continuing until Late Ordovician time. A middle–late Silurian maximum age for the deposition of the Msikaba Formation is given by the age of the youngest detrital zircon found in it. From the *lycopod* fossil evidence, deposition of the Msikaba Formation most likely continued into Devonian time. Possible provenance areas for the detrital zircon populations of the Natal Group and Msikaba Formation were evaluated in the context of a geochronological reconstruction of Gondwana at the time of their deposition. From the dominantly SW-directed palaeocurrents recorded for the members of the Natal Group, regions situated to the northeast of the present outcrop areas are primarily considered as the most probable source terrains. Given the prominent major population of 800–1000 Ma old zircons observed in all the members of the Natal Group, late Stenian – Tonian ancient volcanic arc complexes overprinted by Pan-African metamorphism of central Mozambique, Malawi and southern Zambia are suggested as major sources of detritus to the group. Areas of similar age within Antarctica, India and Sri Lanka should also be considered. These proposed source terrains imply that some sediment was transported over fairly long distances, thereby inferring the presence of large fluvial systems at the time of deposition. Sediment transport over long distances is also supported by the well-rounded nature of the majority of the zircon grains. The Natal Sector of the NNMC should also be kept in consideration as a more proximal source of minor Stenian-aged detrital zircon grains. Minor populations of Archean and Palaeoproterozoic zircons present in some members of the Natal Group were likely sourced from immediately adjacent rocks of the Kaapvaal and Grunehogna cratons. Post-orogenic Cambrian – Early Ordovician granitoids of the Maud Belt of East Antarctica and the Unango and Nampula complexes of west-central Mozambique probably made some lesser contributions.

It is likely that the same areas that sourced the Natal Group succession also acted as sources of detritus to the Msikaba Formation, which is in accordance with the overall SW-directed palaeocurrents reported for the formation. A late Neoproterozoic – Cambrian age component is more important in the Msikaba Formation than in the Natal Group. Granitoid plutons of Cambro-Ordovian and Silurian age of the Trans-Antarctic Mountain Range are suggested as a possible source of detritus of this age range, and the difference could reflect progressive unroofing of relatively younger plutons within these suggested source areas during Ordovician–Devonian–Carboniferous time. Longshore currents likely played an important role in the dispersal of sediments. The continental block of the Deseado Massif, containing late Silurian – early Carboniferous granitoids, should also be considered as an alternative source of zircons of Silurian age given that this unit is thought to have been in close proximity to the southern tip of South Africa during early Palaeozoic time.

It is also important to consider the deposition of the Natal Group and Msikaba Formation in a much larger context. The two units were most likely deposited within a continental-scale basin, rather than in a small, localized basin. Present-day exposures of these two units indeed represent only relicts of much thicker and much more extensive sedimentary series. The significantly thicker Natal Group succession probably underwent major uplift and erosion prior to deposition of the disconformably overlying Msikaba Formation. In turn, a thick layer of Msikaba Formation sediments most likely extended north of the Dweshula palaeographic high over the red beds of the Natal Group, before being removed by erosion at the base of the continental glacial ice cap during Carboniferous time.

The inferences from our zircon provenance studies on the nature and extent of the basin or basins in which the Natal Group and Msikaba Formation sediments were deposited remains tentative. The questions of the age relationship of the two units and the time gap at their disconformity are central in this context, and more light could likely be shed on this topic if sampling of these two successions could be carried out at single locations across the disconformity. The four localities featuring well-exposed, accessible contacts between Natal Group and Msikaba Formation as described by Hicks (2010) could potentially be well suited to such a study. On a different scale altogether, the question of the character of the basins can be addressed by comparative work on detrital zircon populations in Cape Supergroup sedimentary units, which is currently being undertaken.

Supplementary material

To view supplementary material for this article, please visit http://dx.doi.org/10.1017/S0016756815000370

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