Precambrian Research 182 (2010) 124–148

Contents lists available at ScienceDirect

Precambrian Research

journal homepage: www.elsevier.com/locate/precamres

Mesoproterozoic geology of the Nampula Block, northern Mozambique: Tracing fragments of Mesoproterozoic crust in the heart of Gondwana

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ARTICLE INFO

Article history:
Received 22 February 2010
Received in revised form 29 June 2010
Accepted 9 July 2010

Keywords:
Geochemistry
Geochronology
Geodynamics
Mesoproterozoic
Mozambique
Nampula Block

ABSTRACT

The Nampula Block covers over 100,000 km^2, making it the largest Mesoproterozoic crustal segment in northern Mozambique and an important component of the Neoproterozoic to Cambrian (Pan-African) East African Orogen. It is bounded in the north by the WSW–ENE trending Lúrio Belt. The oldest rocks (Mocuba Suite) are a polydeformed sequence of upper amphibolite-grade layered grey gneisses and migmatites associated with intrusive trondhjemite-tonalite-granodiorite and granitic orthogneisses. A banded gneiss, interpreted as a meta-volcanic rock, yielded a U-Pb SIMS zircon date of 1127 ± 9 Ma. Metamorphic rims, dated at ca. 1090 Ma, probably grew during a later magmatic phase, represented by the tonalitic Rapale Gneiss, two samples of which were dated at 1095 ± 19 and 1091 ± 14 Ma, respectively. The earliest (D_1) deformation that took place at approximately this time, was associated with high grade metamorphism and migmatisation of the Mocuba Suite. The geochemistry of these rocks suggests that they were generated in a juvenile, island-arc setting. The Mocuba Suite is interlayered with extensive belts of meta-pelitic/psammitic, calc-silicate and felsic to mafic meta-volcanic paragneisses termed the Molócuè Group. U-Pb data from detrital zircons from a calc-silicate paragneiss gave a bimodal age distribution at ca. 1100 and 1800 Ma, showing derivation from rocks of the same age as the Mocuba Suite and a Palaeoproterozoic source region. The age of the Molócuè Group has been directly determined by dates of 1092 ± 13 and 1090 ± 22 Ma, obtained from two samples of the leucocratic Mamala Gneiss (meta-felsic volcanics?), one of its major constituent components. The final phase of Mesoproterozoic activity is represented by voluminous plutons and sheet-like bodies of foliated megacrystic granite, augen gneiss and granitic orthogneiss of the Culicui Suite, which have A-type granite geochemical characteristics and are interpreted to have been generated in a late tectonic, extensional setting. Three samples from the suite gave identical ages of ca. 1075 Ma. The Nampula Block was extensively reworked during the major (D_2: Pan-African) collision orogen in Late Neoproterozoic to Cambrian times, when the major regional fabrics were imposed upon the Mesoproterozoic rocks under amphibolite-facies metamorphic conditions. In the dated samples, this orogenic event is represented by metamorphic zircon

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0301-9268/$ – see front matter
doi:10.1016/j.precamres.2010.07.005

rim ages of ca. 550 to 500 Ma. The new data indicate that the Mesoproterozoic rocks of the Nampula Block were originally accreted to a Palaeoproterozic crustal Block and the Nampula Block only reached its current position, separated from the other Mesoproterozoic blocks of NE Mozambique by the Lúrio Belt, during Neoproterozoic collision and plate movements. The geological history of the Nampula Block is comparable with that described from other parts of the Mesoproterozoic orogenic belts of the Kalahari craton and helps to constrain an integrated model of their evolution.

1. Introduction

The crust of NE Mozambique is composed of predominantly medium to high grade rocks with Mesoproterozoic (ca. 1.15–0.95 Ga) protolith ages (Fig. 1). In the extreme NW, where Mozambique abuts Tanzania and Malawi, a small area of Palaeoproterozoic rocks, known as the Ponta Messula Complex is exposed. The Mesoproterozoic basement is locally overlain by a series of dismembered Neoproterozoic granulite nappes known as the Cabo Delgado nappes (Fig. 1), which were emplaced during the East African Orogeny (Viola et al., 2009). The Meso- and Neoproterozoic crustal blocks were finally juxtaposed and intruded by large volumes of granitic rocks during the Late Neoproterozoic to Cambrian, East African Orogeny at ca. 550 Ma (e.g. Bingen et al., 2009; Grantham et al., 2008).

NE Mozambique is traversed by a major straight WSW-ENE-trending structure known as the Lúrio Belt (Cadoppi et al., 1987; Pinna et al., 1993; Sacchi et al., 1984, 2000; Viola et al., 2009). It extends over 600 km from the coast near Nacala (Fig. 2), westwards to the Malawi border and effectively separates a complex area to the north, comprising a number of Meso- and Neoproterozoic terranes ("complexes": Boyd et al., 2010) from a large contiguous crustal block in the south termed the Nampula Block. The Lúrio Belt is expressed by a strong zone of flattening in the east, which grades laterally into a complex zone of anastomosing shear zones and folds towards the southwest (see Viola et al., 2009).

The Nampula Block covers about 100,000 km^2, making it the largest crustal block in NE Mozambique. It consists of mainly Mesoproterozoic rocks, formed during the widespread ~1 Ga mountain building episode but with an intense Neoproterozoic-Cambrian overprint, imposed during the formation of the East African Orogen and the supercontinent Gondwana. The Nampula Block thus forms an important component in models for the geometry and evolution of both the supercontinents of Rodinia and Gondwana. To the south and east the Nampula Block is covered by various Phanerozoic cover formations of the Mozambiquan coastal plains.

During a major Nordic Development Bank, World Bank and South African Government-sponsored geological mapping programme that ran from 2000 to 2005, the whole of NE Mozambique was mapped at 1: 250,000 scale, including the Nampula Block. The greater part (>90%) of the exposed area of the Nampula Block was mapped by two groups, the Council for Geoscience, South Africa (CGS) and the Norconsult Consortium (staffed by geologists from the Norwegian and British Geological Surveys), in collaboration with the National Directorate of Geology, Mozambique (DNG). The results of these surveys are reported in Grantham et al. (2007), Macey et al. (2007) and Norconsult Consortium (2007). This paper provides an overview geological description of the entire Nampula Block by presenting a new lithostratigraphic scheme, backed up by U-Pb zircon geochronology and geochemical analyses of all the major units. This new insight allows us to propose new tectono-magmatic models for the origins of the main Mesoproterozoic rock units, characterise the major orogenic events and to discuss the spatial, temporal and tectonic relationships between the Nampula Block and other Mesoproterozoic blocks of the Kalahari craton.

This paper focuses on the Mesoproterozoic evolution of the Nampula Block. A detailed account of the subsequent intense late Neoproterozoic orogenic cycle responsible for the current juxtapositioning of Meso- and Neoproterozoic crustal blocks is reserved for a later publication.

2. Previous studies of the Nampula Block

The first systematic geological surveys of NE Mozambique, including the Nampula Block were undertaken by the BRGM (French Geological Survey) and the Italian group Aquater in the 1970s and early 1980s (e.g. Jourde et al., 1974; Jourde and Vialette, 1980; Aquater, 1983). These mapping projects recognised roughly the same rock types across the Nampula Block but, confusingly, often allocated different names to each lithostratigraphic unit (Table 1). The results of these mapping projects, including geochemical and geochronological data, were compiled in reports cited above and published in a series of articles (e.g. Sacchi et al., 1984; Cadoppi et al., 1987; Costa et al., 1992, 1994).

This geological framework formed the basis for a series of 1:250,000-scale maps compiled by Ferrara in the mid-1980s and the 1: 1,000,000 geological compilation of Pinna and Marteau (1987) culminating in the seminal geological overview paper of Pinna et al. (1993). New geochronology allowed Kröner et al. (1997), Jamal (2005) and Sacchi et al. (2000) to suggest revisions to the tectono-metamorphic models proposed for the region. Jacobs and Thomas (2002) considered that the Nampula Block represented a contiguous block of Mesoproterozoic crust ("LuNa microplate") that was accreted to the Kalahari Craton during the Pan-African orogeny.

The recently completed internationally funded regional mapping program saw the remapping of the whole of Mozambique at 1:250,000 scale accompanied by the acquisition of new petrographic, geochronological and geochemical data written up in the geological reports of Grantham et al. (2007), Macey et al. (2007), Norconsult Consortium (2007) and Pekkala et al. (2008). This manuscript represents one of a series of papers that publish the results of these survey reports (see also Viola et al. (2009), Grantham et al. (2008), Bingen et al. (2009), Thomas et al. (2010) and Boyd et al. (2010)).

3. Major rock types of the Nampula Block

Where possible, the current study has retained the lithostratigraphic nomenclature of previous workers (Table 1) but with two main modifications. First, the meta-plutonic rocks have been removed from the supracrustal groups and assigned to distinct units. Secondly, since metasedimentary and metavolcanic rock contacts are very rarely observed, we consider the subdivisions of supracrustal units into formations, as proposed previously, to be unrealistic; instead all the supracrustal rocks are classified as lithodemic units. In our simplified scheme the Mesoproterozoic rocks can be assigned to four main lithodemic units on the basis of field observations, petrography, geochemistry and geochronology (Grantham et al., 2007; Macey et al., 2007; Norconsult Consortium, 2007; Boyd et al., 2010). In order of decreasing age, these are the

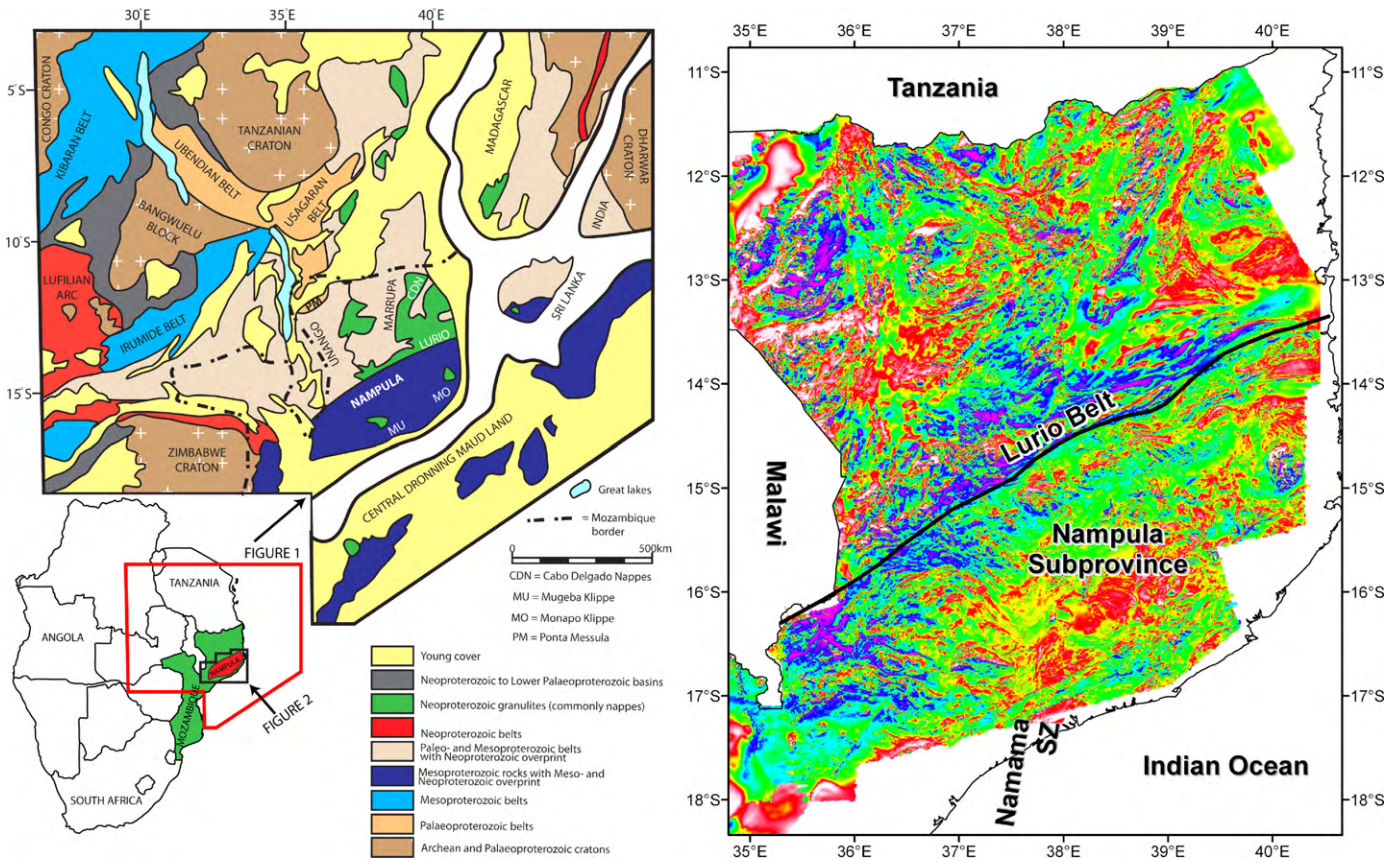

Fig. 1. Location of the Nampula Block within NE Mozambique with restored adjacent Gondwana fragments. Latitude and longitude refer to present-day Africa (modified after Kröner, 2001; Hanson, 2003; Grantham et al., 2008; Bingen et al., 2009). PM = Ponta Messula. The airborne magnetic image shows the major regional structures of northern Mozambique (data courtesy of DNG, Maputo).

Mocuba Suite (ca. 1125 Ma meta-volcanic-plutonic rock assemblage), **Rapale Gneiss** (ca. 1095 Ma intrusive orthogneiss), **Molócuè Group** (ca. 1090 Ma supracrustal paragneiss, metavolcanic rock assemblage) and **Culicui Suite** (ca. 1070 Ma intrusive granitic orthogneisses).

The Mocuba Suite gneisses are distinguished from the remainder of the Mesoproterozoic rocks in that they are strongly migmatitised, being the only unit to preserve the effects of a Mesoproterozoic high grade metamorphic and deformation (D_1) event (e.g. Sacchi et al., 1984). All of the Mesoproterozoic rocks developed amphibolite-grade penetrative gneissic fabrics during the intense Neoproterozoic/Cambrian East African orogeny (D_2).

The Neoproterozoic/Cambrian orogeny also involved the emplacement of nappe sheets (preserved as the **Monapo** and **Mugeba** granulitic klippen) and the deposition of a restricted clastic sedimentary rock sequence (**Mecubúri** and **Alto Benfica Groups**), followed by deformation and metamorphism of the Mesoproterozoic rocks and voluminous granitic magmatism (**Murrupula** and **Malema Suites**) during Cambro-Ordovician times. Linear outcrops of granulites (**Ocua Complex**, Fig. 2) define the trace of the Lúrio Belt that forms the northern boundary of the Nampula Block, separating it from the Unango and Murrupa Complexes. These main groupings are shown on a summary geological sketch map of the Nampula Block (Fig. 2).

3.1. Older Mesoproterozoic basement (Mocuba Suite)

3.1.1. Banded grey migmatitic gneiss

These heterogeneous grey gneisses are compositionally banded on all scales (typically layers are 0.2–2 m thick), and usually isoclinally folded. They consist of layers varying in grain size, colour and modal mineralogy. Subtle to large differences in the proportions of quartz (20–40%), plagioclase (An_{20-40}; 25–45%), K-feldspar (10–30%), biotite (5–10%) and hornblende (1–10%) are the principal factors that differentiate the compositional banding (Fig. 3a), along with varying amounts of accessory opaque minerals, apatite, zircon, epidote and titanite. Dark layers have granodioritic-tonalitic-dioritic compositions. The gneisses are strongly migmatitic, with substantial amounts of roughly foliation-parallel quartz-feldspar leucosomes (Fig. 3a). The leucosomes are typically equigranular (~2 mm, <5 mm) and consist of quartz, feldspar and minor biotite and hornblende. Several phases are recognised. Earliest stromatic leucosome veins form rootless intrafolial folds within the gneissic layering, whereas late phases are represented by cross-cutting, sometimes ptygmatically folded melt veins and strain-free patch-type leucosomes. Multiple generations of felsic, aplitic to pegmatitic veins and dykes, both fabric-parallel and discordant, add to the complexity of the gneisses. The gneiss layers are often laterally discontinuous and deformed, commonly displaying pinch-and-swell structures and boudinage. Infolded layers, discontinuous lenses and boudins of melanocratic amphibolite and biotite-rich rock probably represent deformed and dismembered mafic dykes.

The lack of pelitic, quartzitic or calcareous bands within the succession suggests that the banded grey gneiss is mainly composed of meta-volcanic/volcaniclastic rocks, with little evidence for non-volcanic meta-sedimentary protoliths, as previously noted by Sacchi et al. (1984), Cadoppi et al. (1987) and Costa et al. (1992).

3.1.2. Tonalite-trondhjemite-granodiorite (TTG) gneisses

The banded gneisses are typically associated, and interlayered with, large, probably sheet-like bodies of coarse-grained, mesocratic, grey, migmatitic trondhjemite-tonalite-granodiorite

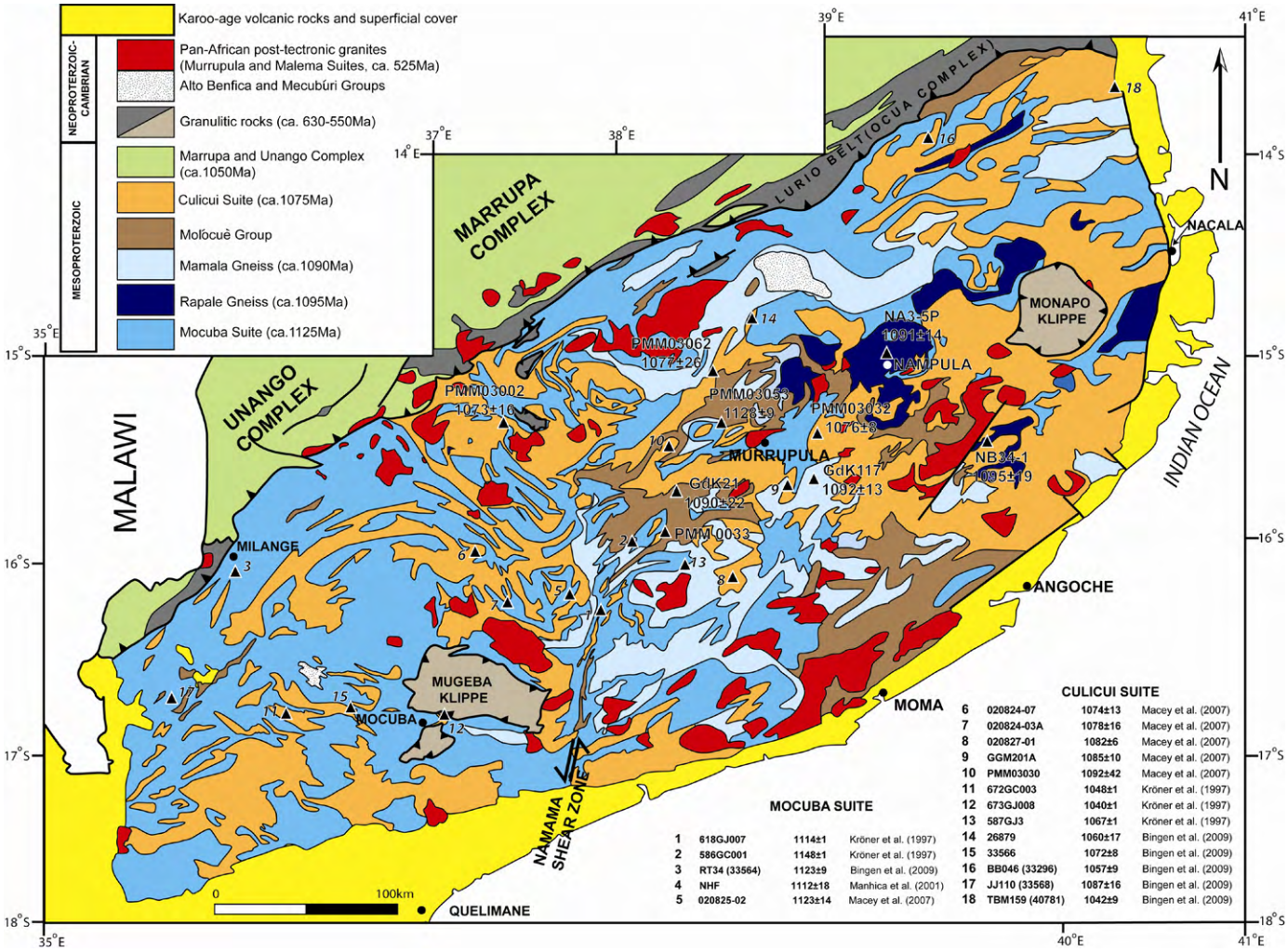

Fig. 2. A simplified geological map of the Nampula Block showing the distribution of the major lithodemic units. This figure represents a simplification of the 1:2,50,000 scale geological map sheets produced by Grantham et al. (2007), Macey et al. (2007) and Norconsult Consortium (2007). Also shown are the locations of the crystallisation ages of the Mesoproterozoic gneisses of the Nampula Block from previous studies (alongside the map) and this study (on the map).

(TTG) orthogneisses. Compositional variation is extreme, ranging from hornblendite (up to metre-scale blocks, pods and boudins of pure hornblende), through meta-gabbro, to mela- and leuco-tonalite, trondhjemite and granodiorite (Fig. 3b). The gneisses show streaky to layered alternations between quartz-feldspar-rich and biotite ± amphibole-rich compositional layers (average1–5 cm thick). Polyphase migmatism is indicated by layer-parallel (stromatic) and cross-cutting, hornblende-plagioclase leucosomes. Leucosome veins are often isoclinally to disharmonically folded, whilst melanosomes consisting of dark, coarse-grained hornblende-biotite occur as boudins, angular blocks, lenses and schlieren. Dark angular blocks and lenses of coarse-grained plagioclase-bearing amphibolite and hornblendite are common. Formerly continuous amphibolite layers are commonly dismembered into trains of pinch-and-swell boudins, with coarse leucosome filling inter-boudin necks. The compositional and migmatitic bands are typically isoclinally folded and refolded.

The mineral assemblage of these rocks comprises medium- to coarse-grained equigranular quartz, albitic plagioclase and biotite ± amphibole ± microcline, with accessory opaque minerals, apatite, titanite and zircon. Mafic minerals typically make up 10–20% of the rocks. Epidote is the principal retrograde mineral. The gneisses generally have granoblastic textures caused by extensive annealing following the intense deformation.

The relationship between this unit and the grey banded gneiss is complex. In some localities it appears intrusive, in that it contains gneissic xenoliths, whereas elsewhere the TTG orthogneisses are intimately interlayered with the banded gneisses and appear to represent part of that sequence. Such ambiguity may suggest that these gneisses may have plutonic and supracrustal components, as might occur in the root-zone of an island-arc, where juvenile calc-alkaline volcanic rocks are intruded by shallow magma chambers. The juvenile nature of the Nampula Block gneisses adjacent to the Neoproterozoic Mecubúri Group was ascertained from the Hf isotopic composition of their zircons (Thomas et al., 2010).

3.1.3. Granitic leucogneiss

In the western part of the Nampula Block the most extensive component of the Mocuba Suite is a generally medium- to coarse-grained, inequigranular, heterogeneous streaky leucocratic granitic orthogneiss. The lithology is characterised by a very variable and irregular fabric, which tends to "swirl" in chaotic fashion (Fig. 3c). The leucogneiss is highly variable, presenting a spectrum of lithologies. One end-member consists of fairly homogeneous pink leucogranite gneiss with minor biotite. At the other extreme is heterogeneous, inequigranular leucogranite with multiple biotite wisps, schlieren and streaks with included, disrupted and folded amphibolite and biotite-amphibolite boudins and lenses, all of which are intruded by irregular and anastomosing

Table 1
Lithodemic subdivisions of the Nampula Block.

	This study after Macey et al. (2007); Grantham et al. (2007) and Norconsult (2007)		Pinna et al. (1993) Excluding stratigraphy north of the Lúrio Belt		Aquater (1983) Variably modified by Sacchi et al. (1984); Cadoppi et al. (1987); Costa et al. (1992)		B.R.G.M. Jourde et al.(1974) and modified by Jourde and Vialette (1980)		
CAMBRO-ORDIVICIAN	**Murrupula Suite**	Syn- to post-tectonic granitoids	Pan African granite & pegmatite		Syn-post Lurian granitoids		Late- and post-Pan African granite and pegmatite		
	Mecubúri and Alto Benfica Groups	Meta-conglomerate & psammite	No equivalent		No equivalent		No equivalent		
NEOPROTEROZOIC	**Ocua Group**	Lúrio belt: granulites & mylonite	LURIO SUPERGROUP	Lúrio Group	No equivalent		Lúrio Group	Lúrio Series	Malema Formation
	Mugeba Complex	**Mugeba Klippe:** granulites & marginal mylonite		Mugeba Group	Mugeba Complex Muaquiua Complex			Mugeba Series	
	Monapo Complex	**Monapo Klippe:** granulites, marginal mylonite, pyroxenite, granite and syenite		Monapo Group	No equivalent No equivalent			Monapo Series Cuamba Series	
	Mafic dykes of unknown pre-D2 age				mafic dykes				
MESOPROTEROZOIC	**Culicui Suite**	Granitic, granodioritic, dioritic and charnockitic augen gneiss	Included augen gneisses in the Nampula Supergroup (below)		Pre-Lurian porphyroblastic granitic and granodioritic gneiss		Included augen gneisses in the Nampula Group (below)		
	Molócuè Group	Paragneisses (meta-pelite, meta-psammite & calc-silicate gneiss/schist, marble) Mafic gneiss, amphibolite Mamala quartzo-feldspathic Gneiss	CHIURE SUPERGROUP	Metolola Group	No equivalent		No equivalent		
				Molócuè Group	Rio Molócuè Group	Monte Inrepele Formation Morrua Complex Rio Nipiodi Formation	Metil-Molócuè Group		Nantira-Nipiodi-Inrepele Formation Metil-Morrua Formation
				Mecuburi Group	Zambezia Group	Cavarro Formation Mamala Formation	Nampula Group or Nampula-Zambezia Group	Mecuburi Series	Mecuburi-Cavarro Formation Nametil Formation
				Nametil Group		*unconformity*			
	Rapale Gneiss	TTG orthogneiss							
	unconformity								
	Mocuba Suite central & eastern outcrops	Banded migmatitic biotite-hornblende gneiss & TTG orthogneiss	NAMPULA SUPERGROUP	Nampula Group		Mocuba Complex		Nampula-Mocuba Series	
	Mocuba Suite western outcrops	Diatexitic leucogranite gneiss		Namarroi zone				Namarroi-Namuli Series	

arrays of inequigranular leucogranite veins, pods, and segregations (Fig. 3c). The granitic leucogneiss is locally patchily charnockitised adjacent to later intrusions of the Culicui Suite. The leucogneiss is typically composed of subequal quartz, altered K-feldspar (microcline) and plagioclase, with minor chloritised biotite, rare garnet or clinopyroxene and accessory opaque minerals and zircon. It occurs in large volumes and probably represents the products of near-eutectic melting of quartzo-feldspathic protolith material.

3.2. Rapale Gneiss

The Rapale orthogneiss is an equigranular, foliated granitoid of tonalitic-granodioritic-trondhjemitic composition (Fig. 2). The Rapale Gneiss represents a new unit first identified during the regional mapping by Macey et al. (2007) who recognised that although the Rapale Gneiss has the similar mineralogy and geochemistry (cf. Section 6) to the Mocuba Suite orthogneisses, the Rapale Gneiss does not preserve the intense D_1 migmatisation textures and occurs as large, more homogenous, mountain outcrops.

The largest body forms a roughly circular, deformed pluton, approximately 20 km wide, which underlies Nampula city (Fig. 2). The orthogneiss is relatively homogenous, meso- to leucocratic and grey in colour. It consists of quartz (10–20%), albitic plagioclase (70–80%) and biotite (5–15%) ± hornblende (up to <5%) ± microcline and accessory opaque minerals, zircon, apatite and titanite. The fabric is strongly gneissic, defined by flattened to streaky, granular quartz-feldspar domains a few mm thick, separated by anastomosing streaks (0.5 mm thick) of lepidoblastic biotite (Fig. 3d). The Rapale Gneiss is typically weakly migmatitic and usually contains less than 5% foliation-parallel quartz-feldspar (±biotite ± magnetite) leucosome veins, although up to 30% leucosome has been observed. The margins of some hornblende-bearing leucosomes are locally associated with *in situ*, patchy charnockitisation, a feature also seen along anastomosing networks of discrete

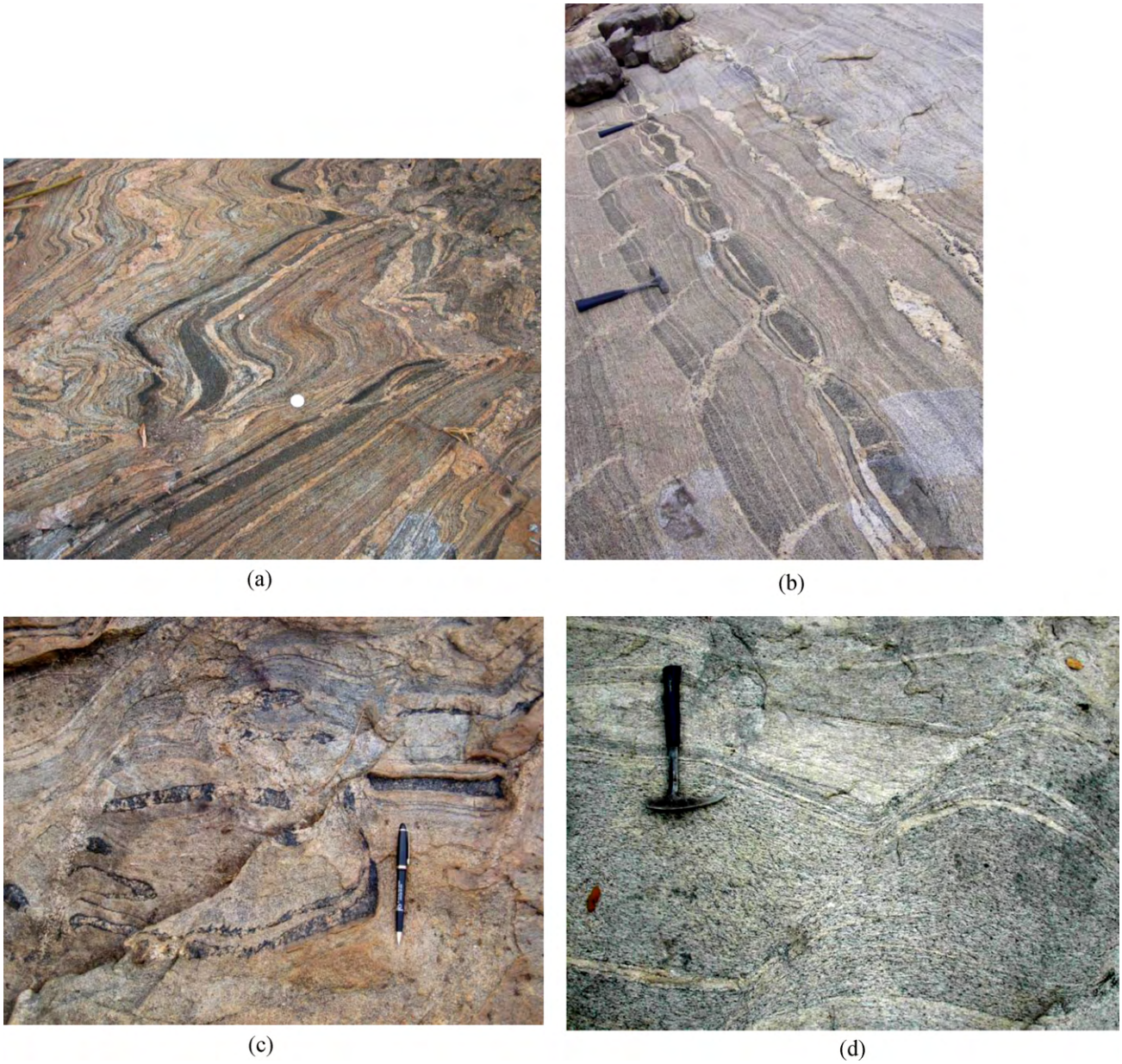

Fig. 3. Field photographs of the Mocuba Suite and Rapale Gneiss. (a) Strong compositional banding in Mocuba Suite migmatitic gneiss, with alternation of felsic, intermediate and more mafic layers; (b) layered coarse-grained tonalitic orthogneiss of the Mocuba Suite, with boudins of darker, hornblende-rich diorite. Note early, layer-parallel, blebby leucosomes and later generation at an angle to the gneissic layering; (c) Migmatitic leucogranitic gneiss with diffuse layering and mafic restite blebs common in the western outcrops of the Mocuba Suite; (d) Typical Rapale Gneiss with tonalitic (dark) and trondhjemitic (light) layers. The layering is truncated by a late ductile shear zone (S_3).

late shears, which may have acted as pathways for late CO_2-rich dehydrating fluids.

A spotted appearance is locally apparent due to dispersed, flat disc-shaped aggregates of biotite, 5–10 mm across. Granular epidote resulting from the breakdown of biotite and plagioclase, occasionally form coronas around the biotite spots. Biotite-rich xenoliths, possibly autoliths, forms flattened disc-shaped bodies oriented parallel to the regional fabric.

3.3. Late Mesoproterozoic supracrustal rocks (Molócuè Group)

The Molócuè Group was originally defined as a belt of supracrustal rocks in the south-central parts of the Nampula Block (e.g. Aquater, 1983; Sacchi et al., 1984). Pinna et al. (1993) later included these rocks with the other supracrustal belts (Metangula, Chiúre, Metolola, Mécuburi and Nametil (Nantira-Metil) Groups) of NE Mozambique in a "Chiúre Supergroup". However, current ideas regarding the tectonostratigraphy of NE Mozambique, preclude the Mesoproterozoic supracrustal rocks of the Nampula Block from correlation with the other crustal blocks north of the Lúrio Belt (Norconsult Consortium, 2007; Viola et al., 2009; Bingen et al., 2009).

The regional mapping programs by Aquater (1983) and Macey et al. (2007) recognised that the Molócuè Group represents supracrustal cover to the older, previously tectonised, Mocuba Suite, citing evidence such as the presence of a polymictic conglomerate with pebbles of Mocuba Suite migmatite near the base of the supracrustal package (locations ~15°37.6′S, 38°11.4′E; 15°30.2′S, 38°19.0′E; 15°34.7′S, 38°15.3′E) and the absence of the early (D_1) fabrics and strong migmatisation evident in the Mocuba Suite (Sacchi et al., 1984; Cadoppi et al., 1987; Costa et al., 1992). The unconformity is not exposed.

Unequivocal evidence of primary sedimentary or volcanic textures has not been preserved in these rocks. Their fabrics, while possibly parallel to original, primary variations in composition, are invariably strongly transposed. The Molócuè Group make up only about 15% of the surface area of the Nampula Block, occurring as relatively thin belts, lenses and screens between the voluminous intrusive rocks. In this study, we subdivide the group into a number of informal lithodemic units. The order in which the constituent lithodemic units are presented does not imply original order of superposition, although the Mamala Gneiss appears to be at the base and may therefore be the oldest component.

3.3.1. Mamala Gneiss

Sacchi et al. (1984) identified two main groups of quartzo-feldspathic gneiss: the Mamala and the Cavarro Formations, and considered them equivalents of the 'leptitic-leptynitic' Nametil and Mécuburi Formations of Jourde and Vialette (1980). Aquater (1983) considered the Mamala Formation to represent interlayered meta-rhyolitic lavas and pyroclastic rocks, and they further subdivided the unit into three subtypes based on rock textures, grain size and the proportions of biotite, pyroxene and magnetite. It has proved impractical, however, to map these subdivisions on a regional basis.

Typically the Mamala Gneiss consists of fine- to medium-grained equigranular (0.5–1.0 mm), leucocratic off-white to cream coloured, leucogranitic gneiss with roughly equal proportions of microcline, plagioclase (An_{20-30}-oligoclase) and quartz, and minor amounts of biotite (<5%) ± garnet, sillimanite and rare clinopyroxene. It commonly contains magnetite (0.5–3%, up to 10%), which occurs as equigranular (0.5–1.0 mm, up to 5 mm) subhedral to euhedral grains, or ~3–5 mm spherical or linear grain clusters, disseminated throughout the rock. This is responsible for the characteristic positive aeromagnetic signature of the rocks. Zircon and apatite are the most common accessory phases, and muscovite occurs as a retrograde mineral, especially after sillimanite.

In outcrop, the Mamala Gneiss ranges from massive to compositionally banded and is commonly migmatitic with foliation-parallel leucosomes making up to 15–20% of the rock mass (Fig. 4a). The gneissic foliation is defined by lepidoblastic biotite and compositional layering, the latter caused by minor variations in proportions of biotite, quartz and feldspar that probably reflect primary compositional differences. Stromatic migmatite banding and a quartz-feldspar grain-flattening fabric also contribute to the gneissic foliation. Some outcrops are homogenous with a fine-grained sugary texture and a poorly defined foliation with magnetite as the sole mafic mineral. Although the Mamala Gneiss has been interpreted as a meta-acid volcanic unit (see Jourde et al., 1974; Sacchi et al., 1984; Cadoppi et al., 1987), parts of it may represent minimum melt segregations which migrated from their host rocks during peak metamorphism to form mappable leucosome bodies. Some layers in the Mamala Gneiss are anhydrous garnet-quartz-feldspar gneisses, commonly with trains of millimetre-sized garnets strung out along the foliation. These layers may constitute the products of dehydration melting reactions, although other evidence for such high grades of metamorphism is limited to rare pyroxene-bearing layers within the gneiss (Aquater, 1983). In places, the quartzo-feldspathic gneiss contains metre-scale layers with disseminated disc-shaped sillimanite-muscovite nodules (~2–5 cm). These aluminous layers may represent primary volcano-sedimentary intercalations or deeply weathered paleosols in the protolith (the 'Cavarro Formation' of Cadoppi et al., 1987). In the western part of the Nampula Block, the Mamala Gneiss is dominated by more heterogeneous, inequigranular, strongly migmatised, streaky leucogneisses in which the fabric is locally isoclinally, chaotically or disharmonically folded.

3.3.2. Mafic and ultramafic gneiss and amphibolite

Mafic rocks are common throughout the Molócuè Group, occurring on the metre- to kilometre-scale as layers, pods and lenses. They are predominantly layered amphibolites, with less common intercalations of amphibole-epidote-pyroxene-garnet gneiss, talc-, chlorite- and anthophyllite schist. Epidote-rich rocks also occur, mainly as pods and lenses (Sacchi et al., 1984; Cadoppi et al., 1987). The metamafites are locally interlayered with the Mamala Gneiss to form a bimodal mafic-felsic association, suggestive of a volcanic protolith. Elsewhere the amphibolites are interbanded with impure quartzites. These include pyroxene-amphibole-epidote layers that Sacchi et al. (1984) regarded as siliceous sediments with pyroclastic additions.

Metabasic masses are typically composed of massive, foliated to banded, medium-grained amphibolite consisting of sub-equal plagioclase and hornblende + pyroxene ± biotite, accessory magnetite + titanite and secondary epidote ± calcite. The layering in the rocks is due to the segregation between those dominated by dark amphibole + pyroxene and those with abundant feldspars ± quartz (Fig. 4b). The preferred orientation of amphibole, biotite and pyroxene grains further defines the fabric. The ratio of pyroxene to amphibole varies considerably, from rocks with only hornblende to those dominated by clinopyroxene. Most, however, contain both in sub-equal proportions. Amphibole commonly forms poikiloblasts or streaks which partly include feldspar grains. In places the mafic minerals are draped around feldspars resulting in lepidoblastic texture. The clinopyroxene forms small, tabular, subrounded, single grains or aggregates of grains, or as large poikiloblasts forming continuous irregular networks. In some cases the amphibole contains magnetite exsolution lamellae and grains. Plagioclase, the main felsic phase, occurs interstitially between the mafic layers or as single grain inclusions in mafic mineral porphyroblasts. Finer grained, equigranular, leucocratic layers display granoblastic polygonal texture. Some smaller masses of amphibolite within the sequence are garnetiferous. These are medium- to coarse-grained and inequigranular rocks, with spherical garnet porphyroblasts up to 2 cm in diameter, set in a medium-grained (ca. 1 mm) matrix with interlobate texture, composed of zoned plagioclase, brown hornblende and clinopyroxene, with minor garnet, opaque mineral, biotite and apatite. The garnet porphyroblasts contain inclusions of hornblende and are surrounded by symplectitic rims of plagioclase + hornblende + clinopyroxene, as alternating lamellae ca. 20 μm thick, and an outer halo enriched in hornblende, several mm thick. The mafic rocks are typically migmatitic, with blebby, coarse-grained leucosomes containing up to 10% amphibole with quartz and plagioclase (Fig. 4b). Leucosomes are both parallel to and cross-cutting with respect to the foliation.

3.3.3. Paragneisses

A relatively minor proportion of the Molócuè Group consists of metasedimentary paragneiss such as metapelite, quartzite, calc-silicate gneiss and marble.

Metapelitic and *metapsammitic paragneiss/migmatite* is a common and distinctive component of the group, usually forming bodies on the tens of metres to kilometre-scale. Pelitic quartz-feldspar-biotite-garnet ± sillimanite ± cordierite parageneses interlayered with quartz-rich psammitic gneisses are a typical association (Fig. 4c). The gneisses are strongly folded and invariably migmatised, with local diatexitic features. The rocks are inequigranular, with grain size ranging from <0.5 to 5 mm with seriate to interlobate grain boundaries and the foliation is defined by planar-oriented, decussate biotite and accentuated by gradational compositional layering. Large K-feldspar megacrysts are common, in association with quartz and plagioclase, in places with myrmekitic textures. Garnet porphy-

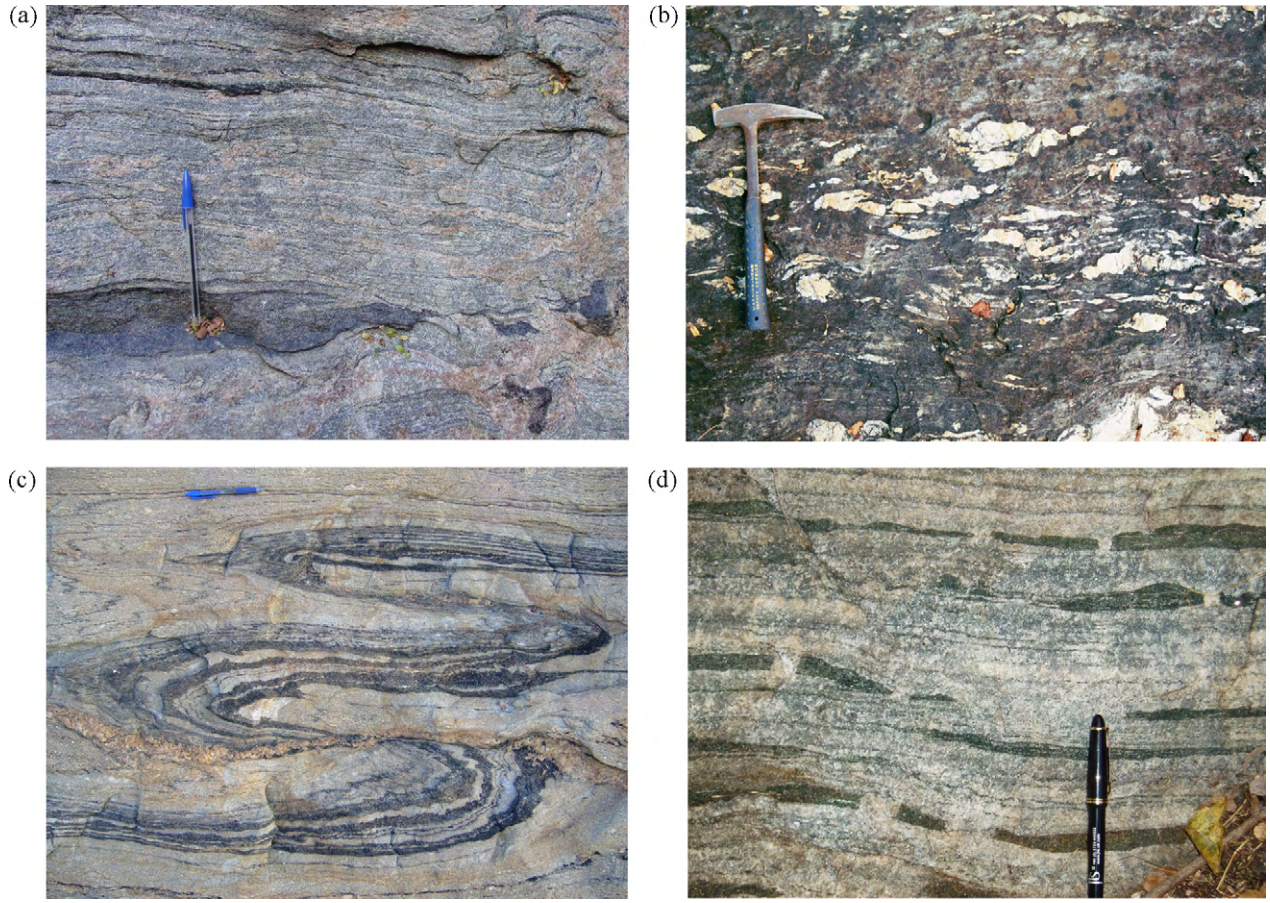

Fig. 4. Field photographs of the Molócuè Group. (a) Layered, leucocratic biotite-bearing quartz-feldspathic Mamala Gneiss, interpreted as a meta-rhyolite; (b) Amphibolite with blebby leucosomes; (c) Banded paragneiss with interlayered quartz-rich meta-psammitic gneiss (light) and garnet-biotite meta-pelitic gneiss (dark); (d) Quartzitic calc-silicate gneiss, with granoblastic quartz and minor feldspar (light-grey) and disrupted epidote-titanite-amphibole layers (dark). The dated sample PMM00033 came from this unit.

roblasts, up to 5 mm in diameter, typically contain inclusions of biotite and quartz and are commonly surrounded by plagioclase rims. Minor phases include opaque minerals, apatite, zircon and monazite.

Quartzite and ferruginous quartzite bands (Banded Iron Formation-BIF) usually occur as discontinuous layers less than one or two meters thick, with a strike length of up to 5 m. More extensive bodies occur in the Milanje area in the western part of the Nampula Block. The textures range from fine annealed to coarse granular and the colour varies from milky white to glassy to pale reddish-brown (due to iron-staining) or black in rocks rich in magnetite. BIFs show alternating quartz-rich and magnetite + garnet-rich layers. Quartzites are composed of up to 90% quartz, with subordinate garnet, magnetite, muscovite and occasional amphibole and feldspar. Quartz is typically elongated and anhedral with amoeboid shapes and irregular grain edges. Some quartzites were strongly annealed with very coarse quartz. For example the pure, coarse-grained quartzose rocks associated with a NE-trending fault (Liciro lineament; Fig. 2) are white to glassy, massive, quartz-rocks, with grain size often in excess of 1 cm (up to 4 cm in some places). It is unclear if this unit represents a primary coarse orthoquartzite or a recrystallised mass quartz that was injected into a fault zone. Other quartz-rich units are banded and contain layers of garnet, orthopyroxene and opaque minerals alternating with quartz bands. These appear to be banded pyroxene-garnet meta-quartzites, similar to gondites. In other outcrops, there is a transition from quartz-rich rocks to those with calc-silicate affinities, composed of feldspar ± clinopyroxene ± brown biotite ± opaque minerals (Fig. 4d).

Meta-carbonate and calc-silicate rocks are rare in the Molócuè Group. In a few localities, very coarse-grained (up to 5 cm) calcite marbles were encountered with boudinaged, disrupted and folded layers and pods of calc-silicate rocks and fine-grained garnetiferous gneisses, alternating on a decimetre scale. Forsterite-diopside-tremolite-phlogopite marble was observed in one locality. With increasing levels of impurities, calc-silicate minerals such as diopside, garnet, titanite and muscovite appear (with the latter predominant in the impure to pure marbles). Rare, strongly banded calc-silicate gneisses consist of alternating hornblende-epidote-rich and quartz-feldspar-rich bands between 1 and 5 mm thick. Such rocks comprise hornblende (15%) set in a roughly equigranular (0.5–3 mm) groundmass of epidote (20%), K-feldspar (10%), quartz (35%), plagioclase (5%), calcite (1%) and titanite (4%). Prismatic tremolite-actinolite (10%) grains appear to overprint the hornblende and apatite and opaque minerals occur in trace amounts.

3.4. Late Mesoproterozoic intrusive rocks: Culicui Suite

The granitoid orthogneisses of the Culicui Suite represent one of the most voluminous, widespread and characteristic lithological units in the Nampula Block. These meta-plutonic rocks were previously included in the Nampula Group/Supergroup (Table 1), however, during the recent regional mapping program the orthogneisses were separated out as the Culicui Suite (Macey

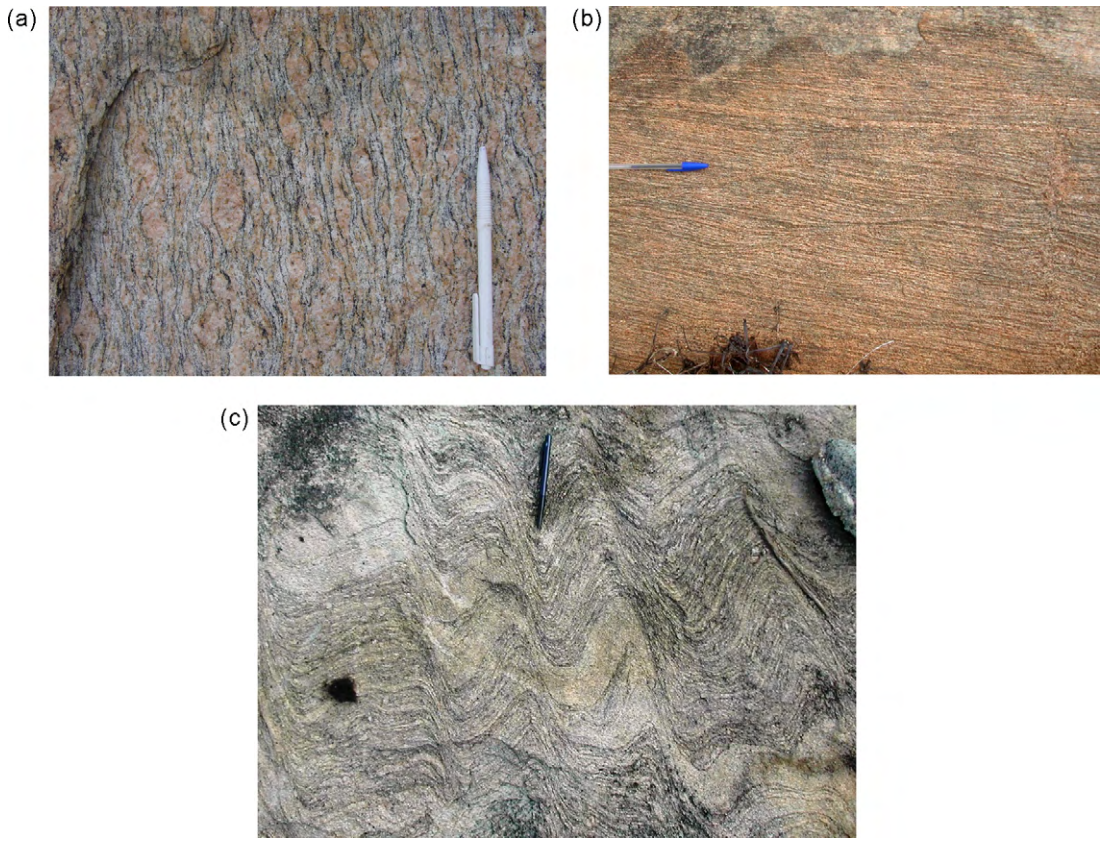

Fig. 5. Field photographs of the Culicui Suite. (a) Typical pink K-feldspar megacrystic granite orthogneiss/augen gneiss. (b) Medium-grained, non-megacrystic leucocratic orthogneiss phase. (c) Late ductile (S_3) crenulations in Culicui Suite leucocratic orthogneiss.

et al., 2007). The suite forms bodies on all scales, with the largest plutons covering over 1000 km^2 in area and forming large, prominent mountain ranges. Intrusions have sheet-like to irregular forms, oriented parallel to the regional foliation. A number of different compositional and textural plutonic facies have been recognised (see Macey et al., 2007), but the most characteristic and widespread lithology is coarse-grained, pink-weathering, K-feldspar megacrystic granite/leucogranite orthogneiss and augen gneiss, which is locally dark green and charnockitic, with orthopyroxene. The typical megacrystic varieties are characterized by strongly aligned, foliation-parallel, pink, subhedral tabular Carlsbad twinned orthoclase megacrysts constituting 5–40% by volume of the rocks and typically measuring 10 mm × 25 mm (Fig. 5a). They are enclosed in a streaky, foliated, coarse-grained grey- to pink quartz-feldspar-biotite matrix. These rocks grade, with increasing strain, to strongly foliated augen gneisses, in which the megacrysts are strongly recrystallised. In the most highly strained zones the augen-textured orthogneisses often exhibit an intense stretching lineation defined by highly elongate recrystallised polycrystalline ribbon-aggregates of quartz and/or feldspar (rods) and the preferred orientation of flattened ellipsoids of mafic minerals (mostly biotite). Strongly recrystallized K-feldspar augen are aligned parallel to the maximum elongation direction. The penetrative foliation in the Culicui Suite rocks is locally weakly deformed by open folds and commonly cross-cut by discrete leucosome-filled shear bands/crenulations. Typical modal mineralogy of orthogneisses is quartz (15–30%), K-feldspar (40–60%; generally microperthite, as megacrysts and in the matrix), plagioclase (~10%), biotite (10–15%), magnetite (≤1%) sporadic orthopyroxene and/or hornblende in charnockitic varieties, with accessory apatite, titanite, opaque minerals and zircon. Xenoliths are common in contaminated zones as amphibolite (locally isoclinally folded) and biotite-rich schlieren, typically 2–8 cm thick. These probably represent deformed mafic dykes (Section 3.5) and partly-digested country-rock gneiss remnants respectively.

Although the majority of the Culicui Suite consists of K-feldspar megacrystic granites, there are also medium- to coarse-grained equigranular varieties. These form small tabular bodies, with the exception of the Inricui pluton (10 km SW of Murrupula; Fig. 2) which occurs as a 50 km long ENE-trending elongate intrusion. In other areas, pale orange- to cream-coloured streaky quartzo-feldspathic leucogranite gneisses are closely associated and in places interlayered with the granite orthogneisses, from which they can be distinguished on the basis of their paucity of mafic minerals (<5%: Fig. 5b). Late crenulation of the main, regional fabric is a common feature (Fig. 3c).

Very rarely, relatively thin lenses of meta-gabbro and diorite gneiss occur as concordant bands within the Culicui meta-granite bodies. In the absence of geochronological data, these more mafic rock types are cautiously included in the Culicui Suite on the basis of their close association with the augen gneisses and similarities in tectonic fabrics.

3.5. Mafic dykes

The Mocuba Suite, Rapale Gneiss, Mamala Gneiss and Culicui Suite locally contain thin infolded layers (30–200 cm thick), discontinuous lenses and ovoid boudins of amphibolite and biotite-rich rock, which we consider to represent metamorphosed dykes. The age of these intrusions is poorly constrained by the youngest age for the Culicui Suite and the age of the late Neoproterozoic D_2 deformation and metamorphism, as discussed below.

3.6. Neoproterozoic to Cambrian rocks

The Mesoproterozoic rocks of the Nampula Block are associated with a number of Neoproterozoic lithodemic and plutonic igneous rocks units. These do not form the subject of this paper and are described elsewhere (Grantham et al., 2007; Macey et al., 2007; Norconsult Consortium, 2007; Thomas et al., 2010; Boyd et al., 2010), but for completeness, they are briefly documented here.

3.6.1. Granulite klippen and lenses in the Lúrio Belt

The central part of the Nampula Block is tectonically overlain by the Mugeba and Monapo klippen (Figs. 1 and 2), composed of granulite facies gneisses (Jourde and Vialette, 1980; Sacchi et al., 1984; Siegfried, 1999; Macey et al., 2007; Grantham et al., 2007). They are probably the erosional remnants of originally far more extensive nappes, which may be correlated with the Cabo Delgado nappes north of the Lúrio belt (Viola et al., 2009). Both klippen are elliptical in outcrop and measure some 30 km across. They are dominated by granulites with mafic, leucogranitic, meta-pelitic, meta-carbonate, meta-quartzitic and meta-volcanic compositions. Peak metamorphic conditions have been calculated at approximately 900–1000 °C and >1.0 GPa (Roberts et al., 2005; Grantham et al., 2007, 2008). The granulites have Mesoproterozoic protolith ages and are locally intruded by felsic, mafic and ultramafic plutonic rocks dated at about 635 Ma and with metamorphic ages ranging from 615 to 579 Ma (Kröner et al., 1997; Grantham et al., 2007, 2008; Macey et al., 2007). Along the Lúrio belt, similar granulite gneisses occur as discontinuous layers, pods and lenses. They are collectively referred to as the Ocua Complex and are interpreted as a tectonic mélange that formed within the Lúrio belt during a high-pressure granulite grade metamorphic event dated at 557 ± 16 Ma (Engvik et al., 2007; Viola et al., 2009; Bingen et al., 2009).

3.6.2. Metasedimentary rocks: Mecubúri and Alto Benfica Groups

These two sequences of metasedimentary rocks are interfolded with the central part of the Nampula Block. Both groups comprise clastic sequences of meta-psammites and meta-conglomerates, which were strongly deformed, metamorphosed to sillimanite grade and locally migmatised. The relatively unsheared contacts with the surrounding Mesoproterozoic gneisses suggest that both groups are largely autochthonous and were deposited unconformably on the exhumed Nampula Block basement. The depositional environment of the sequences is interpreted as largely proximal fluvial in small, intracontinental, fault-controlled basins. U-Pb analyses of detrital zircons constrain a maximum, early Cambrian depositional age of around 530 Ma for the Mecubúri Group (Thomas et al., 2010).

3.6.3. Intrusive granitoid suites: Murrupula and Malema Suites

The Nampula Block Mesoproterozoic gneisses and the granulites were intruded by relatively large volumes of late- to post-tectonic alkali granitoids of the Murrupula Suite, dated at ca. 530–495 Ma (Macey et al., 2007; Grantham et al., 2007, 2008; Jacobs et al., 2008a). The weakly- to undeformed suite comprise plutons of coarse-grained porphyritic granite, medium- to fine-grained equigranular granite, with rarer monzodiorite and syenite. The similarly aged Malema Suite comprises a series of small sub-circular plutons and ring complex of alkali granite, monzonite and charnockite intruded along, and adjacent to, the Lúrio Belt (Bingen et al., 2009).

4. U-Pb zircon geochronology of the Mesoproterozoic rocks

A limited number of U-Pb zircon dates have been published from the Nampula Block (from the Mocuba and Culicui Suites, see Table 2). In our study, a total of nine representative samples of all the major lithodemic units of the Nampula Block were selected for U-Pb zircon SIMS dating. The samples were analysed at ANU, Canberra, Australia with a SHRIMP II instrument. Analytical techniques are given in Appendix 1 and the analytical data are presented in Appendix 2. Cathodoluminescence (CL) images of typical zircons analysed from selected samples are given in Fig. 6.

4.1. Mocuba Suite and Rapale gneiss

Zircons from one sample of the Mocuba Suite and two of the Rapale Gneiss have been dated:

Sample PMM03053 (15°22.468′S; 38°24.671′E), from the Mocuba Suite is a, banded, grey migmatitic gneiss. It has a tonalitic/dacitic composition, made up of quartz (30%), plagioclase (45%), K-feldspar (10%), hornblende (5%) and biotite (10%) with accessory apatite and zircon. It shows the earliest (D_1) phase of deformation as intrafolial folds and refolded leucosomes. Thirteen of the eighteen analyses from the cores of oscillatory zoned zircons yielded a concordia age of 1127.6 ± 8.9 Ma [MSWD = 1.3, probability = 0.17] (Fig. 7a), which is considered to record the crystallisation age of the dacitic protolith. The crystallisation date is in broad accord with other ages for the Mocuba Suite (Table 2).

A metamorphic zircon overgrowth on one zircon gave a $^{206}Pb/^{238}U$ age of 1091 ± 15 Ma, that we interpret as either the date of D_1 migmatisation or the metamorphism associated with intrusion of younger granitoids (e.g. Rapale Gneiss).

Sample NA3-5P (15°03.589′S; 39°15.289′E) is a tonalitic Rapale Gneiss. It yielded a discordia line with an upper intercept age of 1091 ± 14 Ma [MSWD = 0.9, probability = 0.57] (Fig. 7b). The upper intercept age is taken as the best estimate for magmatic crystallisation of the orthogneiss. The zircon data from a second Rapale Gneiss of tonalitic composition, *Sample NB34-1* (15°28.310′S, 39°44.999′E), define an upper intercept age of 1095 ± 19 Ma and an equivalent concordia age at 1095 ± 8 Ma (Fig. 7c). This date is within error of sample NA3-5P and is also interpreted as the crystallisation age of the tonalite. These new ages represent the first dates of the Rapale Gneiss.

4.2. Molócuè Group

Three samples of the Molócuè Group have been dated. The rocks are thought to have been deposited upon the Mocuba Suite after deformation and migmatisation of the latter (Aquater, 1983; this study). Two samples (GdK117, GdK21) are of Mamala Gneiss. They are thought to be acid metavolcanic rocks which would therefore directly date the extrusion of the gneiss and tightly constrain the age of group as a whole. Detrital zircons in a layered quartzite-calc-silicate rock (PMM00-033) were dated in order to assess the provenance of the sediments.

Sample GdK117 (15°39.265′S; 38°53.900′E) is a weakly migmatitic quartzo-feldspathic facies of the Mamala Gneiss. Twenty-three zircons were analysed. The cores of nine of them are concordant to slightly reversely discordant. They yielded a weighted mean $^{207}Pb/^{206}Pb$ age of 1092 ± 13 Ma [MSWD = 1.10, probability = 0.36] (Fig. 8a). This is regarded as the crystallisation age of the original volcanic rock and thus the age of formation of the lower part of the Molócuè Group. The analysis of five metamorphic zircon rims gave a mean $^{207}Pb/^{206}Pb$ age of 555 ± 12 Ma [MSWD = 1.68, probability = 0.67]. This age is typical for Pan-African metamorphic rims (e.g. Bingen et al., 2009).

Sample GdK21 (15°42.098′S; 38°12.090′E), the second quartzo-feldspathic Mamala Gneiss, is interpreted as a meta-rhyolite belonging to a bimodal felsic-mafic metavolcanic protolith. It is interleaved within a paragneissic sequence of meta-pelites, quartzites, meta-psammite and calc-silicate rocks. Analyses of twenty zircons provided a spread of discordant data with an

Table 2
U-Pb zircon geochronology of the Mesoproterozoic rocks of the Nampula Block.

Sample number	Lithology	Method and laboratory	Latitude	Longitude	Age	Source
Crystallisation ages						
Mocuba suite						
PMM03053	Migmatitic tonalitic gneiss	U-Pb SHRIMP, ANU	−15.37446	38.41120	1128 ± 9	This study
020825-02	TTG gneiss	U-Pb SHRIMP, NIPR	−16.33250	37.62833	1123 ± 14	Macey et al. (2007)
618GJ007	Biotite gneiss	Single Grain Evaporation	−16.36444	37.80944	1114 ± 1	Kröner et al. (1997)
586GC001	Granodiorite gneiss	Single Grain Evaporation	−16.03333	38.03389	1148 ± 1	Kröner et al. (1997)
RT34 (33564)	Migmatitic leucogneiss	U-Pb SHRIMP	−16.16099	35.96479	1123 ± 9	Bingen et al. (2009)
NHF	Augen gneiss	U-Pb SHRIMP	−19.06332	33.31556	1112 ± 18	Manhica et al. (2001)
CVGN	Granodiorite gneiss	U-Pb SHRIMP	−19.10374	33.50380	1108 ± 12	Manhica et al. (2001)
Rapale Gneiss						
NA3-5P	TTG gneiss	U-Pb SHRIMP	−15.05982	39.25482	1091 ± 14	This study
NB34-1	TTG gneiss	U-Pb SHRIMP	−15.47183	39.74998	1095 ± 19	This study
Molocue Group						
GdK117	Quartz-feldspar gneiss	U-Pb SHRIMP	−15.65442	38.89833	1092 ± 13	This study
GdK21	Quartz-feldspar gneiss	U-Pb SHRIMP	−15.70164	38.20151	1090 ± 22	This study
Culicui Suite						
PMM03062	Augen gneiss	U-Pb SHRIMP, ANU	−15.14362	38.39240	1077 ± 26	This study
PMM03032	Granodiorite gneiss	U-Pb SHRIMP, ANU	-15.31785	38.97760	1076 ± 8	This study
PMM03002	Augen gneiss	U-Pb SHRIMP, ANU	−15.42238	37.39240	1073 ± 16	This study
020824-07	Megacrystic charnockite	U-Pb SHRIMP, NIPR	−16.07139	37.16500	1074 ± 13	Macey et al. (2007)
020824-03A	Tonalite gneiss	U-Pb SHRIMP, NIPR	−16.33944	37.39389	1078 ± 16	Macey et al. (2007)
020827-01	Augen gneiss	U-Pb SHRIMP, NIPR	−16.21278	38.49556	1082 ± 6	Macey et al. (2007)
GGM201A	Augen gneiss	U-Pb SHRIMP, NIPR	−15.71222	38.75306	1085 ± 10	Macey et al. (2007)
PMM03030	Augen gneiss	U-Pb SHRIMP, ANU	−15.48491	38.21662	1092 ± 42	Macey et al. (2007)
672GC003	Biotite granite gneiss	Single Grain Evaporation	−16.87222	36.27056	1048 ± 1	Kröner et al. (1997)
673GJ008	Trondjemite gneiss	Single Grain Evaporation	−16.88972	37.01416	1040 ± 1	Kröner et al. (1997)
587GJ3	Q-F gneiss	Single Grain Evaporation	−16.10722	38.26722	1067 ± 1	Kröner et al. (1997)
26879	Granitic gneiss	CAMECA	−14.94392	38.51711	1060 ± 17	Bingen et al. (2009)
33566	Granitic gneiss	ICPMS	−16.85479	36.56667	1072 ± 8	Bingen et al. (2009)
BB046 (33296)	Augen gneiss	ICPMS	−13.91802	39.45072	1057 ± 9	Bingen et al. (2009)
JJ110 (33568)	Augen gneiss	U-Pb SHRIMP	−16.85157	35.74006	1087 ± 16	Bingen et al. (2009)
TBM159 (40781)	Granitic gneiss	ICPMS	−13.64866	40.39258	1042 ± 9	Bingen et al. (2009)
Metamorphic Ages						
Mocuba Suite						
PMM03053	Migmatitic tonalitic gneiss	U-Pb SHRIMP, ANU	−15.37446	38.41120	1091	This study
020825-02	Tonalitic gneiss	U-Pb SHRIMP, NIPR	−16.33250	37.62833	1091 ± 37	Macey et al. (2007)
020825-02	Tonalitic gneiss	U-Pb SHRIMP, NIPR	−16.33250	37.62833	527 ± 18	Macey et al. (2007)
RT34 (33564)	Leucogneiss	SHRIMP	−16.16099	35.96479	520 ± 8	Bingen et al. (2009)
673GJ6	Granulite	U-Pb SHRIMP	−16.91528	37.09139	1028 ± 7	Costa et al. (1994)
DJ43	Migmatitic bt gneiss	SHRIMP	−14.05936	39.92715	516 ± 41	Jamal (2005)
DJ43	Migmatitic bt gneiss	SHRIMP	−14.05936	39.92715	520 ± 2	Jamal (2005)
DJ43	Migmatitic bt gneiss	TIMS	−14.05936	39.92715	524 ± 39	Jamal (2005)
Rapale Gneiss						
NA3-5P	TTG gneiss	U-Pb SHRIMP	−15.05982	39.25482	449 ± 96	This study
NB34-1	TTG gneiss	U-Pb SHRIMP	−15.47183	39.74998	604 ± 42	This study
Culicui Suite						
PMM03062	Augen gneiss	U-Pb SHRIMP, ANU	−15.14362	38.39240	505 ± 10	This study
PMM03032	Granodiorite gneiss	U-Pb SHRIMP, ANU	−15.31785	38.97760	514 ± 12	This study
PMM03002	Augen gneiss	U-Pb SHRIMP, ANU	−15.42238	37.39240	525 ± 20	This study
020824-07	Megacrystic charnockite	U-Pb SHRIMP, NIPR	−16.07139	37.16500	1023	Macey et al. (2007)
020824-07	Megacrystic charnockite	U-Pb SHRIMP, NIPR	−16.07139	37.16500	513 ± 10	Macey et al. (2007)
26879	Granitic gneiss	CAMECA	−14.94392	38.51711	543 ± 23	Bingen et al. (2009)
33566	Granitic gneiss	ICPMS	−16.85479	36.56667	1019 ± 18	Bingen et al. (2009)
BB046 (33296)	Augen gneiss	ICPMS	−13.91802	39.45072	517 ± 11	Bingen et al. (2009)
BB046 (33296)	Augen gneiss	ICPMS	−13.91802	39.45072	513 ± 19	Bingen et al. (2009)
JJ110 (33568)	Augen gneiss	U-Pb SHRIMP	−16.85157	35.74006	493 ± 8	Bingen et al. (2009)

upper intercept at 1090 ± 22 Ma [MSWD = 1.5, probability = 0.08] (Fig. 8b). One analysis of a zircon embayment growth feature gives a near concordant metamorphic age of ca. 510 Ma. The older age is regarded as an estimate of the crystallisation age for the original lava and is in good agreement with the age of the Molócuè Group obtained from sample GdK17. These are the first direct ages published for the Molócuè Group. In addition, the crystallisation ages of both samples constrain the age of the D_1 deformation and migmatisation of the Mocuba Suite to between 1127 and 1090 Ma. The Cambrian intercept age provides an approximate estimate for the timing of zircon growth during Pan-African metamorphism, and is coeval with post-collisional granitoids of the Murrupula Suite (e.g. Jacobs et al., 2008a) and metamorphic zircon rims in Cambrian gneisses of the Mecubúri Group (Thomas et al., 2010).

Sample PMM00-033 (16°05.483′S; 38°10.467′E) is a siliceous calc-silicate gneiss, taken from the metasedimentary part of the Molócuè Group. It consists of alternating ~2 mm-thick compositional bands containing quartz (35%), epidote (20%), microcline (15%), green-brown hornblende (15%), blue to green pleochroic tremolite-actinolite (10%), titanite (4%, <0.4 mm), calcite (1%) and accessory apatite, zircon and opaque minerals. Concordant or near-concordant zircons of two age-populations are seen at ca. 1100 and 1800 Ma. This indicates the presence of a detrital component derived from rocks coeval with the Mocuba Suite and older, Palaeoproterozoic sources respectively (Fig. 8c). The youngest concordant zircon core gave an age of 1115 ± 19 Ma, which can be regarded as the maximum age of deposition of the Molócuè Group. Most of the metamorphic rims are significantly discordant, except for

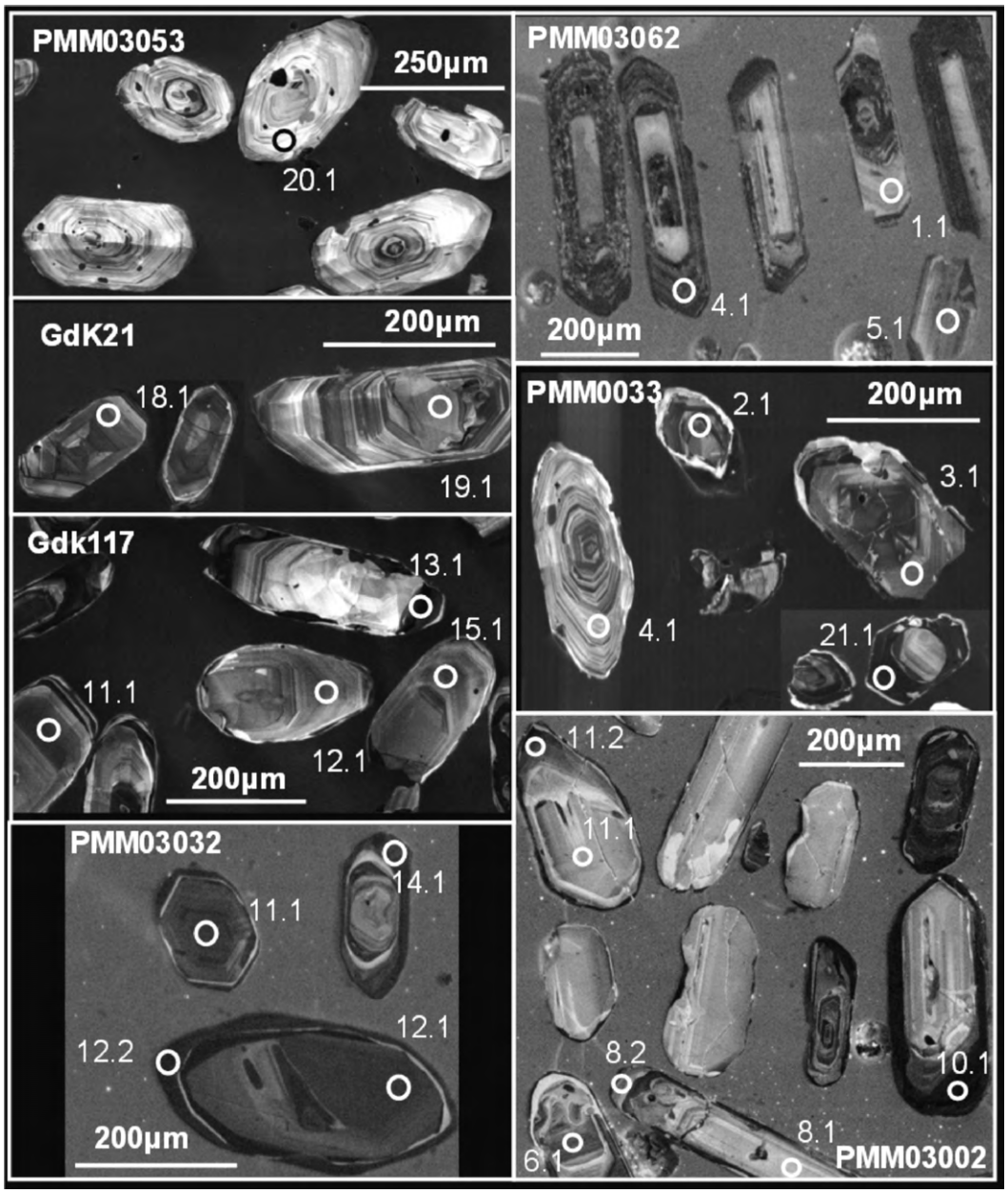

Fig. 6. CL images of representative zircons from analysed samples, with analytical spots indicated.

one grain that yielded a concordant age of ca. 1017 Ma. This age is difficult to interpret and could either represent a mixing apparent age or be equivalent to the similar poorly understood 1019 ± 18 Ma zircon age identified by Bingen et al. (2009). Costa et al. (1994) also quote a U-Pb SHRIMP metamorphic age of 1028 ± 7 Ma for a "granulite", suggesting that Nampula Block, at least locally underwent an end-Mesoproterozoic metamorphic event at this time.

4.3. Culicui Suite

Three representative samples of the main granitic orthogneiss phase of the suite were selected for dating:

Sample PMM03062 (15°08.617′S, 38°23.545′E) is a megacrystic granite orthogneiss from the type area of the suite (Culicui pluton). Of the twenty zircons analysed, thirteen were zircon cores, of which the four least discordant analyses give a mean $^{207}Pb/^{206}Pb$ age of 1077 ± 26 Ma [MSWD = 0.25, probability = 0.86] (Fig. 9a). This is considered to be the crystallisation age of the rock. The remainder of the analyses on cores are discordant, possibly representing metamict grains. Seven rim analyses were made. The two most concordant, from relatively homogenous rims, are near-concordant and gave a mean $^{206}Pb/^{238}U$ age of 505 ± 10 Ma [MSWD = 0.18, probability = 0.67]. The remaining analyses of rims are discordant and apparent ages are distributed between ca.700 and 600 Ma. A line regressed through all the data give intercepts at 1064 ± 27 Ma and 514 ± 37 Ma [MSWD = 2.8].

Sample PMM03032 (15°19.0715′S, 38°55.655′E), is weakly migmatitic banded granodiorite orthogneiss comprising 1–2 cm layers of quartz, plagioclase and K-feldspar alternating with layers rich in hornblende and biotite. Twenty analyses were carried out on eighteen zircon grains. Twelve of the fifteen cores analysed provide a minimum weighted mean $^{207}Pb/^{206}Pb$ crystallisation age

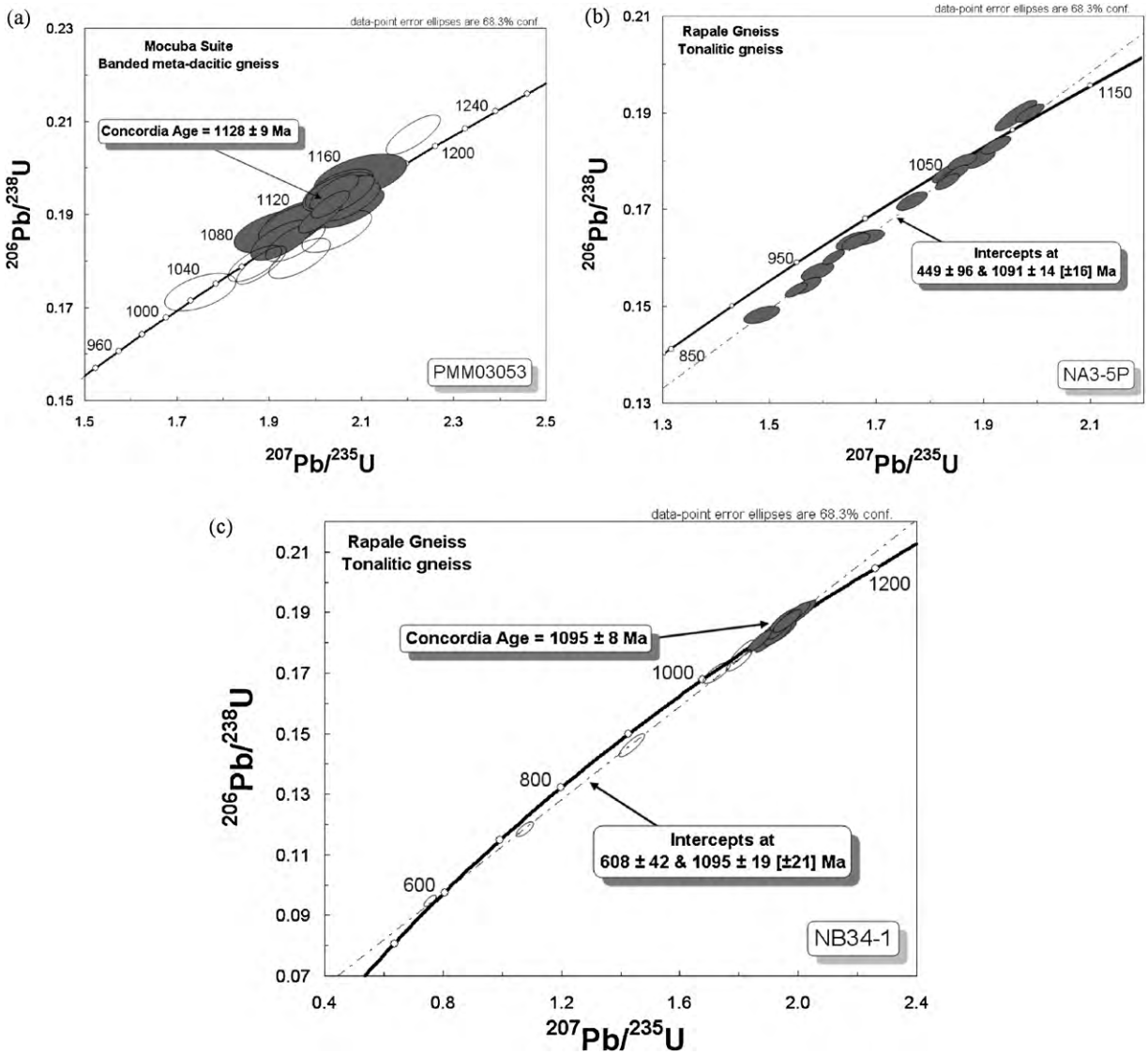

Fig. 7. Concordia plots for (a) Mocuba Suite: Sample PM03053, migmatitic, banded, grey supracrustal gneiss. (b) Tonalitic Rapale Gneiss Sample NA3-5P. (c) Rapale Gneiss Sample NB34-1.

of 1075.5 ± 8.3 Ma [MSWD = 1.30, probability = 0.25] (Fig. 9b). One low-U core gives an older, near-concordent age of ca. 1250 Ma and represents inherited zircon. The remaining discordant data probably reflect mixture of rim and core and/or Pb-loss. Five analyses of metamorphic rims yield slightly reverse discordant ages with a $^{207}Pb/^{206}Pb$ age of 514.4 ± 12 Ma [MSWD = 0.08, probability = 0.97], a $^{206}Pb/^{238}U$ age of 537.9 ± 7.8 Ma [MSWD = 0.41, probability = 0.80] and a concordia age of 530 ± 7.2 Ma [MSWD = 0.26, probability = 0.95].

Sample PM03002 (15°25.343′S, 37°23.923′E) is a granitic augen gneiss. Twenty-three analyses on 20 zircon grains were analysed. Seven analyses of zircon cores yield a mean $^{207}Pb/^{206}Pb$ age of 1073 ± 16 Ma [MSWD = 0.90, probability = 0.49] (Fig. 9c). Five metamorphic rims yield a mean $^{207}Pb/^{206}Pb$ age of 525 ± 20 Ma [MSWD = 0.25, probability = 0.86]. The remaining 12 analyses range discordantly between ca. 1000 Ma and 550 Ma. Some of these may be a mixture of core and rim material, while others may have undergone Pb loss.

The above data are broadly consistent with five published ages of the Culicui Suite (see Table 2) ranging from 1087 ± 16 Ma to 1057 ± 9 Ma (one with metamorphic overgrowths at 1019 ± 18 Ma) reported in Bingen et al. (2009).

5. Geochemistry of the Mesoproterozoic rocks

A total of 164 representative samples of the major lithodemic units of the Nampula Block were selected for major and trace element geochemical analysis, including rare earth elements (REE). Samples were collected from the least altered and weathered outcrops and, in the case of the migmatitic rocks, from the least partially melted components of the outcrop. The bulk of the samples were analysed by ICP-AES and ICP-MS by N. Walsh at the ICP Laboratory at Royal Holloway, University of London, while some were carried out by XRF at the Geological Survey of Norway. Analytical techniques are described in Appendix 1 and the geochemical data are presented in Appendix 2. To prevent cluttering, the RE and trace element spider diagrams presented here include only selected representative samples. A more complete set of geochemical plots including harker bivariate and spider diagrams displaying all samples is available in Appendix 3.

Element mobility is an important consideration when investigating the geochemistry of rocks that have been subjected to intense deformation, high grades of metamorphism and partial melting (e.g. Crowley et al., 2000). Inspection of element

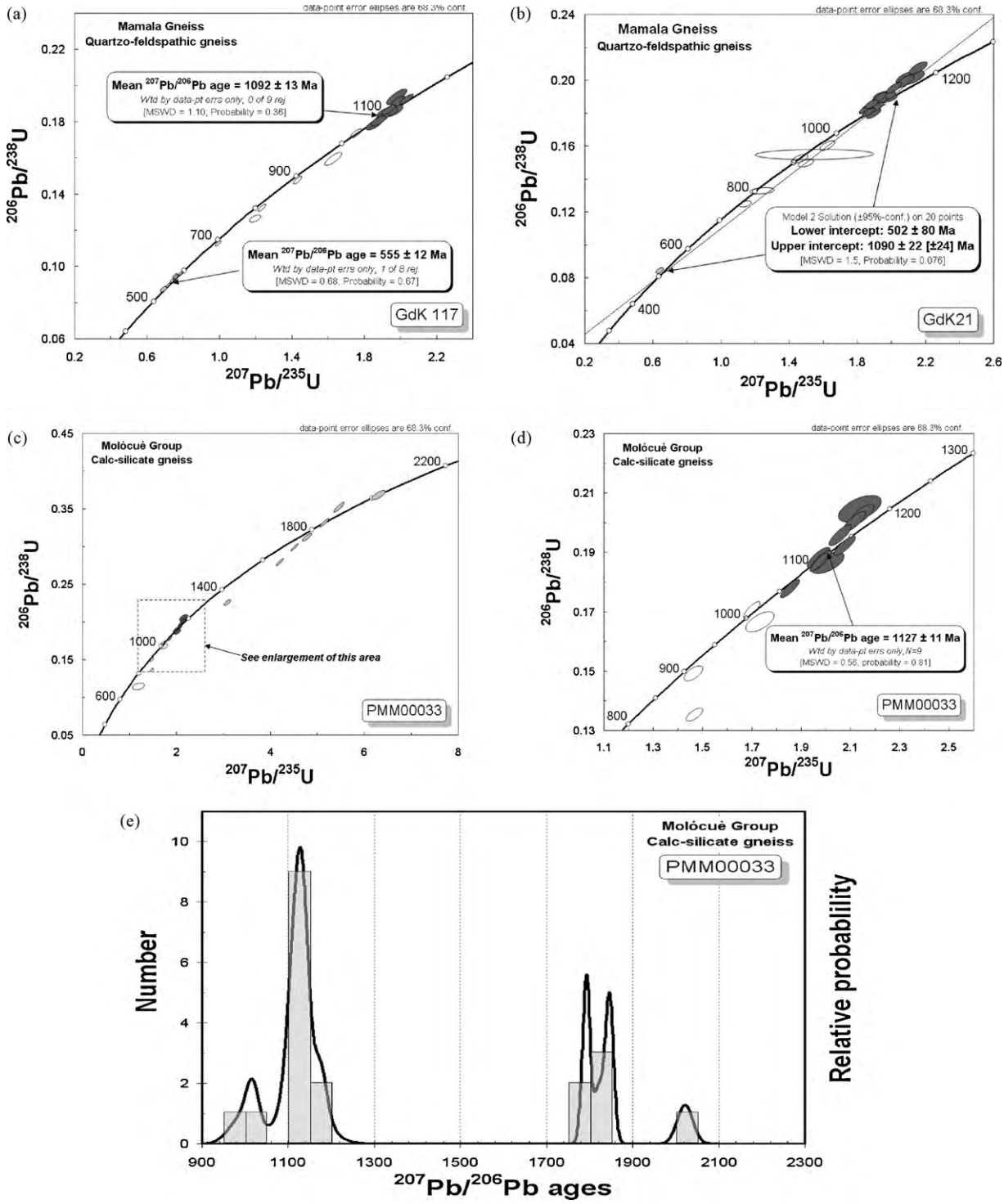

Fig. 8. Concordia plots for Molócuè Group samples: (a) Mamala Gneiss GdK117; (b) Mamala Gneiss GdK21; (c) Concordia plot of detrital zircon analyses from siliceous calc-silicate gneiss sample PMM00-033; (d) Enlargement of part of (c), around 1100 Ma; (e) Age-distribution histogram, showing bimodal Meso- and Palaeoproterozoic provenance ages.

variation diagrams of the Mesoproterozoic gneisses of the Nampula Block (Appendix 3) shows variable and often significant amounts of open system behaviour of the mobile elements (e.g. alkali elements, Ba, Rb), with the largest scatter displayed by the migmatitic rocks of the Mocuba Suite and the quartzo-feldspathic Mamala Gneiss. Nevertheless, the majority of the gneisses yield largely consistent major, trace and RE element compositions that allow for rock classification and clear inter unit discrimination, and with igneous fractionation trends suggesting limited subsolidus modification of the immobile element geochemistry (Appendix 3).

5.1. Mocuba Suite

The 39 samples of migmatitic orthogneiss and banded grey gneiss have a range of intermediate to felsic compositions (mostly 56–72 wt% SiO_2, mean = 67.4 ± 5.7%) and generally have elevated CaO and Na_2O and low K_2O contents relative to the Culicui

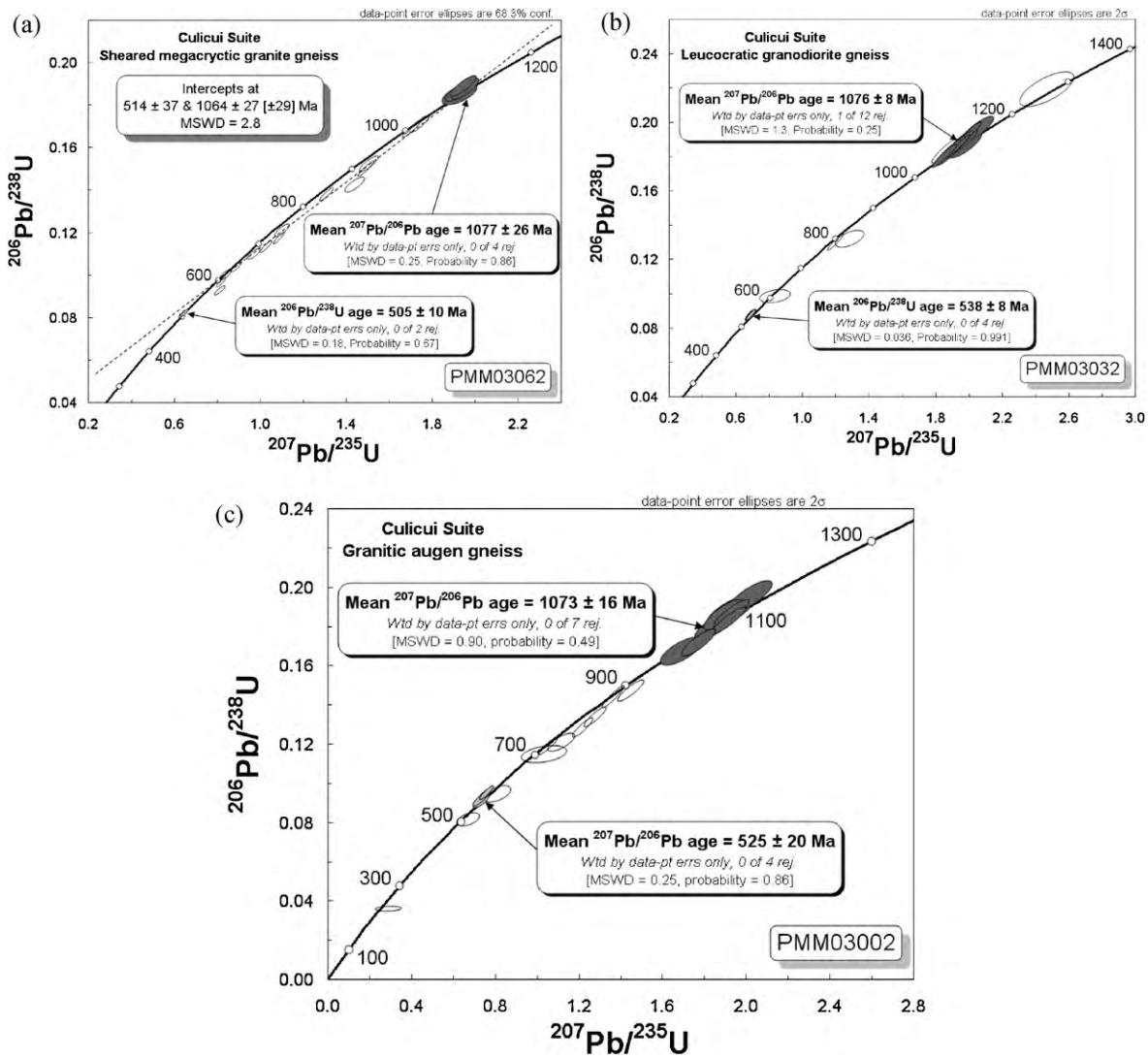

Fig. 9. Concordia plots for Culicui Suite. (a) Megacrystic granite orthogneiss Sample PM03062; (b) Granodiorite orthogneiss sample PMM03032; (c) Augen gneiss sample PM03002.

Suite (Appendix 3). Consequently, the majority of migmatitic orthogneisses classify as meta-granodiorites, tonalites and trondhjemites on the O'Connor (1965) feldspar normative diagram (Fig. 10a). The banded grey gneisses plot across the rhyolite, dacite and andesite fields of the total alkali versus silica (TAS) diagram (Fig. 10b). The wispy granitic leucogneisses of the western outcrops of the Mocuba Suite are distinguished by having higher K_2O and Na_2O.

The Mocuba Suite are mostly metaluminous to weakly peraluminous (molar A/CNK < 1.1; Fig. 10c). This, together with the mostly intermediate compositions, relatively high CaO and low K_2O contents, a paucity of aluminous mineral phases, low initial $^{87}Sr/^{86}Sr$ values of 0.7027 (Costa et al., 1992) and quartz $\delta^{18}O$ values mostly between 7.9 and 9.9‰ (Macey et al., 2007) indicate that the Mocuba meta-granites have igneous rather than sedimentary protoliths.

Most of the Mocuba Suite gneisses have sub-alkaline compositions and define calc-alkaline trends when plotted on the AFM diagram of Irvine and Barager (1971) (Fig. 10d). Primitive mantle-normalised trace element spider diagrams for representative samples of the suite (Fig. 11a) show relatively high alkali element contents (Rb, Ba, Th, K) and distinct negative Nb–Ta and Ti anomalies indicative of rocks derived from an island-arc setting (e.g. Baier et al., 2008). Chondrite-normalised REE diagrams show consistent near flat patterns with moderate to strong LREE enrichment (mean $La_N/Yb_N = 15.0 \pm 11.9$) and negative Eu anomalies (mean $Eu/Eu^* = 0.70 \pm 0.22$, minus 1 outlier; Fig. 11b). In addition, the gneisses plot mostly in the volcanic arc granite (VAG) field on the Rb-Y-Nb discrimination diagrams of Pearce et al. (1984) (Fig. 11c and d). The Mocuba Suite gneisses are the oldest known rocks in the Nampula Block and yielded no older xenocrystic zircons. The geochemical and geochronological data indicate that the Mocuba Suite developed as part of one or more juvenile calc-alkaline volcanic arc complexes with limited input of continental crust.

5.2. Rapale Gneiss

The Rapale Gneiss samples yield more restricted chemical compositions than the Mocuba Suite with 15 of the 18 samples having SiO_2 concentrations of between 69.3 and 73.9%. The unit is characterised by high Na_2O (3.5–5.5%; mean 4.8 ± 0.5) and low K_2O (mostly < 2.3%), resulting in tonalite, trondhjemite and granodiorite (TTG) classifications on the TAS plot and O'Connor normative diagram (Fig. 10a and b; Appendix 3). The TTG gneisses have a clear I-type granitoid character, with alumina saturation index (ASI) values between the peraluminous-metaluminous fields

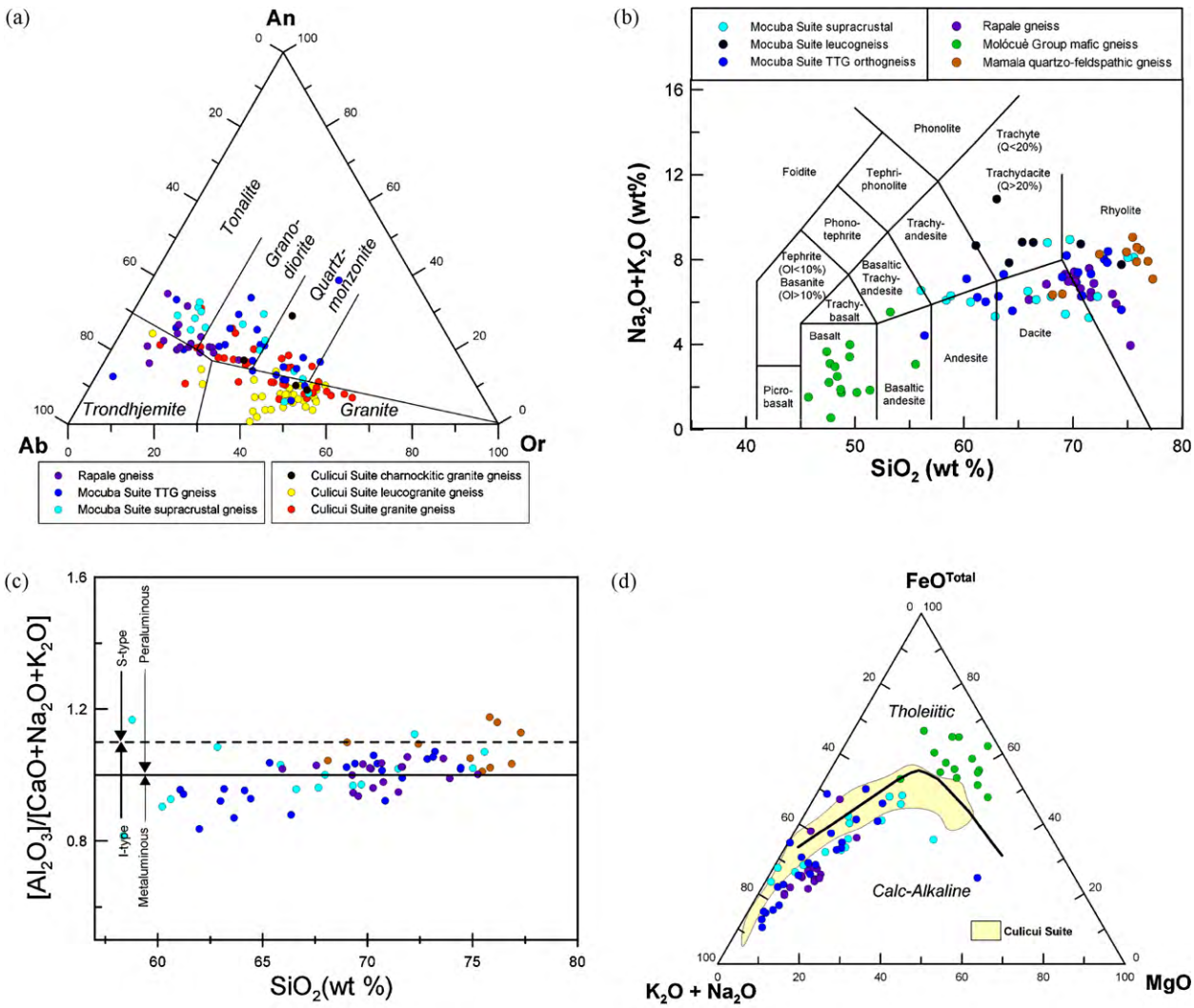

Fig. 10. Geochemical diagrams of the Mocuba Suite, Rapale Gneiss and Molócuè Group. (a) Ab-An-Or after O'Connor (1965); (b) Silica versus alkalis (TAS), with fields after Cox et al. (1979); (c) A/CNK versus silica after Shand (1943); (d) AFM after Irvine and Barager (1971).

(A/NCK = 0.94–1.06; mean 1.0) and an absence of peraluminous minerals (Fig. 10c). The Rapale Gneiss defines calc-alkaline trends on an AFM diagram and plot in the 'volcanic arc granite' field of tectonic discrimination diagrams (Figs. 10d and 11c). Normalised trace element and REE spider diagrams show relatively high contents of Rb, Ba, Th and K, distinct negative Nb–Ta and Ti anomalies, straight REE patterns with moderate LREE enrichment (mean $La_N/Yb_N = 12.1$) and weak negative Eu anomalies (mean $Eu/Eu^* = 0.93$; Fig. 11a and b). These major and trace element data indicate that, like the Mocuba Suite, the Rapale Gneiss was most likely derived from the melting of igneous source rocks in a volcanic-arc setting.

5.3. Molócuè Group

Samples from the Mamala Gneiss fall into two distinct geochemical groupings (Fig. 10b). Meta-rhyolites are rich in SiO_2 (SiO_2 = 72.4–77.3%, $n = 8$) and K_2O but have low concentrations of CaO, MgO and Fe^{Total}. Meta-dacites are more intermediate (SiO_2 = 67.4–72.3%; $n = 13$ including data from Cadoppi et al., 1987) and are relatively enriched in CaO, Al_2O_3 and Na_2O, but depleted in MgO and K_2O. Chondrite normalized REE plots also reveal differences, with rhyolitic gneisses having higher relative REE abundances and strong negative Eu anomalies (mean $Eu/Eu^* = 0.38 \pm 0.14$; mean $La_N/Yb_N = 5.6 \pm 2.8$, 1 outlier removed), whereas meta-dacites have only minor Eu anomalies and higher LREE/HREE ratios (mean $La_N/Yb_N = 15.9$; Fig. 11b). There is some geographical control on the distribution of the two groups suggesting that the geochemical differences are primary. The dacitic rocks mainly occur west of the Namama shear zone (Fig. 2) whereas the meta-rhyolites are located along the Namama shear and in closer association with the Molócuè Group supracrustal rocks. Despite differences in major and REE element compositions however, the Mamala Gneisses are uniformly peraluminous (ASI = 1.01–1.18, mean 1.08) and display consistent primitive mantle normalized trace elements patterns with enrichment of incompatible elements and strong negative Ba, P and Ti anomalies (Fig. 11a). In contrast to the Mocuba Suite, the Mamala Gneiss yielded a high initial Sr value of 0.7134 (Costa et al., 1992), confirming the presence of a significant component with long crustal history.

Of the 15 samples of Molócuè Group mafic gneiss analysed, 13 have relatively restricted SiO_2 content between 45.7 and 51.4% and classify mainly as basalts on the TAS plot (Fig. 10b). MgO values are more variable, ranging from 3.6 to 8.2% (mean 6.3 ± 1.4%) and Mg numbers range from near primitive values of 0.65 to evolved values of 0.35. The mafic rocks are almost always silica oversaturated

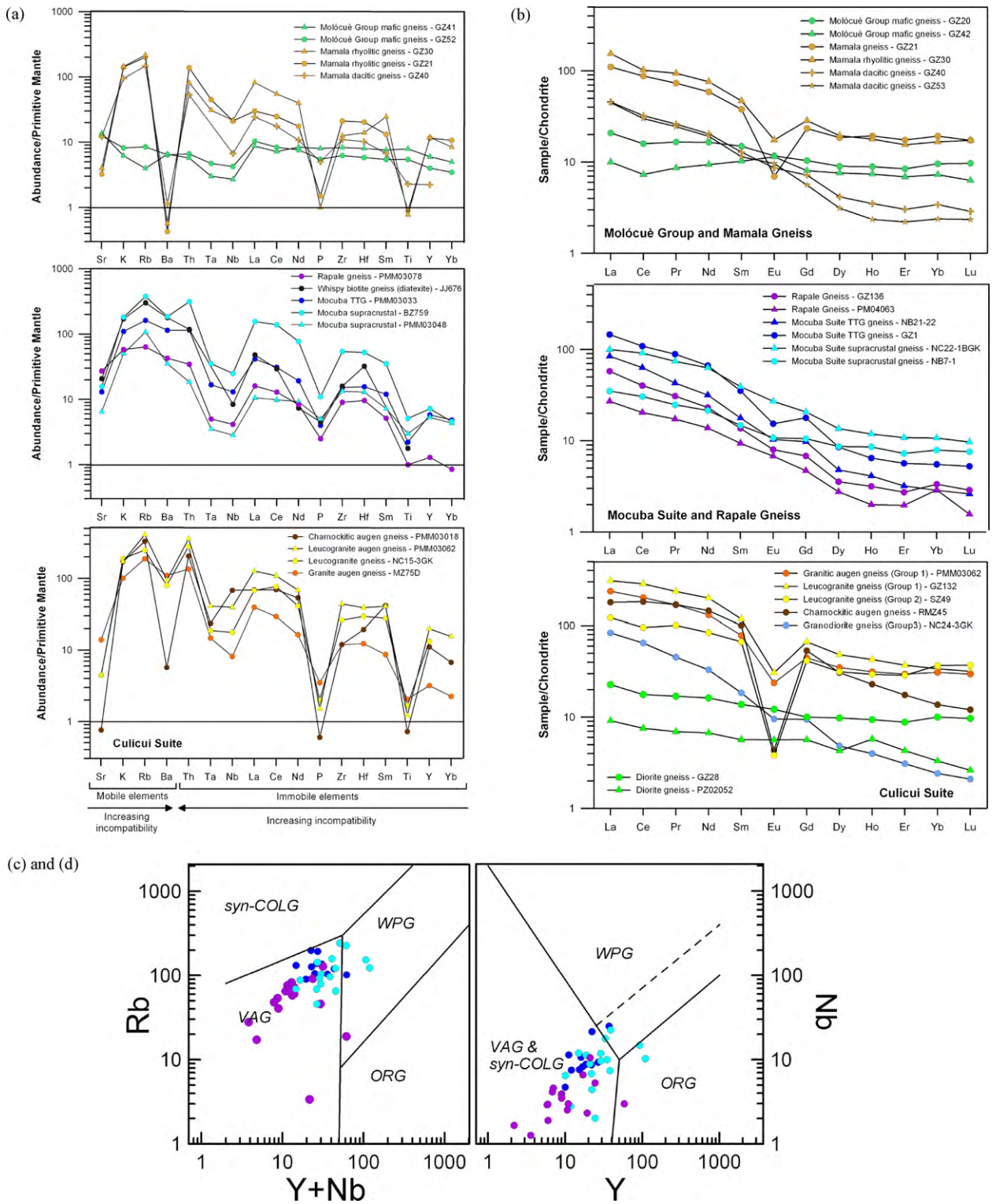

Fig. 11. (a) Primative mantle-normalised spidergrams of selected elements for the main lithodemic units (normalisation values after Sun and McDonough (1989)); (b) Chondrite-normalised REE plots for the main lithodemic units; (c and d) Rb versus Y + Nb and Nb versus Y plots, after Pearce et al. (1984). Granite types: Syn-COLG = syn-collision; VAG = volcanic arc; WPG = within plate and ORG = ocean ridge.

and orthopyroxene and diopside normative. The amphibolites display consistently near-flat normalized trace element patterns with slight to moderate negative Ta-Nb anomalies normally associated with arc-derived magmas. The REE patterns are similarly near-flat with abundances roughly 10 times chondrite values (Fig. 11b). The Molócuè Group mafic rocks define a tholeiitic trend on the AFM diagram (Fig. 10d) and, with low Zr/Y, Ti/Y, Nb/Y and moderate Ti/V ratios, plot in the MORB and plate-margin fields of geochemical tectonic discrimination diagrams (Pearce and Norry, 1979; Shervais, 1982; Meschede, 1986). The mixed arc and MORB signatures suggest the amphibolites and hence the remainder of the group developed in a back-arc setting (Taylor and Martinez, 2003).

5.4. Culicui Suite

Of the 82 samples of the Culicui Suite orthogneiss, only 8 classify as gabbro and syenodiorite. The majority (54 samples) have SiO_2 content above 70% classifying them mostly as granite, granodiorite, quartz monzonite and leucogranite on the modified normative O'Connor and TAS diagrams (Figs. 10a and 12a). The granitic orthogneisses generally yield elevated concentrations of K_2O, FeO and $\sum$REE, but low CaO, MgO and transition metals and are mostly very weakly peraluminous (ASI range: 0.91–1.11, mean: 1.02 ± 0.05, 3 outliers removed; Fig. 12b; Appendix 3). The primitive mantle normalized trace element diagrams show enrichment of LILE elements. Whilst having higher overall trace element abundances, they largely mimic the sawtooth patterns of the Mocuba-Rapale host rocks with negative Nb–Ta, P and Ti anomalies (Fig. 11a). The charnockite shows very similar patterns to the granitic gneisses, but commonly with enrichment in Nb and depletion in Sr and Ba.

The Culicui Suite granite gneisses display the most evolved chondrite-normalised REE patterns of all the Mesoproterozoic rocks (Fig. 11b). The REE patterns of the suite roughly correlate with the differentiation index with four main subgroups identified (Fig. 11b; Appendix 3). Most of the equigranular and megacrystic granite and leucogranite gneisses have high REE abundances, display moderate LREE enrichment and have moderate negative Eu anomalies (Group 1) but some the charnockites and samples of leucogneiss have extreme negative Eu anomalies (Group 2). The granodioritic gneisses generally have flatter REE patterns and limited negative Eu anomalies (Group 3), whereas the gabbroic-dioritic members of the suite display near-flat patterns without Eu anomalies (Appendix 3).

The Culicui Suite orthogneisses, in general, have a number of characteristics indicative of A-type granites. This includes high FeO^{tot}/MgO, Ga/Al, $\sum$REE, Y and Zr contents, and low CaO, MgO, Sr, Sc, V, Cr, Ni, Co concentrations (Loiselle and Wones, 1979; Whalen et al., 1987; Eby, 1990, 1992). In addition, most of the orthogneisses plot in A-type granite field of the SiO_2-FeO^{tot}/MgO, Zr-Ga/Al and Ga/Al-Zr + Ce + Nb + Y diagrams of Whalen et al. (1987) and Eby (1990) (Fig. 12c and d), and largely as within-plate granites on the Rb-Y + Nb and Nb-Y tectonic discrimination diagrams of Pearce et al. (1984) (Fig. 12e). The meta-granites are further classified as type-A2 on the Nb-Y-Ce plot of Eby (1992) and are characteristic of A-type granite melts derived from continental crust (Fig. 12d).

6. Structural history and metamorphism

In this section we summarise the structural history of the Nampula Block (following Macey et al., 2007; Norconsult Consortium, 2007). While this paper is focussed on the Mesoproterozoic evolution, outcrop pattern/distribution of lithological units, regional fabrics and metamorphic grade were largely imposed during the Neoproterozoic to Cambrian East African Orogeny, necessitating a description of these topics here.

The rocks of the Nampula Block exhibit structural fabrics formed as a result of at least three major ductile and semi-ductile deformation orogenic episodes during the Mesoproterozoic (D_1) orogeny and the late Neoproterozoic (D_2) to early Palaeozoic (D_3) Pan African Orogeny. Superposition of these three phases gives rise to a complex regional structural pattern (Fig. 13).

6.1. Mesoproterozoic Orogeny

D_1 deformation and high grade M_1 metamorphism was associated with significant amounts of partial melting and the development of metamorphic and migmatitic banding in Mocuba Suite rocks (Fig. 3a). It is largely the presence of these early migmatite textures and D_1 fabrics that serve to distinguish the Mocuba Suite from the younger gneisses in the field (Sacchi et al., 1984; Cadoppi et al., 1987; this study). The S_1 planar fabrics were largely transposed during the younger penetrative late Neoproterozoic D_2 orogeny and now represent disharmonic S_{1-2} composite gneissic fabrics, with primary structural evidence for the D_1 event limited to rare rootless, isoclinal, hook-fold interference structures, such that the vergence of D_1 structures cannot be ascertained. Since the Rapale Gneiss and the Molócuè Group appear to be unaffected, and thus post-date, the D_1 event, the age-data from these units presented above (ca. 1095–1090 Ma) must represent the minimum age for the D_1 orogeny. The maximum age of D_1 is constrained by the youngest age for the Mocuba Suite (Table 2). The single metamorphic zircon overgrowth from the Mocuba Suite sample with an age of ca. 1090 could possibly provide a direct age for the D_1 event, or formed as a result of thermal metamorphism related to the intrusion of the Rapale Gneiss or Culicui Suite. Evidence for an end-Mesoproterozoic event at ca. 1020 Ma is recorded in some samples (e.g. Costa et al., 1994; Bingen et al., 2009; Table 2). However, this event remains enigmatic in that it was not recorded in any of our samples, nor is any obvious structural or metamorphic evidence seen in the rocks.

6.2. Neoproterozoic to early Palaeozoic Orogeny

The principal regionally pervasive S_2 ductile foliation (gneissosity, local schistosity) that developed in all of the Nampula Block rock types (except the younger Murrupula Suite granites and pegmatites), formed during a progressive fold-and-thrust event involving phases of folding, coaxial refolding and coplanar thrusting (for a detailed structural model see Macey et al., 2007). The main outcrop-scale structural elements defining the penetrative S_2 planar fabric in the pre-D_2 rocks vary between rock types and include the alignment of platy and prismatic minerals, metre to tens of metre-scale, compositional and metamorphic layering, fabric-parallel stromatic migmatite layering, preferred orientation of flattened megacrysts and penetrative grain flattening fabrics. The earliest phases of the Murrupula Suite porphyritic granites (ca. 530 Ma) display alignment of tabular phenocrysts parallel to the regional S_2 gneissosity and most likely developed as the magma cooled in the waning regional D_2 stress field. Progressive refolding of the S_2 fabric is evident in outcrop as isoclinal F_2 fold hinges as well as large scale (tens of kilometres) regional F_2 fold structures evident on the geological maps (e.g. Figs. 4c and 13c and well seen on the aeromagnetic image of Fig. 1).

The S_2 foliations and F_2 fold axial planes trend mostly NE-SW (parallel to the Lúrio Belt) and dip at moderate angles (mean $43 \pm 23^\circ$, mode 30°, $n = 4056$; Macey et al., 2007; Aquater, 1983) to the north and NW across much of the northern and central Nampula Block but become progressively more complex and bimodal in nature toward the Mozambique coast with both north- to NW-dipping and south- to SE-dipping planar structures commonly recorded (data presented in Grantham et al., 2008). The fold axes of F_2 isoclinal folds and the long axis orientations of stretched prismatic minerals and feldspar augen define the generally west- to NW-plunging L_2 lineations in the gneissic rocks but towards the south the lineations show a bimodal variation plunging to the west and ESE. The D_2 fabrics appear to have developed during largely coaxial flattening strain, with rotational simple shear structures generally localised along discrete (D_3) shear zones. The eastern Lúrio Belt, the Namama Shear Zone and the basal mylonites of the Monapo and Mugeba klippen all represent major

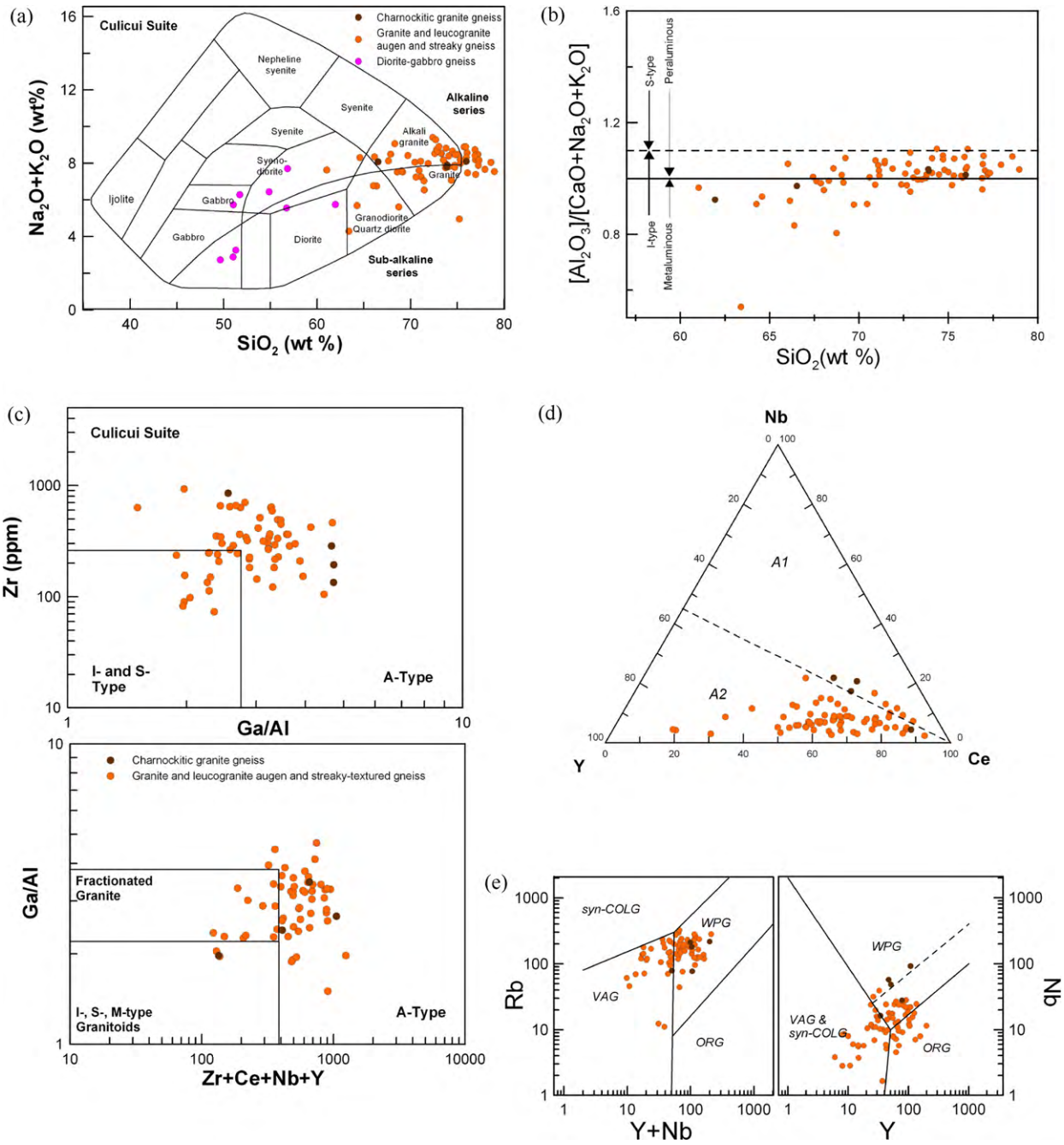

Fig. 12. Geochemical diagrams for the Culicui Suite. (a) versus alkalis (TAS), with fields after Cox et al. (1979); (b) A/CNK versus silca after Shand (1943); (c) Zr versus Ga/Al and Ga/Al versus Zr + Ce + Nb + Y plots after Eby (1992); (d) Y-Nb-Ce plot after Eby (1992); (e) Rb versus Y + Nb and Nb versus Y plots, after Pearce et al. (1984). For explanation of acronyms see Fig. 11.

shear structures (Fig. 13) adjacent to which the S_2 and L_2 fabrics are reoriented and along which the fabrics are completely transposed.

A lack of suitable samples has prevented direct dating of the S_2 foliation. However, a weakly deformed Murrupula Suite porphyritic quartz monzonite with twinned euhedral tabular K-feldspar phenocrysts aligned parallel to the regional S_2 foliation yielded a crystallization age of 533 ± 5 Ma, providing an age constraint on the waning D_2 stress field (Macey et al., 2007). The remaining undeformed samples of Murrupula Suite granites yield ages between 525 and 495 Ma indicating that the thermo-magmatic episode continued well into the Palaeozoic (Macey et al., 2007; Jacobs et al., 2008a).

In outcrop, the S_2 fabric is locally deformed by largely symmetrical, wavy, gentle to open F_3 folds and F_3 crenulations (e.g. in the Culicui Suite: Fig. 5c), both of which are commonly associated with cross-cutting spaced S_3 planar melt-filled structures. The S_3 foliations are non-penetrative, discrete sub-vertical planar structures with spacings of between 10 and 100 cm. The S_2 foliation is usually dragged into S_3 shears at the margins of such "flanking" structures (e.g. Passchier, 2001) and both sinistral and dextral shear senses have been recorded. Conjugate sets of shear bands are also common. The S_3 foliation planes are filled with thin diffuse sheets of undeformed, equigranular quartz-feldspar ± biotite ± magnetite granitic partial melt and, more rarely, equigranular granite dykes of the Murrupula Suite. The disjunctive S_3 cleavage and associ-

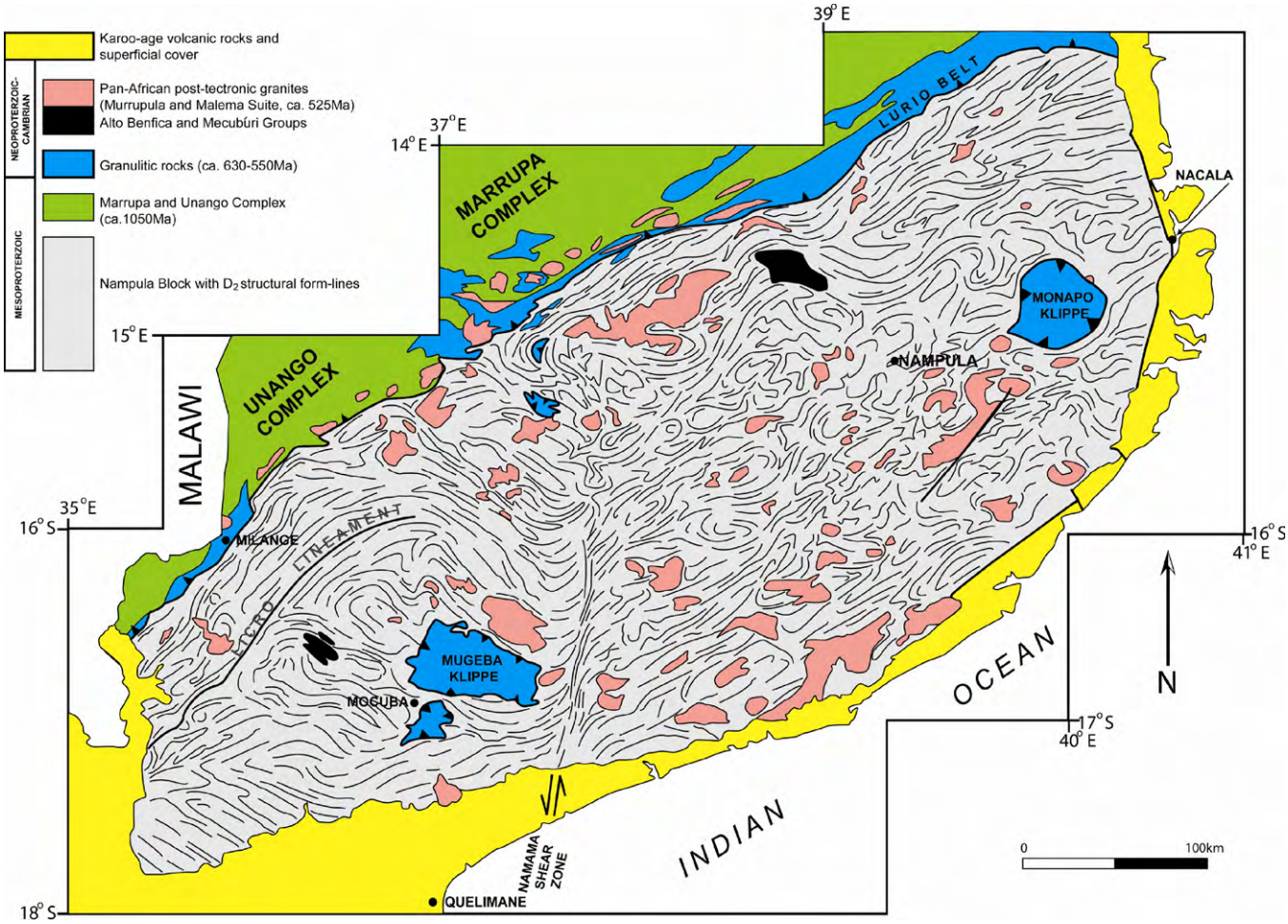

Fig. 13. Major structural trends in the Nampula Block.

ated flanking structures are best developed in the Culicui Suite granitic augen and streaky orthogneisses, but is observed in all pre-Murrupula Suite rocks.

The D_3 structures are possibly related to the event responsible for the development of the Namama Shear Zone (NSZ), a NNE-trending, east-vergent large-scale sinistral shear zone, which extends for over 100 km in a NW-facing open arc across the central parts of the Nampula Block (Fig. 13). The shear zone is approximately 20 km wide and is represented by a series of discrete sub-vertical mylonite zones along which the maximum strain was partitioned. The mylonitic bands are characterised by strong flaser and quartz-feldspar ribbon textures, recrystallisation and grain-size reduction. Locally, blastomylonites with mantled σ-type feldspar porphyroclasts (2–3 mm) are observed. Sacchi et al. (1984) and Cadoppi et al. (1987) argued that the Namama structure represents a thrust belt comprising a stack of approximately east-vergent thrust sheets. However, most of the associated (L_3) mineral stretching lineations within the shear zone plunge at a relatively low angle (mean $26^\circ \pm 17^\circ$, mode 20°) to the SE suggesting a dominantly sinistral transtensional shear sense with a relatively minor vertical component (Macey et al., 2007). The overall sinistral shear sense of the Namama shear zone is clearly evident on the form line map in the form of mega-scale drag fold structures (Fig. 13) and the simple rotation of these layers back into their pre-Namama unfolded positions suggests a displacement of at least 50 km. In addition, the shear is also responsible for the development of mega-scale Type 1 and 2 interference structures adjacent to the NSZ.

6.3. Metamorphism

The D_1 deformation in the Nampula Block was associated with high grade metamorphism as indicated by significant partial melting of the Mocuba Suite.

Peak metamorphism during the Pan-African orogeny was typically mid-upper amphibolite facies with characteristic prograde mineral assemblages represented by hornblende-plagioclase in mafic units and garnet-biotite-cordierite-staurolite and garnet-biotite-sillimanite-cordierite in pelitic gneisses (Cadoppi et al., 1987). In contrast to the D_1 event, D_2 was associated with more limited and localised partial melting. Orthopyroxene is rarely preserved as relict grains in magmatic charnockites (e.g. in the Culicui Suite) or as rare localised diffuse fluid-driven vein charnockitisation (e.g. in the Rapale Gneiss). The presence of metamorphic orthopyroxene and the absence of muscovite in the meta-pelites suggest that, at least locally, parts of the Nampula Block reached granulite facies during D_2.

Pressure constraints are difficult to constrain for the Nampula Block due to the absence of rock types with suitable mineral assemblages. The only reliable constraints are provided by sillimanite-bearing quartzo-feldspathic gneisses implying temperatures of at least ca. 700 °C and pressures lower than ca. 0.7–0.8 GPa (Grantham et al., 2008). Retrograde metamorphism is common with epidote, chlorite, biotite and muscovite as the most common replacement minerals. Metamorphic overgrowths on the zircon grains collected from the pre-D_2 rocks range between about 555 and 505 Ma (Section 4; Macey et al., 2007; Bingen et al., 2009).

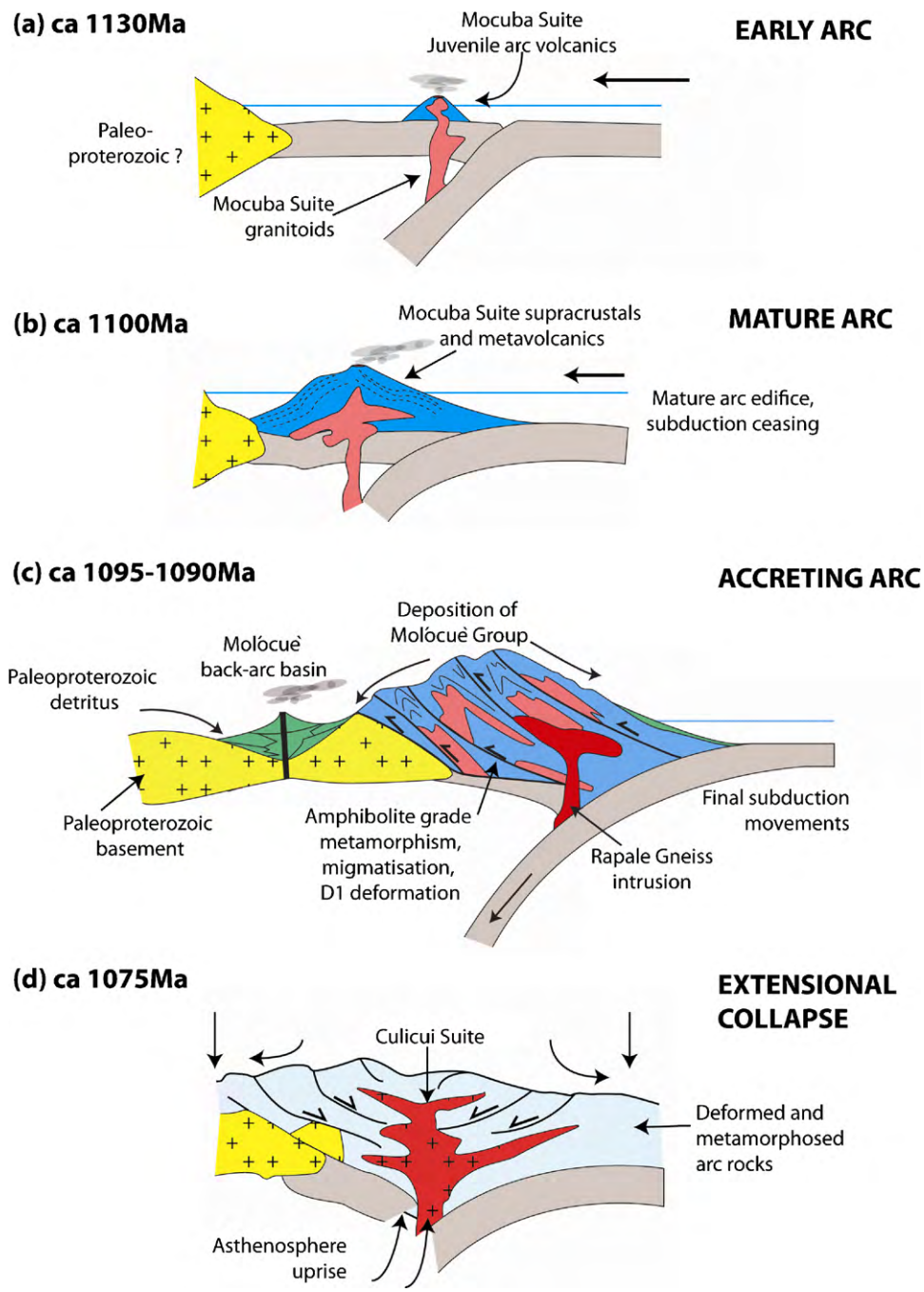

Fig. 14. Cartoons showing the evolution of the Nampula Block. (a) ca. 1130 Ma: Early juvenile arc initiated by subduction showing generation of extrusive and intrusive phases of the Mocuba Suite. (b) ca. 1100 Ma: Mature arc, possibly adjacent to a block of Palaeoproterozoic crust, in late stages of its development. (c) ca. 1095 to 1090 Ma: Mature arc is uplifted and accreted to Palaeoproterozoic continent with intrusion of Rapale Gneiss into the arc roots. D_1 deformation and main phase of the Mesoproterozoic orogenesis, with high-grade metamorphism, migmatisation. Clastic detritus from both arc and continent are shed into basin (back-arc?) repository of the Molócuè Group (sedimentary and volcanic rocks). (d) ca. 1075 Ma: Post-accretion uplift in extensional tectonic regime, emplacement of large bodies of Culicui Suite, A-type granitoid orthogneisses.

7. Summary of geological history of the Nampula Block

The Nampula Block is the largest Mesoproterozoic crustal Block in NE Mozambique, with a different lithodemic assemblage to those to the north of the Lúrio Belt, which forms its northern margin. Integrating the field, geochronological and geochemical data, a model for its evolution can be proposed by reference to Fig. 14.

ca. 1130 to 1100 Ma (Fig. 14a and b): The oldest rocks (Mocuba Suite) are a polydeformed sequence of upper amphibolite-facies layered grey gneisses and migmatites associated with intrusive TTG and granitic orthogneisses. A sample of banded gneiss, interpreted as a meta-volcanic rock, yielded a U-Pb SHRIMP zircon date of 1127 ± 9 Ma. Five of the six published crystallisation ages for the Mocuba Suite range between 1123 and 1108 Ma, with only one sample yielding an older age of 1148 Ma (Table 2). The geochemistry of these rocks suggests that they were generated in a juvenile, island-arc setting associated with ocean subduction. With time, the arc edifice would have grown and matured and its roots thoroughly invaded by plutonic granitoids (seen as the TTG and granitic orthogneisses).

ca. 1095 to 1090 Ma (Fig. 14c): The metamorphic rim on a Mocuba Suite zircon, dated at ca. 1090 Ma, probably grew during the emplacement of younger felsic TTG magmatic phase, represented by the tonalitic-trondhjemitic Rapale Gneiss, two samples of which were dated at 1095 ± 19 and 1091 ± 14 Ma respectively. The emplacement of the Rapale Gneiss was probably associated with the final phases of subduction and synchronous with the accretion of the mature arc onto Paleoproteroic continental crust. The earliest (D_1) deformation and associated amphibolite-grade metamorphism (M_1) and migmatisation of the Mocuba Suite, took place at approximately this time. The Mocuba Suite is interlayered with extensive belts of meta-pelitic/psammitic, calc-silicate and felsic to mafic meta-volcanic supracrustal gneisses termed the Molócuè Group. U-Pb data from detrital zircons from a quartzose calc-silicate paragneiss show a bimodal age distribution with peaks at ca. 1100 and 1800 Ma. The former shows derivation from rocks of the same age as the Mocuba Suite in the adjacent accreting arc. The older population suggest that the arc docked with Palaeoproterozoic crust. Both the Mocuba Suite arc and the older continental crust were uplifted and exposed at this time and contributed detritus to the Molócuè Group metasedimentary rocks, possibly in a back-arc setting. The supracrustal succession comprises both metasedimentary rocks (quartzites, calc-silicate rocks, marbles, meta-pelites and psammites) and metavolcanic rocks (leucogneisses and amphibolites). For the first time the age of the Molócuè Group has been directly determined by dates of 1092 ± 13 and 1090 ± 22 Ma, obtained from two samples of the leucocratic (metarhyolite?) Mamala Gneiss, one of its major constituent formations. It is uncertain whether the metamorphic fabrics seen in the Molócuè Group are at least partly Mesoproterozoic in age, imposed during the waning phases of D_1 accretion, or resulted wholly from the major Neoproterozoic to Cambrian Pan-African collision ($D_{2\text{-}3}$). Certainly, the Molócuè Group does not show the earliest phases of deformation and migmatisation (D_1) seen in the Mocuba Suite.

ca. 1075 Ma: Following arc-accretion, the final phase of Mesoproterozoic orogenic activity corresponds to voluminous plutons and sheet-like bodies of foliated megacrystic granite, charnockite, augen gneiss and granitic orthogneiss of the Culicui Suite (Fig. 14d). These have A-type granite geochemical characteristics, which we interpret as having been generated in a late tectonic, extensional setting. The three samples from the suite presented in this study gave statistically identical ages of ca. 1075 Ma, but previous published ages suggest the suite may range in age from 1040 to 1085 Ma (Table 2).

The Nampula Block was extensively re-worked during the major ($D_{2\text{-}3}$) Pan-African collision in Late Neoproterozoic to Cambrian times, when the major regional fabrics were imposed upon the Mesoproterozoic rocks under amphibolite-facies metamorphic conditions. In the samples dated in this study, this major orogenic event is represented by metamorphic zircon rim ages of ca. 550 to 500 Ma.

8. Regional implications

The Nampula Block probably made up the NE part of a major Mesoproterozoic mobile belt which was accreted to the old cratonic nucleus of the Kalahari craton (combined Archaean Kaapvaal-Zimbabwe-Grunehogna cratons and various Palaeoproterozoic blocks). This mobile belt, fragmented by Gondwana break-up, consisted of (from west to east) the Namaqua-Natal belt (South Africa), the Falkland microplate, the Haag Nunatak block (West Antarctica) and the Maudheim belt of East Antarctica (Bauer et al., 2003; Jacobs et al., 2008b). The belt, with a restored length of over 3000 km is possibly a major part of a worldwide system of "Grenvillian" orogens associated with the amalgamation of the supercontinent of Rodinia (e.g. Li et al., 2007). The eastern parts of the belt were pervasively re-worked during the Neoproterozoic-Cambrian Pan-African orogeny associated with assembly of Gondwana, whereas the western parts (west of Heimefrontfjella) were not. Despite this overprint, the belt shows a remarkable continuity of geological evolution. This evolution can be outlined in terms of snapshots of Kalahari Craton paleogeography at the time of arc initiation at ca. 1300 to 1130 Ma (Fig. 15a) and during the time of post-collisional extension between ca. 1080 and 1050 Ma (Fig. 15b).

8.1. Early arc development and accretion

Apart from the western Namaqua belt in western South Africa, where complex accretion of Precambrian blocks of various ages took place, the earliest rocks are arc-related coeval volcanic-plutonic sequences. These are diachronous from west to east, with older arcs forming between 1300 and 1200 Ma in the Areachap and Mzumbe terranes of eastern Namaqualand and Natal respectively (Fig. 15a). East of Natal, arc development was younger, at around 1130 Ma and arc-related volcanic and plutonic rocks (including the Mocuba Suite of the Nampula Block) are recorded from West Falkland, the Haag Nunatack block of West Antarctica (Rb-Sr isochron of ca. 1150 Ma on granodioritic orthogneisses in Millar and Pankhurst, 1987 not shown in Fig. 15a), Dronning Maud Land (East Antarctica) and north to western Mozambique (Manhica area) and the Nampula Block.

Accretion and medium- to high-grade metamorphism of these arcs took place during the main Mesoproterozoic orogenic phase as recorded by metamorphic zircon overgrowths in the period ca. 1090 to 1070 Ma (e.g. Bingen et al., 2009).

8.2. Late orogenic extension and emplacement of A-type granitoids

In all areas along the belt, the last phases of major Mesoproterozoic magmatic activity are represented by voluminous bodies of porphyritic A-type granite and minor charnockite similar to the Culicui Suite in the study area. These rocks are often associated with late ductile shear zones and have been linked to a period of late-orogenic extension within the belt (Thomas et al., 1993; Grantham et al., 2001; Eglington et al., 2003). A considerable spread of U-Pb zircon ages have been recorded from these rocks, ranging from ca. 1100 to 1030 Ma. It is not always certain if this spread represents a real age variation or is related to the complex U-Pb zircon systematics of these rocks which has been identified in a number of studies on the suite, most notably the Oribi Gorge Suite of Natal (see discussion in Eglington et al., 2003). From the distribution of age data of these rocks, all of which have associated uncertainties of at least 20 Ma, shown on Fig. 15b, it is clear that no obvious age trend is apparent for emplacement of these rocks; all but a few dates from the quoted references fall within the range 1060 ± 30 Ma.

8.3. From Kalahari to Gondwana: other palaeogeographic constraints

As noted, the eastern part of the Mesoproterozoic mobile belt, including the Nampula Block was pervasively re-worked during the Late Neoproterozoic orogeny, which was responsible for the final juxtaposition of the collage of terranes now seen. In NE Mozambique today, the Nampula Block is in tectonic contact along its northern margin by the ENE-WSW-trending Lúrio belt. The main movements along this historically controversial structure are certainly Neoproterozoic-Cambrian (e.g. Viola et al., 2009; Engvik et al., 2007), but the distribution of the Mesoproterozoic blocks before their juxtaposition is speculative. New geochronology on the rocks

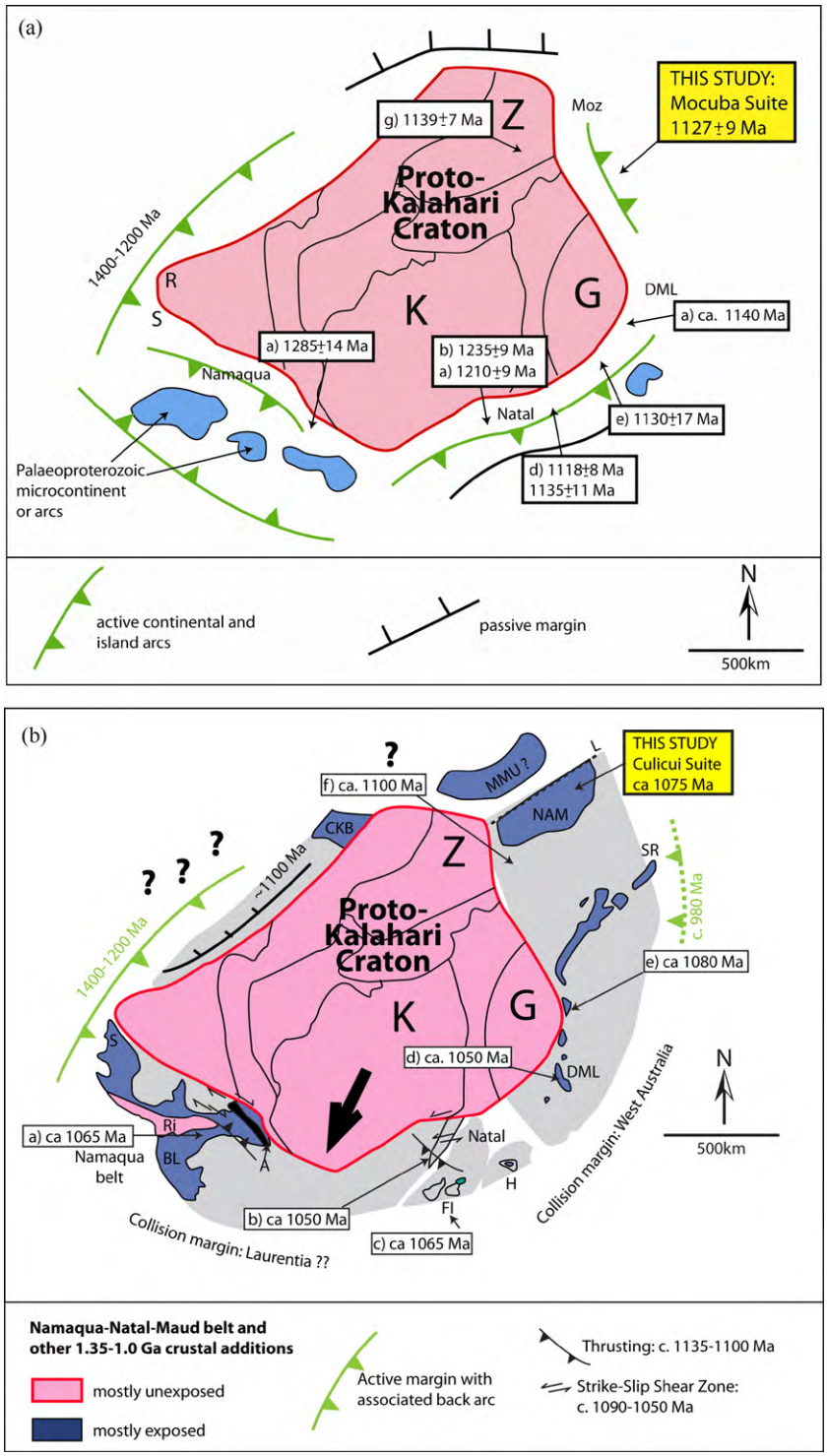

Fig. 15. Growth of the Kalahari Craton modified after Jacobs et al. (2008b). (a) Mesoproterozoic subduction around the Kalahari craton at ca. 1200 to 1100 Ma: showing U-Pb zircon ages of the oldest, juvenile arc-related rocks. Arc-formation commenced in the west with the initiation of the Namaqua-Natal belt at between 1300 and 1200 Ma. To the NE the arcs formed at ca. 1120 Ma. Abbreviations: G, Grunehogna Craton; DML, Dronning Maud Land; K, Kaapvaal Craton; Moz, northern Mozambique; R, Rehoboth Belt; S, Sinclair Belt; Z, Zimbabwe Craton.
(a) Smouspan gneiss (E. Namaqualand): Cornell et al. (1992); (b) Quha gneiss (Natal): Thomas et al. (1999); (c) Mzumbe Suite (Natal): Thomas and Eglington (1989); (d) Big Cape Formation (W. Falkland): Jacobs et al. (1999a); (e) Vikenegga Suite (Heimefrontfjella): Jacobs et al. (1999b); (f) Kvervelknatten gneiss (Kirwanveggan): Jackson (1999); (g) Chimoio gneiss (W. Mozambique): Manhica et al. (2001).
(b) Mesoproterozoic post-accretion, late-orogenic extension and A-type granitoid magmatism around the Kalahari craton at ca. 1050 Ma: showing U-Pb zircon ages of the late tectonic porphyritic A-type granitoids. Abbreviations: A, Areachap terrane; BL, Bushmanland Terrane; CKB, Choma-Kaloma Block; FI, Falkland Islands; DML, Dronning Maud Land; G, Grunehogna Craton; H, Haag Nunatak; K, Kaapvaal Craton; L, Lurio Belt; MMU, Murrupa–Malawi–Unango terrane; NAM, Nampula Block; S, Sinclair; SR, Sør Rondane; Ri, Richtersveld; (a) Spektakel Suite (Namaqualand): e.g. Thomas et al. (1996); (b) Oribi Gorge Suite (Natal): Thomas et al. (1993), Eglington et al (2003); (c) G2 granites (W. Falkland): Jacobs et al. (1999a); (d) Manesigden granite (Heimefrontfjella): Jacobs et al. (1999b); (e) Kirwanveggan orthgneiss (Kirwanveggan): Jackson (1999); (f) Nhansipfe orthogneiss (W. Mozambique): Manhica et al. (2001).

of the Unango and Marrupa Complexes which are in contact with the Nampula Block along the Lúrio belt show that they are younger than the Nampula Block (Bingen et al., 2009). The oldest dates from these two complexes are about 1060 Ma, younger than the late-tectonic Culicui Suite of the Nampula Block, showing that these terranes may not have even been formed at that time. The detrital evidence from the Molócuè Group indicates local (Mocuba Suite arc) and Palaeoproterozic provenance. This implies that the Nampula Block arc was originally accreted to a Palaeoproterozic crustal block and only reached its current position, against the Unango and Marrupa Complexes, during Neoproterozoic collision and plate movements. Hence the location of original formation of the Unango and Marrupa terranes (and hence their relationships to the Kalahari craton) remains unknown and worthy of further investigation.

Acknowledgements

This work has been carried out as part of the Mineral Resources Management Capacity Building Project of the Ministry of Mineral Resources of Mozambique and funded by the South African Government, Nordic Development Fund and the World Bank. The mapping and research was implemented by teams from the Council for Geoscience (South Africa), Geological Survey of Norway, the British Geological Survey and the National Directorate of Geology of Mozambique. The paper is being published with the permission of the National Directorate for Geology, Maputo and the Executive Directors of the CGS and BGS-NERC. Dr Siegfried Laechelt is thanked for many useful discussions in the field. We thank John Carney (internal BGS), Richard Hanson and Kevin Burke for their valuable and insightful reviews of earlier versions of the manuscript.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.precamres.2010.07.005.

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