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THE KAROO VOLCANIC ROCKS AND RELATED INTRUSIONS IN SOUTHERN AND CENTRAL MOZAMBIQUE

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Volcanic rocks and related hypabyssal intrusions of the Mesozoic Karoo large igneous province are wide-spread in southern and central Mozambique and form mesa-like ridges or wide, fertile valleys, depending on the nature and composition of the volcanic flows. The 600 km long, north-south oriented Lebombo mountain range along the border of Mozambique and South Africa is mostly composed of a bimodal association of rhyolitic ash-flow tuffs and ignimbrites and basaltic to andesitic lava flows, while the north-east trending 250 km long Nuanetsi-Sabi volcanic flexure north of the Limpopo river comprises mainly basaltic lava flows with only a few rhyolitic interbeds. Farther to the north, around the Lupata trough, the area covered by the Karoo volcanic rocks is rather limited, whereas in the Tete Province basaltic lavas and more felsic varieties form prominent flat-top mountains and a large dome structure. Mafic and felsic hypabyssal rocks of the Rukore and Gorongosa bimodal intrusive suites form prominent mountains and dyke swarms in central Mozambique. Geochemically, the volcanic rocks are predominantly subalkaline. The mafic lavas associated with the Lebombo monocline and the Nuanetsi-Sabi volcanic flexure are tholeiitic and quite similar to the low-Ti and high-Ti lavas of the Sabie River Formation in South Africa. The mafic lavas from the Lupata trough and in the Tete Province have low-Ti characteristics, but they also include rocks with mildly alkaline affinities. The felsic rocks are subalkaline, peraluminous, and high-K type volcanic rocks with high Fe/Mg ratio and Zr, Nb, Ce, and Y values typical of A-type magmas. The felsic rocks of the Umbelúzi Formation are mainly dacites, whereas the stratigraphically younger felsic rocks of the Movene Formation and the felsic rocks in central Mozambique are mainly rhyolitic. The alkaline volcanic and intrusive rocks in the Pessene area, south Mozambique, may represent the youngest phase of Karoo magmatism in the Lebombo monocline.

Key words (GeoRef Thesaurus AGI): volcanic rocks, rhyolites, basalts, intrusions, geochemistry, Gondwana, Mesozoic, Mozambique.

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INTRODUCTION

The Mesozoic Karoo large igneous province is one of three continental flood-basalt provinces that are associated with voluminous, possibly plume-related magmatism at ~183 Ma and subsequent break-up of the Gondwana supercontinent during the Early-Middle Jurassic period. Volcanic and intrusive rocks belonging to the Karoo province are wide-spread in southern Africa, but they are also found in western Dronning Maud Land, Antarctica (Fig. 1).

The Karoo volcanic rocks, which generally overlie various sedimentary formations of the Karoo Supergroup, consists mainly of tholeiitic to picritic lava flows, felsic pyroclastic rocks, and related dyke swarms and sills, emplaced prior to the break-up of Gondwana and the opening of Indian Ocean (e.g. Cox 1983). The remnants of mafic lava flow fields are confined to seven principal areas: Lesotho, southern Botswana, northern Botswana, Lebombo-Tuli-Nuanetsi-Sabi (the Limpopo triple junction; Burke & Dewey 1973), and Lupata in southern Africa, and Vestfjella and Kirwanveggen in western Dronning Maud Land in Antarctica (Fig. 1).

The Karoo-related volcanic rocks have been extensively studied in South Africa, Botswana, and Antarctica over the last decades in terms of stratigraphy (e.g., Cleverly *et al.* 1984), geochemistry (e.g. Cox *et al.* 1967, Betton 1979, Harris & Erlank 1992, Klausen *et al.* 2003, Jourdan *et al.* 2007a), geochronology (e.g., Allsopp *et al.*1984, Duncan *et al.* 1997, Zhang *et al.* 2003, Riley & Knight 2001, Riley *et al.* 2004, Jourdan *et al.* 2007b), and petrogenesis (e.g., Erlank 1984, Sweeney *et al.* 1994, Luttinen & Furnes 2000, Miller & Harris 2007). The results indicate predominance of compositionally relatively uniform mafic lavas in Lesotho, Botswana, and Kirwanveggen, and markedly heterogeneous lavas in Lebombo, Tuli-Nuanetsi-Sabi, and Vestfjella. Recent geochronological studies indicate emplacement of Karoo-related magmas during a relatively short period from ~185 Ma to ~172 Ma and a distinctive peak of wide-spread magmatic activity at ~182±3 Ma (e.g., Jourdan *et al.* 2007b). The reliably dated samples cover the outcrop areas

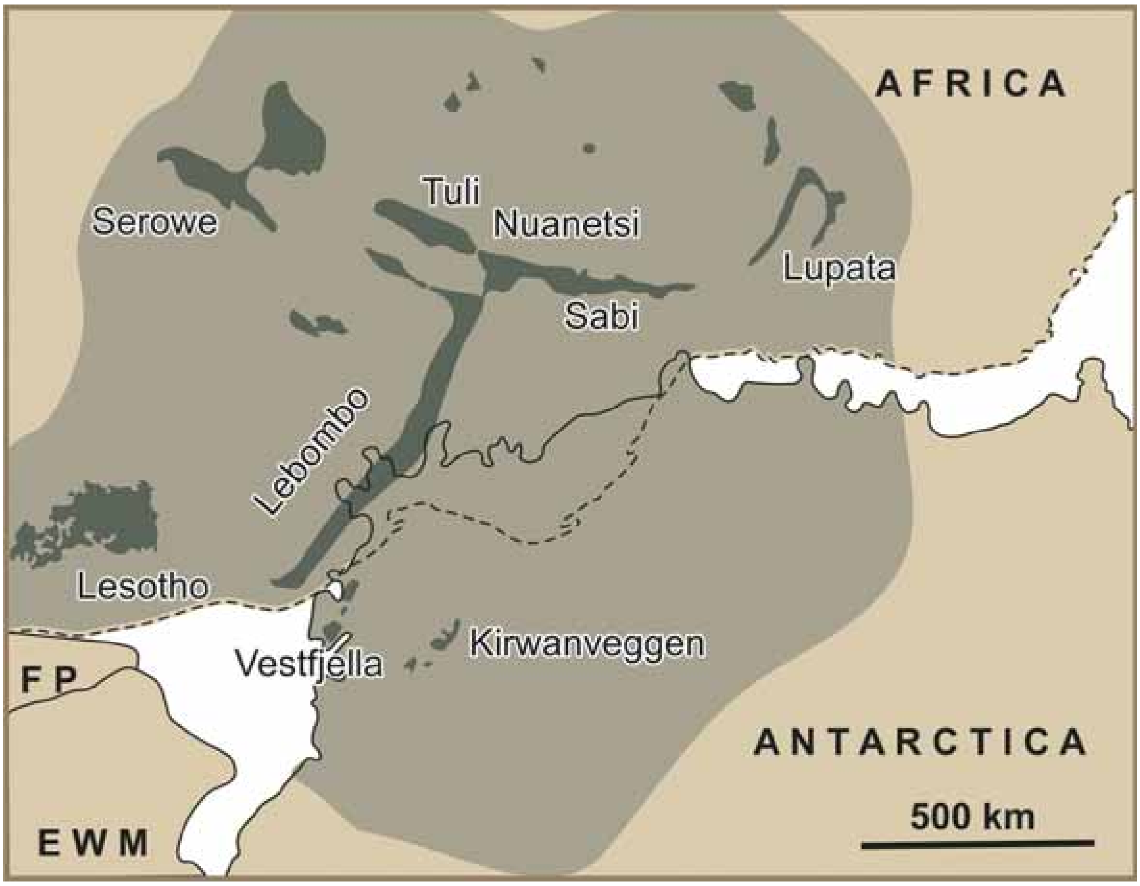

Fig. 1. Distribution of volcanic rocks and major dyke swarms (shaded area) in the African and Antarctic parts of the Karoo large igneous province (dark brown). FP – Falkland Plateau, EWM – Ellesworth Whitmore Mountains. Modified after Lavwer *et al.* 1992.

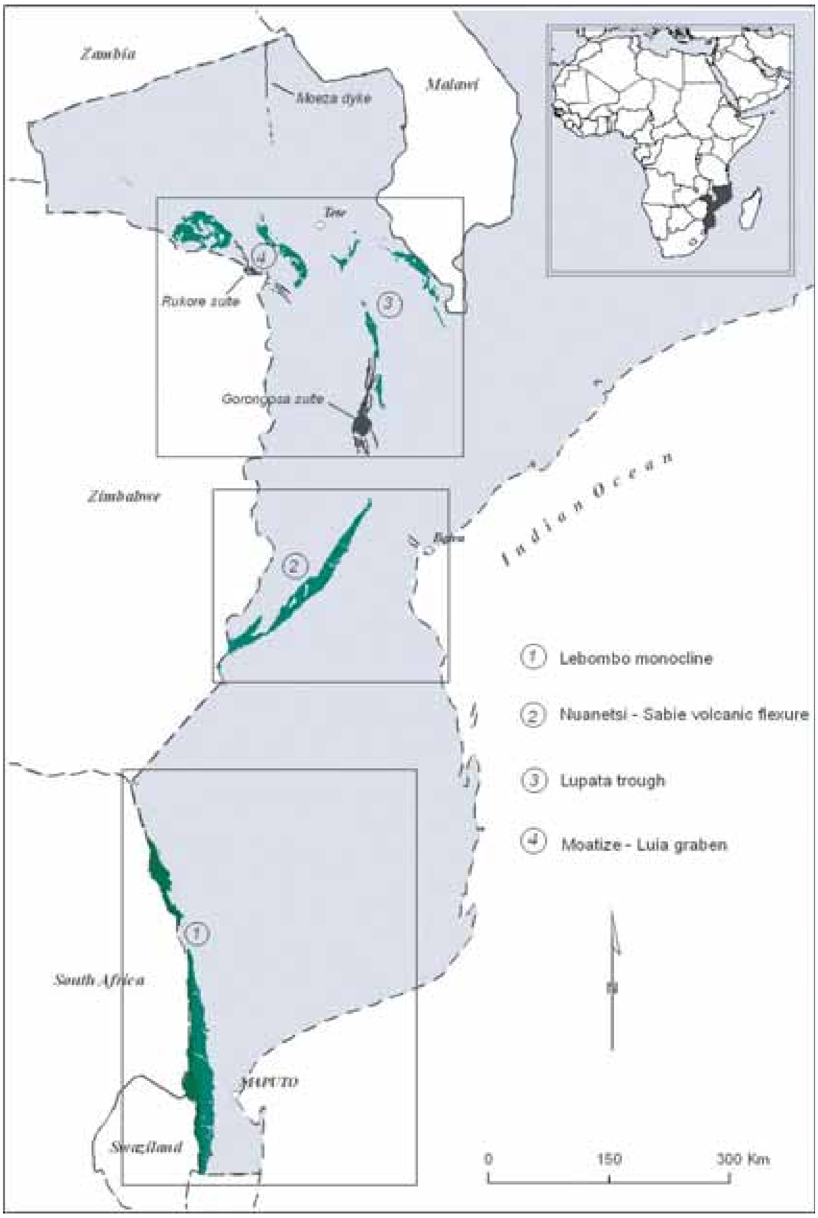

Fig. 2. Location of Karoo volcanic rocks (green) and intrusive suites (black) in southern and central Mozambique. Outlined areas refer to more detailed maps in the text from south to north: Figs 4, 15, 17, respectively.

in South Africa and Botswana in some detail and, together with paleomagnetic constraints (Hargraves *et al.* 1997), indicate coeval emplacement of lavas across the province.

Karoo-related volcanic and intrusive rocks are also found in southern and central Mozambique (Fig. 2). In southern Mozambique, mafic and felsic extrusive rocks are associated with and represent the capping stratigraphic units of the seaward-dipping volcanic succession of the Lebombo Monocline. Further to the north, Karoo-related volcanic rocks are also found within a narrow belt close to the South African and Zimbabwean border. The Nuanetsi-Sabi volcanic flexure is an extension of the Lebombo Monocline and represents one of the rift arms of the Limpopo triple junction structure (Fig. 1). In central Mozambique, Karoo-related successions are found in the Lupata trough and the Moatize-Luia graben.

The Karoo volcanic rocks in Mozambique have been studied mostly by Portuguese geologists during colonial times (e.g., Freitas 1937, Rennie 1937, Assunção *et al.* 1962, Mendes 1965, Pinto & Godinho 1975). These were mostly regional reconnaissance investigations, concentrated on petrography, geochemistry, and economic aspects. The research was interrupted by the independence and civil war. Subsequently, Hunting Geology and Geophysics Ltd. (1984) made a reference to the Lebombo Belt, but mapping was not executed for security reasons.

Pinna *et al.* (1987) published a geological map and established a stratigraphy, and Muchangos (2000, 2006) studied the bentonite and bauxite deposits related to Lebombo felsic volcanic rocks. Recently chemistry of Karoo-age andesitic lavas has briefly been considered by Grantham *et al.* (2004, 2006) and bimodal magmatism by Melluso *et al.* (2006).

During 2002–2007, the Mineral Resource Management Capacity Building Project was implemented under the National Directorate of Geology of the Republic of Mozambique. The main task of the project, conducted by GTK Consortium (hereafter referred to as Consortium), was to re-map, upgrade and improve existing geological maps, in order to create a comprehensive and uniform coverage of geological maps at various scales. During this work, the stratigraphy and nomenclature of the Karoo volcanic rocks were reconsidered, and the geochemical and textural features of these rocks were studied (see GTK Consortium 2006a-c).

This paper is based on the results of geological mapping of the Karoo volcanic rocks and related hypabyssal intrusions in southern and central Mozambique (GTK Consortium 2006a-c). We describe the various volcanic units and their general stratigraphic and geochemical characteristics with emphasis on the physical features of these rocks.

LEBOMBO MONOCLINE

Introduction

The Lebombo Monocline is a 600 km long and 5–30 km wide linear flexure along the boundary between South Africa and Mozambique. Its location is most likely controlled by the sudden transition from normal lithospheric upper mantle to thick Archaean lithospheric upper mantle of the Kalahari Craton or, alternatively, between normal and stretched continental crust. An E-W section over the central part of the flexure reveals flat-lying Karoo sediments resting unconformably on crystalline basement, overlain by a deeply weathered sequence of volcanic rocks dipping to the east. Farther east, the dip of the volcanic rocks increases to a maximum of 45° to 65° east, indicating that the Lebombo Monocline was actively flexing down during the emplacement of the lava flows.

In the Lebombo monocline, mafic and felsic volcanism occurred in pulses, and rhyolites forming the “Great” (Grandes) and “Little” (Pequenos) Lebombo mountains are interlayered with Movene basalts (Figs 3–4). As basalts are poorly exposed due to intense weathering and soil formation, they generally form plain savannas (Fig. 3a). The most exposed rocks are rhyolites that form *cuesta*-type geomorphology, slightly tilted to east (Fig. 3b). Hence, the regional geomorphology is characterised by alternation of cuestas and plane valleys.

Based on a W-E section through the Swaziland sector of the flexure, the following major lithological units can be distinguished (from W to E and from bottom to top):

Fig. 3. a) Typical geomorphology of Lebombo monocline associated basalt plain savannas in Mozambique. b) Rhyolites of the Pequenos Libombos Mountain, slightly tilted cuestas ~40 km SW of the city of Maputo.

Fig. 4. Volcanic formations of the Lebombo Monocline in southern Mozambique. The codes refer to the stratigraphic units described in the text and used in map explanations of the GTK Consortium 2006a, b and c. Basalts (JrLb, JrSba, JrM and JrUb), dacites and rhyolites (JrU) and microgranite (JrUg).

- Karoo Sediments
- Sabie River Basalt Formation
- Jozini Rhyolite Formation (in South Africa)
- Mbuluzi Rhyolite Formation (with basal Oribi beds)
- Movene Basalt Formation (with Sica beds in upper part)
- Pessene alkaline rocks
- Cretaceous and younger cover rocks

There is evidence that the Karoo volcanic rocks continue eastwards beneath the Cretaceous and younger cover at least as far as the coast (Flores 1970, 1973, Darracott & Kleywegt 1974) and probably even farther off-shore. The thickness of the buried lavas beneath the cover sediments has been estimated at 6 to 13 km (Eales *et al.* 1984).

Further northwards, near Pafuri, the Sabie Basalt Formation is underlain (from bottom to top) by:

- Mashikiri Nephelinite Formation
- Letaba Basalt Formation.

Small bodies, sills and dykes of granophyres, rhyolite, dolerite and basalt have invaded the above volcanic strata (e.g., Balule and Rooi Rand Dyke Swarms). All of the above lithological units found in South Africa and Mozambique are summarized in Table 1. It is important to note that in Mozambique, the petrographically distinctive rhyolitic rocks of the Jozini and Mbuluzi Formations (e.g.

Cox & Bristow 1984) are collectively designated as the Umbelúzi Formation (Table 1).

The results of $^{40}Ar/^{39}Ar$ dating of Sabie River basalts range from181.2±1.0 to 184.2±1.0 Ma and are indistinguishable from those of the underlying lava sequences of the Lebombo monocline (Duncan *et al.* 1997). Rhyolite intercalations in the upper part of the formation (Olifants River Beds) have yielded similar SHRIMP ages of 182.0±2.1 and 179.9±1.8 Ma (Riley *et al.* 2004) (Table 1). Rapid emplacement of the Lebombo succession is further demonstrated by SHRIMP zircon dating and $^{40}Ar/^{39}Ar$ dating of rhyolites belonging to the Jozini Formation, which yielded eruption ages of 182.1±2.9 Ma (Riley *et al.*

Table 1. Lithostrathigraphic subdivision of volcanic rocks of the Lebombo Monocline. Only the coloured units are present in Mozambique (Duncan *et al.* 1997, Riley *et al.* 2004). Ages (Ma) refer to the rocks in South Africa.

LEBOMBO MONOCLINE					
South Africa and Swaziland			Mozambique		Code
Formation	Beds	(Age)	Cretaceous and younger cover		
			Pessene	Alkaline lava	JrPal
Movene Basalt			Movene	Basalt	JrM
				Rhyolite breccia	JrMbr
				Pequenos Libombos rhyolite	JrMr
				Fine-grained rhyolite	JrMfr
				Quartz latite	JrMq
Mbuluzi Rhyolite			Umbelúzi		JrU
				Microgranite	JrUg
				Rhyolite with agglomerate layers	JrUa
				Rhyolite	
				Tuff, locally siltstone	JrUt
Jozini Rhyolite		(178.1±0.6) (182.1±2.9) (179.7±0.7)		Dacite and trachydacite	JrUf
				Basalt and massive dolerite	JrUb
Sabie River Basalt (181.2±1.0) (184.2±1.0)	Twin Ridge		Sabie River	Basalt	JrSba
	Mkutshane	(182.0±2.1)			
	Olifants	(179.9±1.8)			
Letaba Basalt		(182.7±0.8)	Letaba-Pafuri Basalt		JrLb
Mashikiri Nephelinite		(182.1±1.6)			
Karoo Sediments					
Basement (Kalahari Craton)					

2004) and 178.9 ± 0.5 Ma (Duncan *et al.* 1997), respectively. The overlying lavas that make up the Mbuluzi rhyolites and the bimodal Movene Basalt Formation have not been reliably dated. A controversial age of 1750±33 Ma was determined for eight zircons separated from a nepheline syenite intrusion within the Movene Basalt Formation; the zircons are probably inherited from a Late-Archean to Early Proterozoic magmatic or sedimentary sources.

Letaba-Pafúri Formation

Random outcrops of basaltic rocks occur in the Limpopo river valley near the village of Pafuri, in the westernmost part of the Gaza Province. Assigned as the Letaba-Pafuri formation they are regarded comparable with the Letaba Formation basalts (*JrLb*), which are exposed on South African side of the border.

Sabie River Formation

Basalts (JrSba)

Basalts of the Sabie River Formation comprise the lowermost lithological unit of the Lebombo monocline in Mozambique. Although forming a pile of basaltic lavas of several kilometres in thickness in South Africa (Cleverly & Bristow 1979), only a narrow sliver of these fine-grained, low-MgO basalts are exposed north of the Singuédzi River on the Mozambican side of the border. At this location, the Sabie River basalts occur in weathered outcrops as massive rocks, lacking amygdules or other features typical to lava flows. Most probably, these outcrops represent massive, medium- to coarse-grained flow cores, with the amygdaloidal flow top being mostly covered. Thin basalt lava flows, which may belong to the Sabie River Formation, also exist east of Ressano Garcia, where contacts between basaltic and rhyolitic lavas can be followed over several tens of metres. Zeolite-filled pipe vesicles at the base of basaltic lava flows attest to the extrusive character of the rock.

Rhyolites

Along the South African border the Sabie River basalts have rhyolitic interbeds, which form low ridges, generally 10–20 m in width, within the poorly exposed basaltic terrain. Some of these ridges comprise pinkish brown, fine-grained, highly vesicular rhyolite lava with occasional flow-banding, clearly indicating an extrusive mode of emplacement. Other ridges with medium- to coarse-grained, massive rhyolites with spheroidal weathering and feldspar phenocrysts may represent subvolcanic dykes or sills. Together, they probably correspond to the lenticular rhyolite units described within the Sabie River basalts more southwards as Twin Ridge, Mkutshane and Olifants Beds (Cox & Bristow 1984).

Umbelúzi Formation

Introduction

A smoothly E-dipping succession of dacitic and rhyolitic rocks assigned to the Umbelúzi Formation overlie basalts of the Sabie River Formation, comprising high-grade ignimbrites, pyroclastic ash-fall deposits, and random lava interflows. Covering most of the rugged Lebombo mountains in south-western Mozambique, it forms a 425 km long and 3–23 km wide belt along the South African - Mozambican border. Northwest of the town of Massingir, the narrow belt broadens into a complicated volcanic structure, reminiscent of an "isoclinal fold", that is over 20 km wide and 100 km long. In Swaziland the thickness of individual flows of this well-studied rhyolite sequence, divided there into Jozini Formation (lower) and Mbuluzi Formation (upper), ranges from 80 to 350 m, some flows being traceable along strike up to 50 km (Eales *et al.* 1984). Based on the observed volcanic features Cleverly & Bristow (1979) suggested an ash-flow to ignimbritic origin for rhyolites of the Jozini Formation.

Dacites and rhyolites (JrU)

Dacitic rocks form several kilometres long, narrow (< 200 m wide) horizons within the rhyolite-dominated rocks of the Umbelúzi Formation, particularly in the middle part of the Lebombo monocline. Dacites differ from pinkish rhyolites by their dark grey to dark violet brown colour. Texturally they are also more massive than typical rhyolites, which often exhibit flow banding. Locally dacites comprise quartz-filled amygdules, implying lava origin for the rock. The main mineral assemblage of dacites includes plagioclase, quartz, clinopyroxene and opaque; feldspar may form phenocrysts of 1 mm in size.

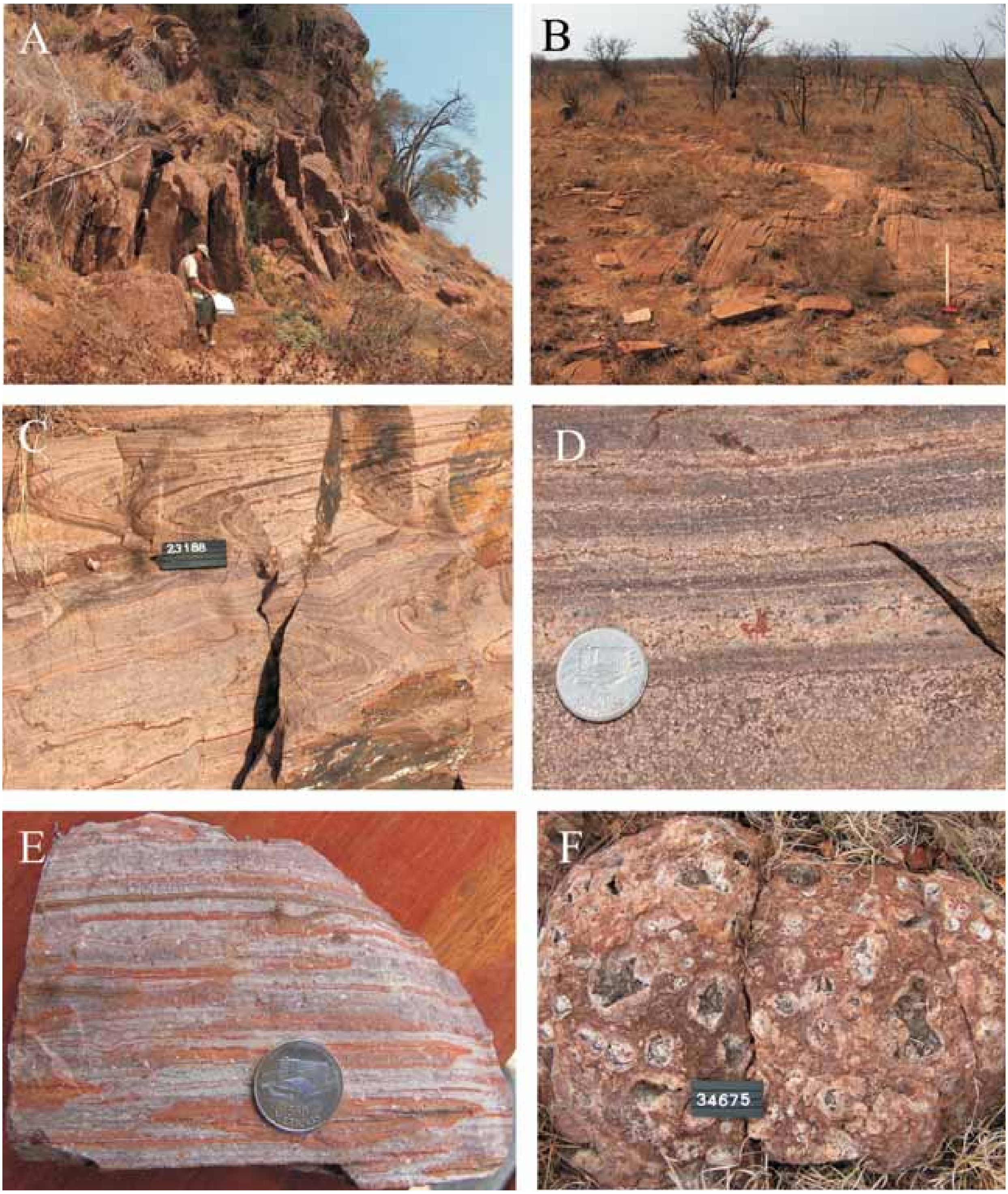

Fig. 5. a) Ramp structure with subvertical shrinkage joints in massive rhyolite flow ~25 km west of the Massingir town. b) Parallel cooling joints in rhyolite of the Umbelúzi Formation. NW of the Massingir dam (0317013/7380421). c) Folded flow bands in rhyolite. Road cut NEE of Namaacha (0412929/7128745). d) Detailed photo of the flow bands. e) Eutaxitic texture in densely welded ash-flow tuff of the Umbelúzi Formation. f) Roundish lithophysae (”thunder eggs”) in a rhyolitic flow. NE of Namaacha (0408713/71415679). Hammer length 65 cm, scale bar 10 cm, coin diameter 2.5 cm.

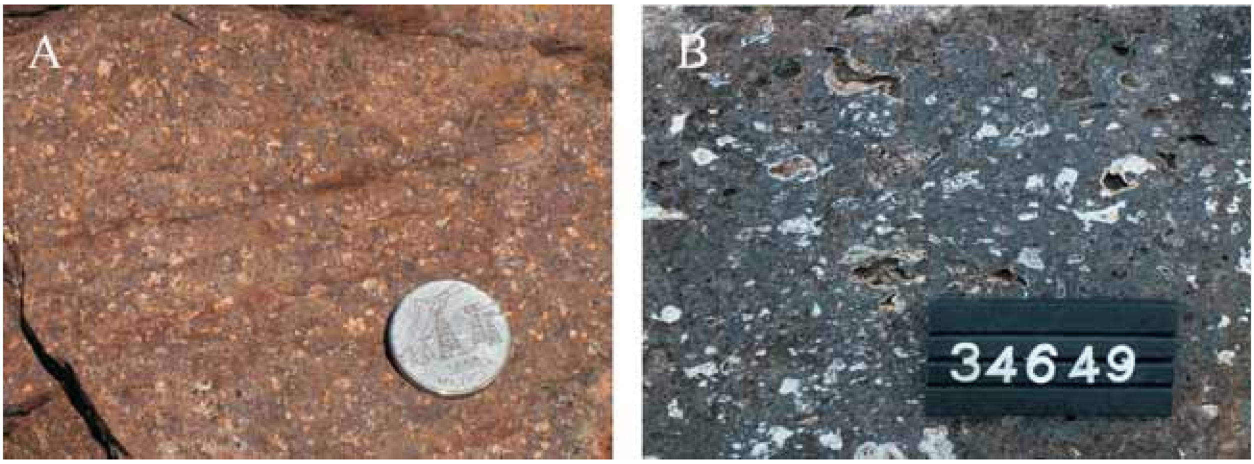

Fig. 6. a) A massive part of a rhyolite flow of the Umbelúzi Formation. Note euhedral feldspar phenocrysts and crystal aggregates. b) Highly vesicular upper part of the same flow. Road cut south of Ressano Garcia (0399017/7183886). Coin diameter 3 cm, scale bar 10 cm.

In the Lebombo Mountains, rhyolitic flows form smoothly (~10º–15°) east tilting terraces, with thickness of single flows probably ranging from some tens of metres up to 200–300 m. Although the rhyolitic rocks generally dip gently, patterns developed during the emplacement and cooling of single flows, including shrinking jointing and ramp structures, may occasionally show variably steep or even vertical attitudes (Fig. 5a). In exposures northwest of the Massingir dam shrinking joints often form a regular pattern of parallel discontinuities (Fig. 5b).

While contacts between successive flows are often covered, subvertical walls of flow terraces often offer excellent sites for field observations. Subhorizontal flow terraces also provide various primary features connected to flow contact zones. Well-developed laminar flow patterns, often intensively flow-folded and contorted, have been found in rhyolite flows of the Umbelúzi Formation throughout the area (Figs 5c-d). A fresh surface of welded rhyolite shows eutaxitic textures (Fig. 5e), and a microphotograph of the same sample reveals dark, vitric bands alternating with light, microcrystalline layers with abundant small (< 0.2 mm) spherulites in various stages of devitrification. Clusters of lithophysae are also commonly found within rhyolitic rocks of the Umbelúzi Formation. The most spectacular clusters are found in the eastern part of the Lebombo range, north-east of the Namaacha border post, where lithophysae form horizons and zones in the lower parts of rhyolitic flows. The size of concentric or star-shaped lithophysae varies from 1–2 cm to 10–15 cm (Fig. 5f).

The volcanic textures found within rhyolitic flows of the Umbelúzi Formation are common in welded ash-flow tuffs and high-grade ignimbrites (e.g. Sheridan & Wong 2005). Similar textures, interpreted to represent high temperature ash-flows, have also been described in the Jozini Formation in South Africa by Bristow & Armstrong (1989). Due to the obvious thickness of single flow units, pink brown to chocolate brown, fine- to medium-grained, massive feldsparphyric rhyolite is a common variety in most flow core outcrops in the area extending from Ressano Garcia to the north of the Massingir dam. Although dense welding and rheomorphism of ignimbrites can produce similar massive and porphyric, lava-like rocks, probably proper lava flows also exist within the ash-flow deposits. In a road cut exposure east of Ressano Garcia, a gradual transition from massive, feldsparphyric rock (Fig. 6a) through a vesicular zone (Fig. 6b) into flow-top breccia may represent a top of a pristine lava flow.

Small inclusions of more mafic components are common everywhere within the rhyolites of the Umbelúzi Formation, but they are particularly common in lava-like rhyolite flows in the wide rhyolite belt north of the Massingir dam. These enclaves generally occur as dark brown, roundish spots or elongated fragments within the flow, but also larger, sheet-like fragments are occasionally observed. On weathered surfaces these globule-like spots, generally ~1–3 cm in size, have been weathered out forming small pits, thus denoting their divergent, less weathering-resistant composition. These features, suggesting coeval eruption, mingling and mixing of compositionally contrasting magmas (see e.g. Yoder 1973, Sparks *et al.* 1977), can be expected within an extensional tectonic regime like the Lebombo monocline, where bimodal basalt-rhyolite magmatism dominates.

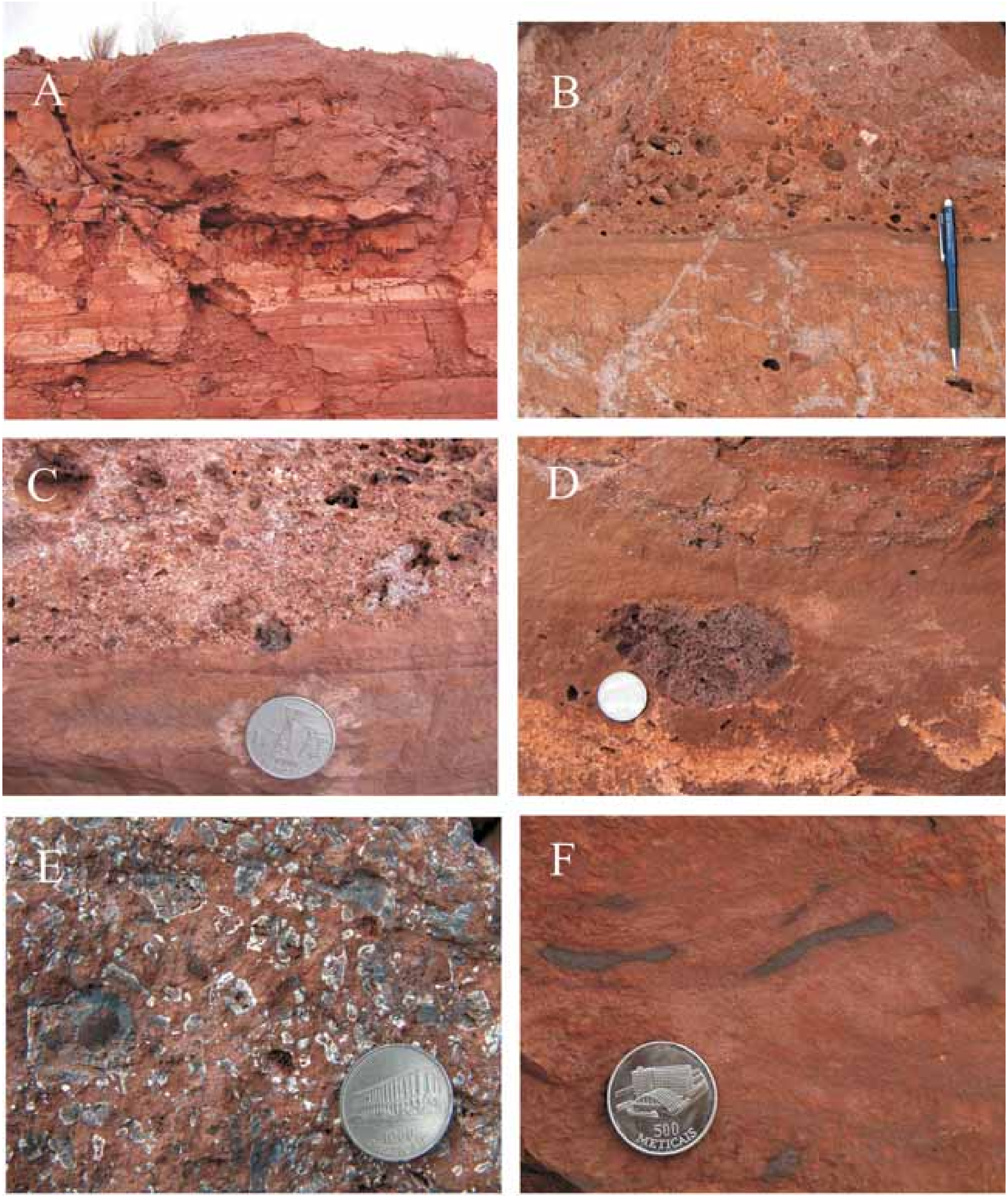

Fig. 7. Ash-fall deposits in rhyolites of the Umbelúzi Formation. a) Tabular bedding of rhyolitic ash-fall tuff. b) A layer of lapilli tuff with pumice fragments on top of a fine-grained tuff with graded bedding. c) Detailed photo of the contact between ash-fall tuff and overlying lapilli tuff layers. d) A pumice fragment embedded in fine-grained tuff. Note shard layers in the upper part of the photo. e) Detailed photo of sharp-edged, partly devitrified fragments of volcanic glass (shards). Rock aggregate quarry north of Mt Ligadjanga (0414117/7107659). f) Collapsed pumice fragments (fiamme) in a fine-grained tuff matrix. Road cut on the EN4 highway (0409944/7169003). Coin diameter 2.8 cm, length of the pen 15 cm.

Basalts (JrUb)

Coeval extrusion of mafic and felsic magmas within the Umbelúzi formation is further manifested by the presence of mafic rocks intercalated with the rhyolites. These are most abundant in regions north-west of Massingir, where they comprise relative narrow (< 200 m), but up to 30–40 kilometres long, elongated units of basaltic flows and subvolcanic sills and dykes. The basaltic interbeds are generally poorly exposed. They are distinguished by their subdued topography and low intensity anomalies on radiometric maps. These fine- to coarse-grained rocks are often rather massive but show typical volcanic textures.

In the northern part of the Lebombo monocline, there are some wide (> 10 m) zones of breccias, which can be lithologically divided into flow-top breccias, solely composed of rhyolitic fragments, and volcanic breccias, where fragment materials comprise lithologically different volcanic rocks. These breccias are parallel to the main structural N-S trend of the monocline.

A breccia zone composed of fragments derived from angular to subrounded felsic and mafic (-intermediate) volcanic rock occurs about eight kilometres south of the Gaza Camp border post. Here, the breccia zone is located at the contact between a voluminous rhyolitic flow and relatively narrow (~50 m), but several kilometres long layer of basaltic andesite. Internal texture of the fragments, generally 5–75 cm in size, is heterogeneous; e.g. rhyolitic fragments are flow-banded, while mafic ones contain phenocrysts. The violet brown, fine-grained matrix of the breccia is also intermediate in composition.

On the eastern side of the Lebombo Mountain range is a long horizon, tens of kilometres, of rhyolitic rocks with tabular bedding, interpreted to represent ash-fall deposits (Figs 7a-f). In an old quarry, located about 6 km north-west of the Goba village, the tile-red rhyolite comprises alternating layers or beds of unwelded pyroclastic material, ranging from fine-grained ash to lapilli. Well-preserved pumice fragments, embedded in places into fine-grained tuff beds (Fig. 7d), and layers of only partially devitrified shards (Fig. 7f) suggest an ash-fall tuff origin for the rock.

Movene Formation

Introduction

The Movene (Basalt) Formation represents the uppermost lithological unit of the Lebombo Monocline (e.g. Eales *et al.* 1984) and extends over 400 km from the Maputo River at the South African border onto the Singuédzi River, north of the town of Massingir (Table 1). Dominating the fertile lowlands between the rhyolitic Lebombo mountain range in the west and sedimentary formations in the east, the Movene Formation mostly comprises a succession of basaltic lava flows, but also includes intercalated rhyolite flows of the Pequenos Libombos Member in the upper part of the basaltic lava pile.

Basalts (JrM)

Compared with the felsic volcanic rocks, basaltic lavas of the Movene Formation are poorly exposed, outcrops being mostly located on river banks. Rare outcrops found in topographically higher places, are generally covered and thus protected by more resistant rhyolitic flows (see Fig. 9).

The field exposures of basalts typically exhibit characteristic features of inflated ropy lava (pahoehoe lava) flows: a massive flow core and highly amygdaloidal lower and upper zone (Fig. 8a). These mafic volcanic rocks are mainly aphyric, although plagioclase porphyritic types are also commonly

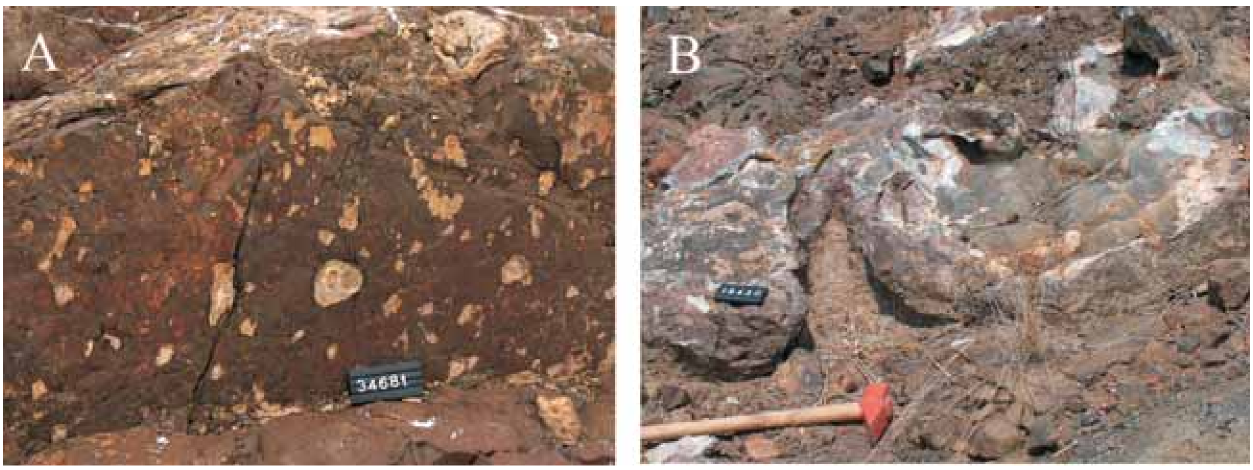

Fig. 8. Amygdaloidal textures in basaltic lavas of the Movene Formation. a) Large, quartz-filled amygdules in the upper zone of basalt flow near the Pequenos Libombos dam (042210/7113705). b) Quartz crystal coated megavesicle in the upper part of the lava flow (0424177/7113835). NW of Mt Portela (0418871/7120492). Scale bar 10 cm.

observed. The thickness of individual flow units varies from <1 m up to ~10 m. The highly amygdaloidal lower part is glassy, thickness commonly < 0.5 m, and may contain pipe amygdules, which are commonly inclined towards the lava flow direction. Both easterly and westerly flow directions are observed, which may reflect local topography of the lava flow field rather than distinctive eruptive centres. The massive flow core of relatively thick (>>1 m) inflated ropy lava units completely lacks amygdules or contains only few of them and often shows spheroidal weathering. The core of the lava flow may contain sub-vertical amygdule cylinders and, just below the upper crust, sub-horizontal amygdule sheets. In the upper part of basaltic flows there are large amounts of roundish amygdules that are commonly 1–10 cm in diameter. In some thick flows, a horizon of megavesicles with diameters of up to one metre has been found (Fig. 8b). The amygdules and the megavesicles are filled mainly with agate, quartz, carbonates, and zeolite. Agate layers in partially filled amygdules provide a useful tool for establishing the postmagmatic tilting of the lava flows. Observations, although sparse, show 6º–8° dipping towards ESE. Some of the ropy lava flow units also have a distinctive flow top breccia.

Rhyolites (JrMr)

A prominent rhyolite ridge of the Pequenos Libombos (Little Lebombo) Mountains in southern Mozambique comprises a succession of variously welded ash-flow tuffs in the upper part of the Movene Formation, north and east of the Pequenos Libombos dam. The north-trending rhyolite interlayer can be followed for over 65 km along strike, its maximum width being about 5 km. The maximum thickness of this succession, known formerly as Sica beds (Cleverly *et al.* 1984), ranges from some tens of metres in the area of Mt Portela to ~100–150 m east of Mt Sica and Mt Pequenos Libombos proper. The unit, which stands out as a resistant cap within the Movene basalt terrain, is cut by several NW-SE trending faults and fractures, while a NW-SE trending sinistral strike-slip fault has divided the ridge into two major parts.

Fig. 9. Contact between a yellowish brown rhyolite flow of the Pequenos Libombos Member (on top) and maroon basaltic lava of the Movene Formation. A quarry on the western side of the Pequenos Libombos Mountain (0421955/ 7119193). Hammer length 65 cm.

Evidence for a pyroclastic emplacement of Pequenos Libombos rhyolite is provided by its gradual transition from a weakly welded basal tuff breccia and a lithophysal zone upwards into an increasingly flow-banded and flow-folded rheomorphic lava-like rock.

The lower contact of the rhyolite unit is exposed at a road cut on top of the Pequenos Libombos ridge, where a maroon coloured zone in the upper part of the underlying basalt flow may represent a hydrothermally altered palaeo-laterite horizon (Fig. 9). The same maroon contact zone is exposed in an old quarry north of the Sica ridge, where large amount of greenish agate amygdules up to 5 cm in diameter are preserved in the oxidised top layer of the basalt flow.

The weathering and alteration of rocks in the contact zone hamper the study of volcanic structures at the base of the rhyolitic flow. Horizons of poorly welded ash-flow tuffs or ash-fall deposits exist in the basal zone of the (lowermost) flow. Elsewhere, the flow base is characterised by chaotic tuff breccias with plastically deformed lithic chips or fragments (Fig. 10a) or by lithophysa clusters, with the size of roundish lithophysae ranging from small spherulitic ones to lithophysae, 10–15 cm in diameter. In some large lithophysae, onion-like weathering is well developed (Fig. 10b).

Densely welded varieties of rhyolitic ash-flow tuffs, consolidated by vapour-phase crystallisation, constitute the major rock type of the Pequenos Libombos Member of the Movene Formation, exposed in most aggregate quarries of the area. Dark brownish red, fine-grained rock is often distinctly flow-banded, with flow folding locally distorting the gentle regional tilting angle of flows (Figs 11a-b). Flow-banded rock comprises dark greenish and light to reddish brown, <1 to 2 mm thick laminas with abundant small (< 0.5 mm) spherules and quartz and feldspar phenocrysts, probably as a result of vapour phase crystallisation (Fig. 11c). Only in zones where the intensity of rheomorphic flow has not been comprehensive, flame-like fiamme and round to lenticular vesicles can still be discerned.

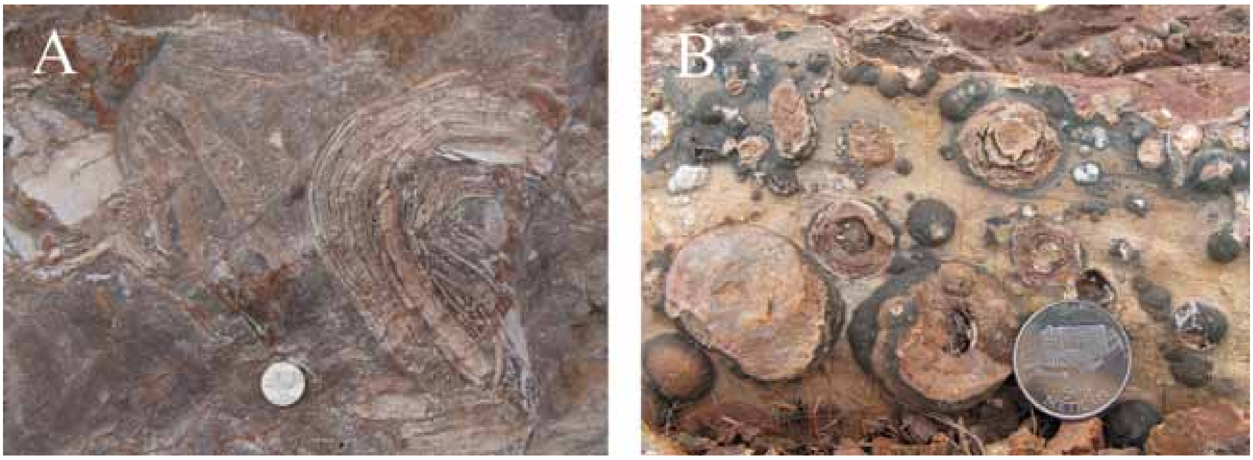

Fig. 10. a) Detailed photo of plastically deformed (ash-flow) tuff fragments in a non-welded zone. A quarry on the western side of the Pequenos Libombos Mountain (0421955/7119193). b) Detailed photo of roundish structure of lithophysae. Old quarry NE of the Portela ridge (0422725/7118163). Coin diameter 3 cm.

On top of the mountain, southeast of the Mt Muguene, there occur two circular-shaped structures, 6–7 m in diameter, which may represent eruption vents for rhyolite flows surrounding these structures. Steeply outwards dipping flows exhibit distinct flow banding and have numerous distorted pumice fragments and gas cavities.

Rhyolite breccia (JrMbr)

A horizon of sub-aerial pyroclastic breccia (tuff breccia), probably tens of metres in thickness, is exposed along the western slope of a separate hill on the eastern side of the Pequenos Libombos ridge proper. Its position as an immediate northern exten-

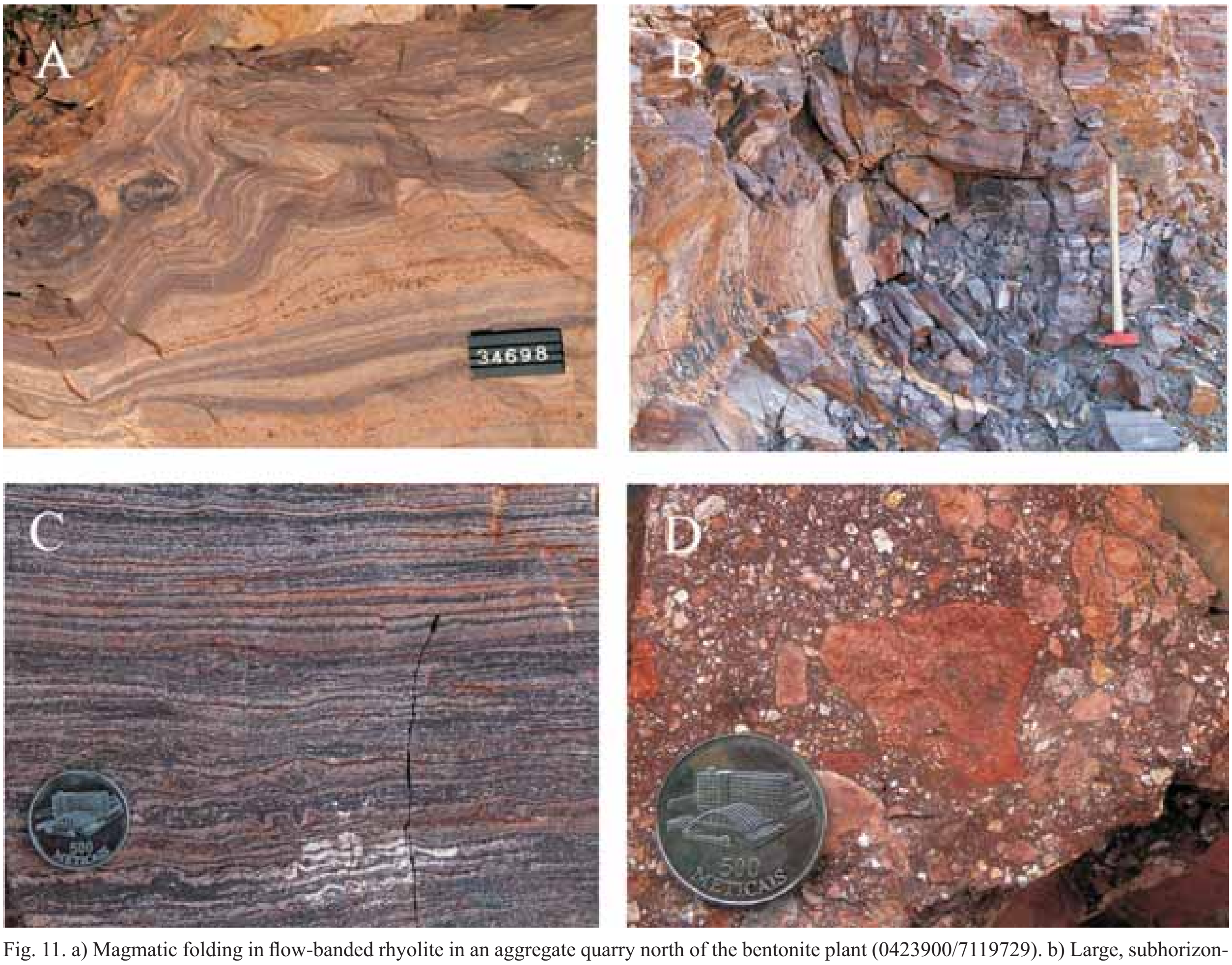

Fig. 11. a) Magmatic folding in flow-banded rhyolite in an aggregate quarry north of the bentonite plant (0423900/7119729). b) Large, subhorizontal flow fold in rhyolite of the same quarry. c) Detailed photo of flow-banded rhyolite with rolled rhyolite clasts. Old quarry north of the Pequenos Libombos dam (0423468/7114906). d) Pyroclastic breccia, comprising supracrustal fragments in a tuff matrix. A hill east of the Pequenos Libombos Mountain (0425129/ 7117510). Hammer length 65 cm, scale bar 10 cm, coin diameter 2.5 cm.

Fig. 12. Banded felsic volcanite with mafic enclaves. Aggregate quarry (0428363/ 71223752). Marker pen length 14 cm.

sion of the southern rhyolite ridge suggests that this unit represents an air-fall tuff breccia or unwelded ash-flow deposit amongst the densely welded ash-flow sheets of the area.

The pyroclastic breccia is composed of lithic (juvenile to accidental) fragments, up to 10 cm in size, in a fine-grained tuff matrix (Fig. 11d). These matrix-supported clasts mostly comprise weathered fragments of basalt, broken lapilli and bombs of vesicular pumice, and light brown chips and fragments of aphanitic rhyolite. Occasional lithic fragments were probably derived from the pre-volcanic Karoo sedimentary strata, not exposed in this area.

Banded felsic volcanite (JmRq)

A light grey or greenish grey variety of felsic volcanic rocks, also assigned to the Pequenos Libombos Member, is exposed in an old aggregate quarry 6 km north-west of the Boane town. Obscure flow banding and rare fiamme suggest ash-flow origin for the aphanitic rock with abundant dark brown, mafic enclaves, generally < 10 cm in size (Fig. 12). Light brownish bands or portions, possibly due to hydrothermal bleaching and alteration of the rock, are also common. Thin, sub-vertical basaltic dykes intrude the rock unit in the quarry.

Pessene alkaline lava (JrPla)

One of the easternmost observed exposures of mafic volcanic rocks in southern Mozambique is massive, aphyric, aphanitic and contains few amygdules. The exposure is located on the top of a small hill and has a minimum diameter of several hundreds of metres. In previous maps this rock has been classified as a basaltic dyke, but it more likely represents a sub-horizontal sill or a lava unit.

As no geochronological data are available and the isolated outcrop is located between areas of basalt lavas and Cretaceous sedimentary rocks, it is currently uncertain whether this rock type belongs to the Movene Formation. Based on geochemical data, the phonotephrite may be comagmatic with the Pessene nepheline syenite intrusion nearby.

Intrusive rocks

Nepheline syenite (JrPns)

A nepheline syenite body is exposed ~8 km SW of the village of Pessene, in the contact zone between Movene basalts and Quaternary sediments. The shape of the subvolcanic intrusion is elongated. In addition to the large outcrop situated in the aggregate quarry near the highway EN4, there are also

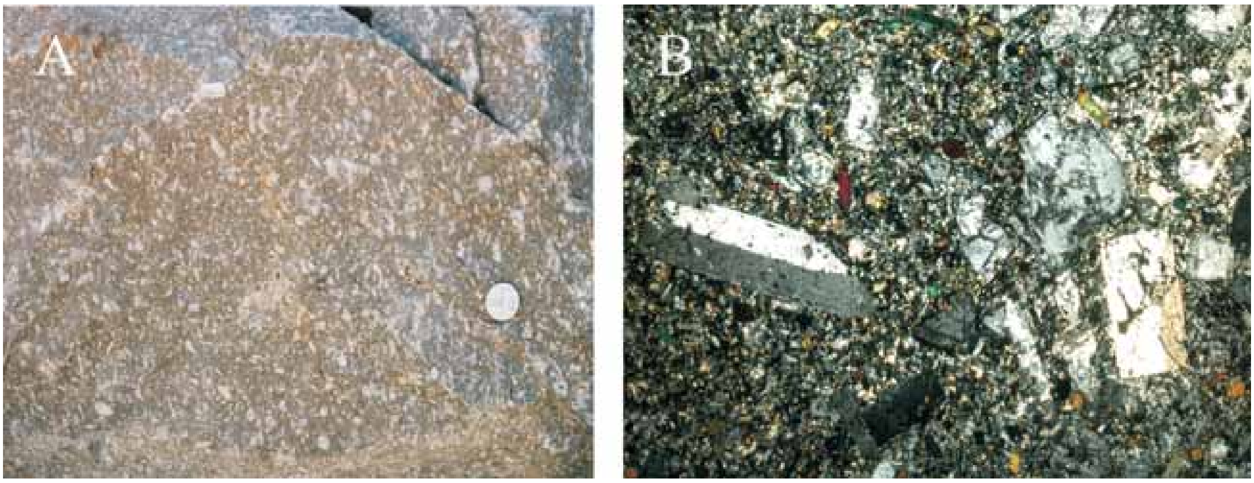

Fig. 13. a) Porphyritic texture of the Pessene nepheline syenite. b) Photomicrograph of nepheline syenite, with euhedral phenocrysts in a microcrystalline ground mass. X-nicols. The Pessene quarry (0431268/7150433). Coin diameter 2.5 cm, photo width 3.5 cm.

some related rocks outcropping 8 km to the south.

Pessane nepheline syenite is a light greenish grey, massive and distinctly porphyritic rock with potassium feldspar, nepheline, aegirine augite and augite as phenocrysts in a microcrystalline to aphanitic ground mass (Figs 13a, b). It also contains some analcite and amphibole. The rock is cut by a dense network of small fractures and joints.

Microgranite

A few elongated microgranite bodies intrude mafic and felsic volcanic rocks within the Limpopo National Park in the northern part of the Lebombo monocline. Microgranites are pinkish grey, massive, locally strongly fractured and spheroidally weathered rocks, which have intrusive contacts against the surrounding basaltic lavas.

The grain size of microgranites ranges from small to medium (0.1–0.5 mm), and granophyric intergrowths between feldspar and quartz grains are common. In addition to quartz and plagioclase, microgranites comprise potassium feldspar, and clinopyroxene phenocrysts, up to 1 mm in size, have also been observed. Obviously, these microgranite intrusions represent the coeval magmatic phase with the Tshokwane granophyre, located nearby in the South African side of the border[1].

[1] see 1:250 000 scale geological map "2230 Tzaneen", published by the Geological Survey of South Africa.

Mafic dykes and sills

Mafic dykes and sills intrude felsic volcanic rocks of the Lebombo sequence, although observations of them are rare. In the north, within the Limpopo National Park, a very fine-grained, vertical mafic dyke impressively cuts the dacite of the Umbelúzi Formation. The weakly zoned dyke has chilled fine-grained margins and the rock comprises small chemical variations parallel to the contacts. The dyke is composed of plagioclase, clinopyroxene and opaques and has a nesophitic texture.

A 5-m-thick basaltic dyke intrudes the Umbéluzi Formation in an old quarry south of the Sabie dam (Fig. 14a). A basaltic sill, more than 20 m thick, intrudes rhyolites of the Pequenos Libombos Member in the western side of the mountain. Exposed in an active aggregate rock quarry, this sill exhibits a prominent columnar jointing, polygonal columns mostly being pentagonal or hexagonal in cross-section (Fig. 14b). An intrusive contact of the sill against the flow-banded rhyolitic host rock is also exposed in the quarry. Columnar jointing is also found in a dolerite sill, situated 20 km north of the Catuane village in southern Mozambique, where the sill forms a small hill in a low-lying landscape of the Movene basalts.

A prominent, NNE-trending, >100-m-thick mafic dyke cuts a thick, basaltic lava flow of the Movene Formation near the Pequenos Libombos dam. The brownish, medium-grained dyke has numerous randomly oriented, chalcedony filled fractures.

Fig. 14. a) Basaltic dyke intruding the Umbeluzi rhyolite. Old quarry south of the Corumana Dam (0412434/7209032) and b) Columnar jointing in a basaltic sill. Quarry on the west side of the Pequenos Libombos Mountain. (0424318/7145314). Length of hammer 65 cm.

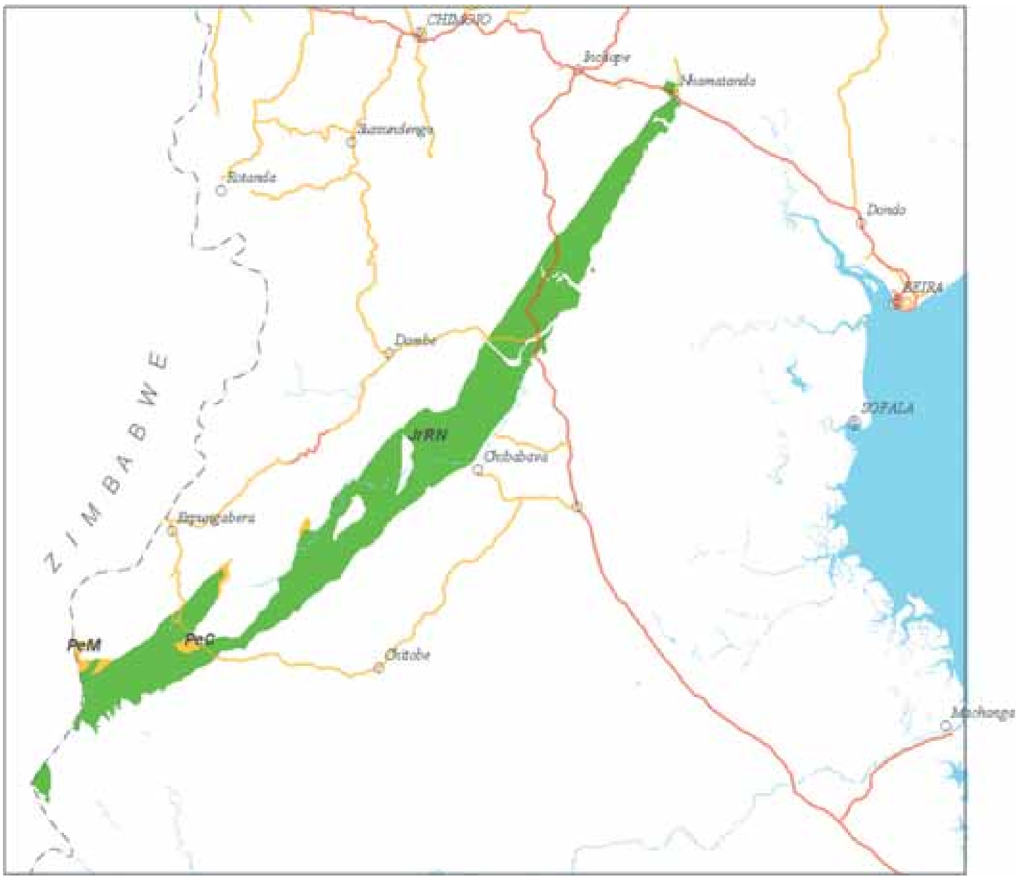

Fig. 15. Location of Karoo-related volcanic (green; JrRN) and sedimentary (light brown; PeC and PeM) formations of the Nuanetsi-Sabi volcanic flexure area. The codes refer to the stratigraphic units described in the text and used in map explanations of GTK Consortium 2006a, b and c.

NUANETSI-SABI VOLCANIC FLEXURE

The Nuanetzi-Sabi volcanic flexure is a zone of basaltic lavas with few rhyolitic beds, extending from the area south of Espungabera up to the Nhamatanda region on the Beira map sheet. These basalts have been incorporated into the Rio Nhavúdezi Formation (JrRN) and are also found in the Lupata trough area, north-east of Serra Gorongosa. Geophysical data imply that the SE margin of this flexure is locally heavily fractured.

Rio Nhavúdezi Formation

A homogeneous pile of basaltic lava flows assigned to the Rio Nhavúdezi formation forms a continuous, 15–25 km wide belt, which extends from the Zimbabwean border over 250 km north-east towards the Nhamatanda village by the Beira–Manica highway (Fig. 15). Near the border, basaltic lavas overlie coal-bearing sediments and conglomerates of the Lower Karoo Moatize (*PeM*) and Upper Karoo Cádzi (*PeC*) formations, while the contact against the metalavas of the Mesoproterozoic Umkondo Group is tectonic. In the east these basalts are mostly overlain by unconsolidated sediments of the Cretaceous Sena Formation. The dark green or greenish brown, fine-grained lavas are frequently exposed along Rio Merenguese and its tributaries, but the most prominent outcrops are in Rio Búzi, where basaltic flows form spectacular rapids and cataracts (Fig. 16a). On the aeromagnetic map, the basalts of the Rio Nhavúdezi formation are characterized by a high magnetic and low radiometric signature. Macroscopically, dark greyish or brownish green, fine-grained basalts are generally aphyric, but also porphyritic varieties with plagioclase phenocrysts have randomly been found. Rare medium-grained varieties within the basalt probably represent massive cores of flows – they could also be dykes or sills.

Fig. 16. Lava features of the Rio Nhavúdezi Formation. a) Rapids in the Bùzi River, formed by basaltic lava flows. b) Quartz-filled megavesicles in the upper part of a lava flow. c) Quartz-filled vesicle cylinder in a basaltic flow. S of Mt Sitatonga (0523719/7743119). d) Zeolite-filled amygdules in the upper part of basaltic lava flow. Rio Merenguese (0470676/7702175). Scale bar 15 cm.

No pyroclastic or sedimentary interbeds have been found within the basaltic succession. Zoned amygdules with chalcedony and zeolite are common in the upper part of subhorizontal to steeply (up to 50^{o}) east dipping lava flows, and irregular megavesicles up to 30–40 cm in size exist in the basalts of Rio Mebahata. There is also a well-developed columnar jointing in some basaltic flows.

Mineralogically, basalts of the Rio Nhavúdezi formation are tholeiites with andesine and pigeonite, but without olivine and olivine tholeiites. In addition to medium-grained sub-ophitic types, also plagioclase porphyritic types are found in places. In the porphyritic types, randomly oriented plagioclase laths are typically 1–6 mm long. These varieties most likely represent the central part of flows, while amygdaloidal types dominate the upper part. Medium-grained types are most common adjacent to the north-western boundary of this SW-NE trending basaltic sequence, whereas amygdaloidal types are more common towards the south-eastern boundary of the formation. The available tectonic measurements of lava flows together with geophysical interpretation indicate that the volcanic sequence is dipping smoothly towards the E or SE.

Based on observed lava flow boundaries and different lava structures e.g., including zeolite-filled amygdules, flow-top mega-vesicles (Fig. 16b), and sub-vertical vesicle cylinders (Fig. 16c), the estimated average thickness of flows is 1–2 metres. The highly vesicular texture (Fig. 16d) and obvious absence of pillows and/or marine or lacustrine interflow sediments, indicate sub-aerial eruption of basaltic magma.

LUPATA TROUGH AREA

An arch-like, discontinuous belt of the Upper Karoo volcanic and sedimentary rocks surrounds the northern end of the Lupata trough in central Mozambique (Fig. 17). There immature arkosic sandstones, limestones, and carbonated sandstones of the Cádzi Formation (*PeC*) are overlain by basalts of the Rio Nhavúdezi Formation or the Chueza Formation (*JrC*), rhyolitic rocks of the Serra Bombuè Formation (*JrSb*) forming a felsic interbed within the mostly basaltic succession. The overlying Cretaceous Lupata Group is composed of coarse clastic sediments and an alkaline volcanic suite, mostly comprising phonolites and trachytes.

The emplacement ages of the Mesozoic lavas and their intrusive correlatives in the Nuanetsi-Sabie volcanic flexure, the Lupata trough, and the Moatize-Luia graben (Fig. 2) have not been accurately dated. New geochronological results of the Consortioum mapping programme provide constraints to the age relationships of these rocks. For example, the intrusions of the Gorongosa Suite have been previously related to Cretaceous alkaline ring complexes (Afonso 1978), but TIMS U-Pb zircon dating of a syenite belonging to the Gorongosa Suite gave a concordant Lower Jurassic age of 181±2 Ma, suggesting emplacement of the syenite during the main stage of Karoo magmatism.

The bimodal Rukore Suite represents another major intrusive assemblage in central Mozambique. The Rukore Suite has been previously regarded to correlate with the Chilwa Alkaline Province in southern Malawi (Cahen *et al.* 1984) and represents post-Karoo age magmatism at ~230–110 Ma (Barton *et al.* 1991). Three zircon fractions from a micrgranite belonging to the Rukore Suite were recently dated by the Consortium using conventional U-Pb geochronology and suggest an age of ~195–180 Ma for the granite (Mänttäri this volume).

The volcanic rocks of central Mozambique have not been dated by isotopic methods before. Traditionally, the basalts and rhyolites of the Chueza Formation, Rio Mázoè Formation, and Bangomatete Formation have been associated with the widespread Karoo magmatism at ~180 Ma. Further to the north, the Moeza dyke represents another likely correlate of the Karoo lavas. A sample from the Moeza dyke for dating yielded a Sm-Nd isochron mineral-whole-rock age of 180±43 Ma.

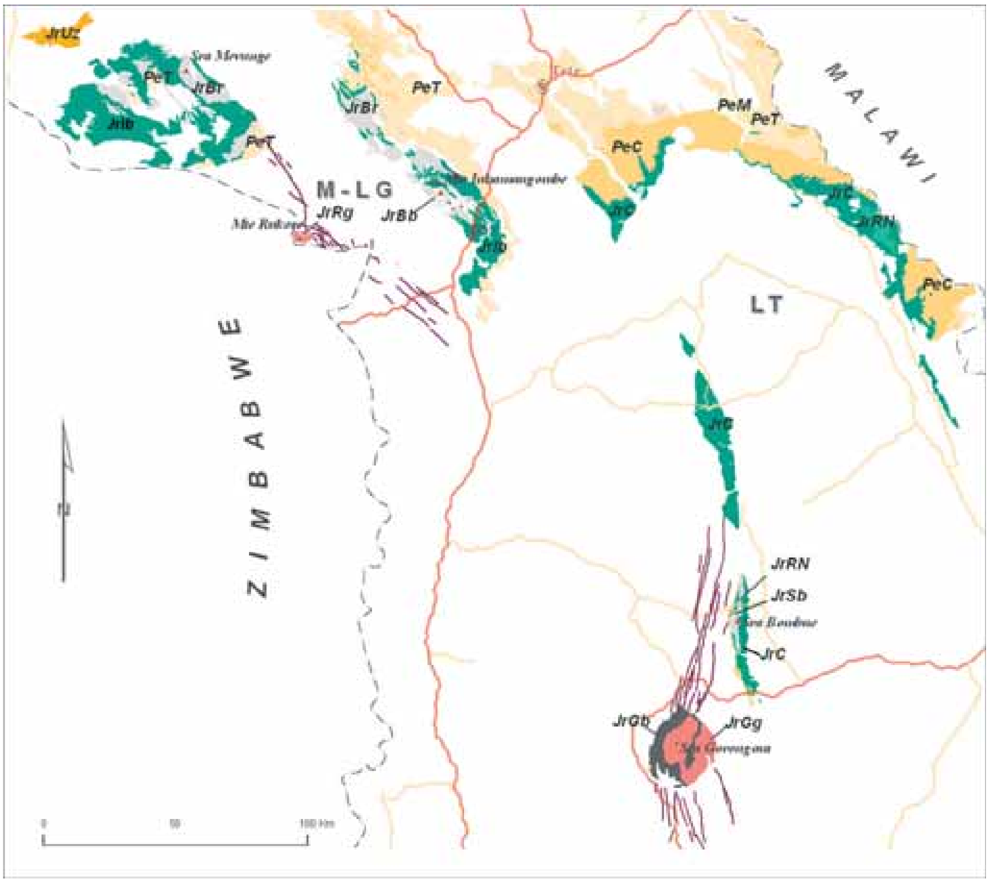

Fig. 17. Location of Karoo-related intrusive (black/red; JrGg, JrGb, JrRg), mafic (green; Jrla, Jrlb, JrRN, JrSb, JrC), felsic (grey/orange, JrBr, JrBb, JrUz) volcanic and sedimentary (light brown; PeM, PeC, PeT) formations of the Karoo Supergroup in the Lupata trough (LT) and Moatize-Luia graben (M-LG) area. The codes refer to the stratigraphic units described in the text and used in map explanations of GTK Consortium 2006a, b and c.

Rio Nhavúdezi Formation

A succession of amygdaloidal basalts, which form the Nuanetzi-Sabi volcanic flexure and are assigned there to the Rio Nhavúdezi Formation, is also randomly found around the Lupata trough. The lower contact of the Formation is exposed in the tributary of Rio Mebahata, where flow-brecciated basaltic lava overlies a conglomerate of the Gádzi Formation. The upper contact with the Serra Bombuè Formation is gradual – thin rhyolitic interbeds are found between basaltic flows in the upper part of the Rio Nhavúdezi Formation in the Mebahata River (Fig. 18).

These dark greyish or brownish green, fine-grained basalts are generally aphyric, but also porphyritic varieties with plagioclase phenocrysts have randomly been found. Rare medium-grained varieties within the basalt probably represent massive cores of flows, but could also be dykes or sills. No pyroclastic or sedimentary interbeds have been found within basaltic succession. Zoned amygdules with chalcedony and zeolite filling are common in the upper parts of subhorizontal to steeply (up to 50^{o}) east dipping lava flows, and irregular megavesicles up to 30–40 cm in size exist in basalts of Rio Mebahata. A well-developed columnar jointing is also present in some basaltic flows.

Fig. 18. Brownish red, rhyolitic interflows of the Serra Bombuè Formation in the upper part of the Rio Nhavúdezi Formation in Rio Mebahata (0636470/8016042). Hammer length 65 cm.

Serra Bombuè Formation

Rhyolitic rocks of the Serra Bombuè Formation form a north-trending ridge on the western side of the Lupata trough, northeast of the Gorongosa Mountain. Less than 4 km in width, but over 30 km long, a rhyolite formation, tilting gently (12º –20º) to the east, was emplaced between basaltic lavas of the Rio Nhavúdezi and the Chueza Formations, clearly differing from surrounding lithologies with its high positive aeromagnetic and radiometric anomalies.

A well-exposed traverse along Rio Mebahata reveals the gradual contact with underlying basalts of the Rio Nhavúdezi Formation, thin felsic lava flows alternating with basaltic flows in the upper part of the Rio Nhavúdezi succession. In a hand specimen, the rhyolite is chocolate-brown and fine-grained, exhibiting locally a well-developed flow banding. A low breccia with spherulitic texture in sharp-edged fragments occurs in the basal part of the rhyolite succession, but otherwise the rock is rather massive, indicating rather thick cooling units.

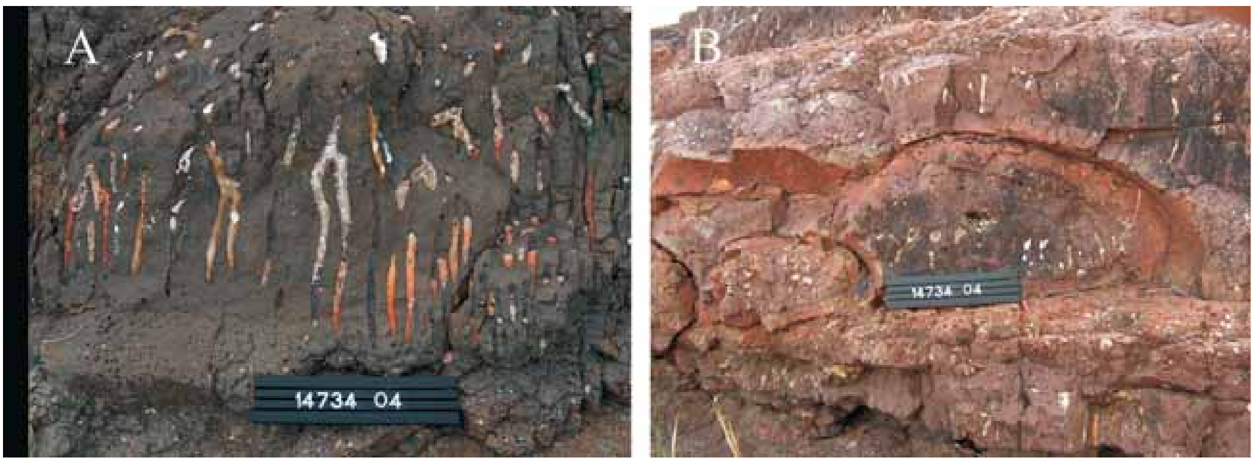

Fig. 19. a) Pipe amygdules at the base of a basaltic flow. b) A vertical cross section of lava lobes in a thin, basaltic lava flow. The Pompue River gorge in the Búzue village (0624901/8092174). Scale bar 15 cm.

Chueza Formation

Basaltic flows of the Chueza formation constitute an uninterrupted exposure between the Sinjal and Chueza settlements on the north-eastern side of the Lupata trough. Here, the upper basalts of the Chueza formation are in direct contact with the lower basalts of the Rio Mázoè formation. Similar basalts are also exposed along the Mt Linhanga escarpment, and at Mt Cuadezo where grey, fine- to medium-grained basalts, some with amygdaloidal structures, form small, scattered hills. Sometimes basalt flows form small *kopjes* in direct contact with the sandstones, or their presence is indicated by basalt boulders. In places, the dark grey-green rocks are porphyritic with plagioclase phenocrysts. Vertical NE-trending basalt feeders are exposed in the Chueza area.

In the western side of the Lupata trough, an excellent section of Chueza basalts can be found at the Búzua village, where a pile of subhorizontal compound lava flows is fully exposed in a Pompue River gorge. There the thickness of single flows varies from 1–2 m into massive, over 5 m thick flow with a regular cooling joint pattern. The upper parts of the flows often have many small, roundish amygdules. Elongated and bent calcite and zeolite-filled pipe amygdules, of up to 15 cm in length at the flow bases, demonstrate the north-western direction of the flows (Fig. 19a).

Locally, well-exposed cross sections of thin pahoehoe flow lobes are found within the basaltic lava succession (Fig. 19b), and a small, collapsed lava tunnel, about one metre in diameter, was also found in a river gorge.

A tectonic contact between Chueza basalts and Mesoproterozoic gneisses is exposed in the southern bank of the Pompue River, about 5 km west of the Búzue village. There the steeply (60°) east dipping contact is rather sharp and mylonitized.

MOATIZE-LUIA GRABEN AREA

A thick succession of sediments and volcanic rocks, assigned to the Karoo Supergroup is found in the fault-controlled Moatize-Luia graben in Tete Province, western Mozambique. Divided into the Lower and Upper Karoo Groups, the former comprises only sedimentary successions, the latter a number of sedimentary formations together with interstratified mafic and felsic Karoo volcanic rocks of Early Triassic to Early Jurassic age.

Deposited into palaeo-depressions of the pre-Karoo basement, the Lower Karoo Group comprises coal-bearing Vúzi (*CbV*) and Moatize (*JrM*) formations, covered by coarse-clastic sediments of the Matinde Formation (*PeT*) (see GTK Consortium 2006d).

At the base of the Upper Karoo Group, immature deposits of the Gádzi Formation (*PeC*) conformably overlie the clastic sediments of the Matinde Formation and are overlain by basalts of the Chueza (*JrC*) and Rio Nhavúdezi (*JrRN*) Formations in the northern end of the Lupata trough. In the west, the sediments of the Matinde Formation are overlain by the basalts of the Rio Mázoè Formation (*JrIa, JrIb*) and felsic volcanic rocks of the Bangomatete Formation (*JrBr, JrBb*).

The epoch is concluded with the emplacement of the bimodal Rukore Suite, dated at 190–180 Ma (Mänttäri, this volume). The latter is coeval with and possibly related to the Gorongosa Suite and the volcanic rocks of Nuanetsi-Sabi and Lebombo monoclines further to the south.

Rio Mázoè Formation

Although rather restricted in extent, the Rio Mázoè Formation is well developed on the Chioco and Tete map sheets, where basaltic and andesitic lavas of the formation overlie sandstones of the Matinde Formation and are overlain by rhyolites of the Bangomatete Formation. The most extensive outcrop areas of the unit exist to the west of Rio Mázoè bridge and in central parts of the Serra Mevunge dome structure. Due to different intensity of weathering, the colour of basaltic lavas varies from dark greyish green to chocolate brown or dark reddish brown, often hampering identification of the actual rock composition. Consequently, radiometric data were generally used to separate basalts from more felsic varieties of the volcanic sequence, basalts exhibiting poor K/Th signature on airborne radiometric maps.

On the riverbanks to the west of the Rio Mázoè bridge, fine-grained basalts form a pile of gently (12º–20º) SWW-dipping lava flows. The estimated thickness of flows, based on vesicle-rich flow contacts, varies from 2–3 m up to 10–15 m in the lower

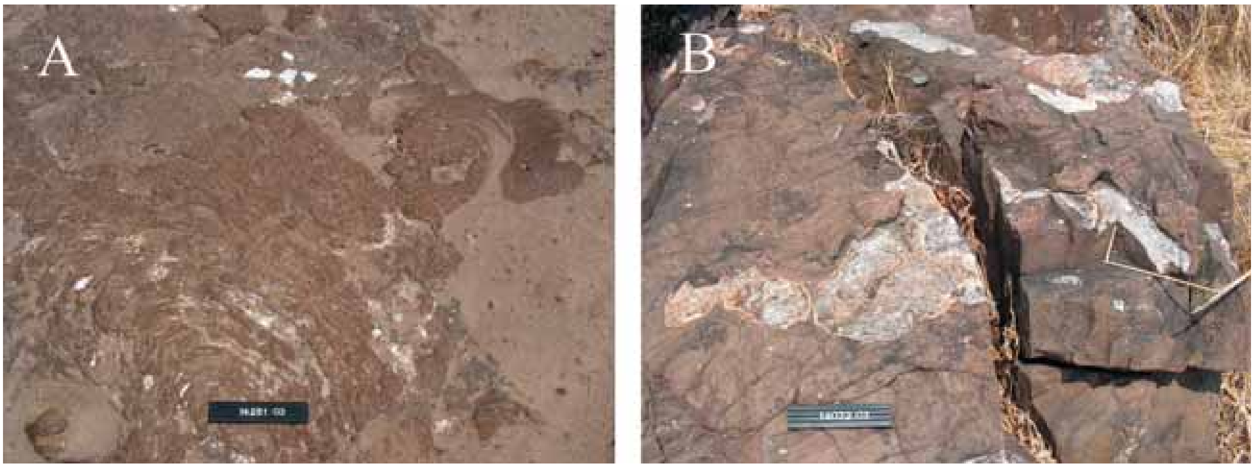

Fig. 20. a) Ropy lava (pahoehoe) structure in basaltic lava flow. Rio Mázoè Formation. West of the Rio Mázoè bridge (0539576/ 8170743). b) Large, zeolite-filled vugs (gas cavities) in the upper zone of basaltic lava flow of the Rio Mázoè Formation. Serra Mevunge dome (0420090/ 8227068). Scale bar 15 cm.

part of the formation. Many features distinctive to flood basalts have also been found: basal pipe-vesicle zones, vertical vesicle cylinders and columnar jointing in the flow cores, and ropy lava structures on the surfaces of flows (Fig. 20a). In the highly vesicular flow tops, calcite and zeolite-filled vesicles and vugs, up to 20–30 cm in size, have often bright, blue-green chrysocolla linings. As no intervening layers of sedimentary or pyroclastic material between lava flows has been observed, the intensity and rate of eruption has probably been rather high, a feature also typical for continental flood basalt provinces.

In the Serra Mevunge dome area, basaltic and andesitic lava flows, identical to those described from the Rio Mázoè area, are exposed between coarse-clastic Lower Karoo sandstones and rhyolite flows of the Bangomatete Formation. Ropy lava structures and pipe vesicles are common, the size of zeolite and calcite-filled vugs in the uppermost flow-top zone locally exceeding 30–40 cm (Fig. 20b). Compared to the Rio Mázoè area, the thickness of these flows is generally lesser. Based on the occurrence of pipe vesicles in the basal zones of flows, several individual flows of less than one metre in thickness have been observed.

Dark green, in places very fractured and, when weathered, chocolate-brown basaltic lavas are exposed in an area 3 km east of the Changara village, forming a mountainous region extending over 10 km by 10 km. Amygdaloidal and porphyritic textures, with altered plagioclase phenocrysts, are also observed. In some areas concentrations of quartz geodes are found in the upper parts of basaltic flows. White agate pebbles are common in the area, and they are probably derived from agate-filled vesicles.

In the Birira area, the basalts are dark grey and sometimes amygdaloidal. These flows may alternate with rhyolite flows. South of Birira, rhyolite flows constitute prominent hills and are interbedded with basalts flows. The rocks are frequently strongly fractured. Ignimbritic enclaves with calcite veins are also present. Approximately 2 km SW of Birira, a 30 cm thick calcite vein, trending 330°/vertical, can be followed over a considerable distance. Its direction corresponds to a NW-SE fault system observed by satellite imagery.

Bangomatete Formation

Extensive and thick rhyolite flows cap basaltic lavas of the Rio Mázoè Formation in the Serra Mevunge dome structure in the NW corner of the Chioco map sheet and in the area east of the Rio Luia and Rio Mázoè confluence, extending from there to the mesa-like Bangomatete Mountain over 80 km northwest.

In the Rio Mázoè area, rocks of the Bangomatete Formation comprise a gently (10–35°) southwest-tilting pile of rhyolitic flows. Observations made along Rio Mázoè and Rio Luia reveal the prevailing pyroclastic nature of these volcanic rocks. In proximity of Mt. Inhamangombe a heterogeneous sequence of rhyolitic rocks shows features typical of variously welded ash-flow tuffs or ignimbrites: volcanic breccias with lithic and/or pumice fragments, lapilli tuffs, fiammes, lithophysae and glomeroporphyric textures suggesting vapour-phase crystallisation.

Light yellowish to dark red (weathered), generally poorly sorted and massive lapilli tuffs and pyroclastic breccias include sharp-edged lithic (welded tuff) fragments or vesicular pumice fragments in various degrees of welding. Also flow banding and associated quartz- and zeolite-filled lithophysae, observed in several outcrops around the mountain, manifest the welding of pyroclastic deposits. Fine-grained, massive or laminated tuffs are locally found in areas more distal to Inhamangombe Mountain; they possibly represent a non-welded facies of ash-flow tuffs or rhyolitic ash-fall deposits.

A well-preserved rhyolitic lava lobe or tongue was found in the gorge of Rio Mázoè, about 10 km E of Mt Inhamangombe. On the top of basaltic lavas of the Rio Mázoè Formation, this chocolate to pinkish brown, fine-grained flow has abundant small, flow-deformed vesicles, parallel feldspar phenocrysts and distinct flow banding. Several large (up to 4 x 8 m in size) apertures within the flow possibly represent a row of volcanic vents (Fig. 21).

Fig. 21. Rhyolitic lava flow with small eruptive vent in background. Rio Mázoè near Mt Inhamangombe (0532910/8170633).

Fig. 22. A chaotic breccia, comprising of large, angular basaltic and rhyolitic fragments, probably representing a talus breccia around the caldera. Bangomatete Formation, north bank of the Rio Mázoè (0524862/8168927). Scale bar 15 cm.

With a prominent escarpment to the north, northeast and southeast, Inhamangombe Mountain forms a circular structure, about 6 km in diameter, near the confluence of Mázoè and Luia rivers. Originally, Hunting (1984) considered it to denote a variety of rhyolitic ash flow tuffs. However, features characteristic of lava flows, for example rubble layers between individual flow units, were also observed by the Hunting team. The general form of the mountain, probably controlled by ring faults, and the presence of rhyolitic lavas, ash-flow tuffs, and ignimbrites, suggest that the Inhamangombe Mountain is a former caldera (Hunting 1984).

The rhyolitic rocks of the area comprise mainly various types of pyroclastic deposits: pumice breccias, agglomerates and variously welded ash-flow tuffs with large amount of quartz-filled lithophysae. The caldera origin of the Mt Inhamangombe is supported by field verification by the Consortium, manifesting the presence of a coarse, chaotic breccia with large (up to 2 m in diameter), angular to subrounded lava and tuff fragments, in the SSE rim of the volcanic structure (Fig. 22). This breccia, which appears to be tens of metres in total thickness, probably represents a talus breccia of a synvolcanic ring-fault system surrounding a magma reservoir (caldera).

Interpretation of satellite imagery and geophysics manifests the presence of rhyolitic rocks of the Bangomatete Formation in the Serra Mevunge dome area. In the northern part of the dome, the volcanic succession shows dips 10º–12º to NE due to local faulting. In the northern and north-western part of the dome, rhyolitic flows form a regular, terrace-like pile of flows. Although no distinct evidence of pyroclastic origin of the flows was obtained during present field verification, their large extent and tabular shape infers to single cooling units of ash-flow tuffs. In the area about 7 km SEE of Mt Chimandau, in river beds and on a weathered top soil of a highly vesicular, frothy-lava like rhyolite there are large amount of spherical agates. These layered chalcedony nodules, commonly known as thunder eggs, and originally developed as gas cavities (lithophysae) in a welded tuff (see Ross & Smith 1961) also refer to the pyroclastic nature of rhyolitic rocks.

In the central part of the Serra Mevunge dome, however, obvious lava structures in rhyolites also indicate extrusion of lava flows. About 5 km NE of Mt Balati, on a hill top outcrop there are dark pinkish brown, dense rhyolitic flows with zeolite-filled vesicles showing flow banding and surface folding, typical of viscous lava (Fig. 23). In the same area rhyolitic lava contains small (< 5 cm) graphite fragments, probably derived from underlying coal-bearing Karoo sediments. Locally felsic lavas are also porphyritic, having small (< 5 mm) quartz and fieldspar phenocrysts in a fine-grained groundmass. Steep to vertical dips of flow banding in lava flows suggest close proximity to volcanic vents.

In the southernmost part of the Luia Dome area, a reddish brown, massive felsic volcanite contains large amount of undeformed, quartz-chalcedony-zeolite-filled amygdules and vugs up to 5–6 cm in diameter. The porphyritic rock has large amount of anhedral feldspar crystals up to 10 mm in size, and locally exist also small (<10 cm), dark, dense fragments of basaltic lava.

An obsidian flow, over 3 m in thickness, is exposed over some hundreds of metres on top of a low hill, about 10 km to the west of Mt Sluxia. The weathered surface of the massive rock is dull grey, while fresh conchoidal fractures show a shiny black glassy lustre. Results of chemical analysis of the rock are similar to those of a rhyolitic lava flow from the Rio Mázoè area. A volcanic breccia with angular fragments of felsic tuff in a fine-grained tuff matrix, possibly representing a flow-top breccia of an ignimbritic flow, is exposed below the obsidian flow.

Fine-grained, pink to reddish amygdaloidal rhyolite flows occur 7 km north of Birira village forming an elongated mountain with a NW-SE orientation, dipping to the SW. The amygdales are generally filled with calcite and, at places, zeolite. Rhyolitic agglomerates are also present. Grey chalcedony and ignimbrite horizons occur elsewhere. The latter show a well-preserved banding, dipping 15º – 20º SW. Distinct flows have been recognised, ignimbritic horizons usually forming the top of the hills. Calcite veins, up to 10 cm in thickness, intersect these volcanic rocks.

Outcrops of weathered amygdaloidal basalts, trending 320º/10º–12º NE are also found in places in the Birira area. The rocks are intensively fractured, with fracture spacing from a few to 10–12 cm, being parallel to the main fracture system with trend of 330º–340º/80º– 90º SW. The contact zone between the Bangomatete rhyolites and underlying Rio Mázoè basalts is located near the observation point 10328-03 (0519978/8181483). The contact is concordant, striking 310°. A subvertical, N-W trending rhyolite feeder with large gas cavities was found intruding basalts near this contact.

Fig. 23. Surface folding of rhyolite lava flow belonging to the Bangomatete Formation. NE of Mt Balati (0402690/8203478). Scale bar 15 cm.

Fig. 24. Quartz-feldspar porphyry dyke with zoned feldspar phenocrysts and small, basaltic enclaves. North of Rio Mázoè (0459259/8191348). Scale bar 15 cm.

INTRUSIVE SUITES OF KAROO AGE; RUKORE

Introduction

The rugged Rukore Mountain in the Tete Province straddles the border with Zimbabwe. There the name *Rukore Intrusive Suite (JrRg)* was coined by Barton *et al.* (1991) for the late Karoo intrusives forming this largely granitic mountain range. The close spatial relation of various granites and dolerite dykes of the area indicate a broadly coeval emplacement of the mafic and felsic igneous products.

Felsic intrusives

Felsic intrusives of the Rukore Suite comprise porphyritic microgranites and granite porphyry dykes, the Rukore granite occupying an elevated area of about 20 km^2 in size on both sides of the Mozambique-Zimbabwe border.

The Rukore granite is pinkish, porphyritic, massive and non-deformed microgranite, where feldspar and quartz are found as euhedral to round, variously corroded and fragmented phenocrysts. Feldspar phenocrysts are in general 1–2 cm in size, commonly with a 1–2 mm thick whitish rim, whereas quartz phenocrysts are up to 5 mm in diameter. Green amphibole forms aggregates up to 10 mm in length, and magmatic mafic enclaves with feldspar xenocrysts are not uncommon suggesting magma mingling.

In thin section granophyric texture is commonly observed around strongly sericitised plagioclase phenocrysts. Some quartz phenocrysts show euhedral shapes, while some are mantled by amphibole. The matrix is composed of widespread micrographic quartz and sericitised plagioclase, the latter strongly predominating over potassium feldspar. Apart from sericitisation, plagioclase is also affected by carbonate and epidote alteration, which also commonly affects amphibole. The common graphic and granophyric textures of the Rukore granite rule out plutonic origin and hypabyssal, subvolcanic origin is favoured.

Several quartz-feldspar porphyry dykes of the Rukore Suite form prominent, blocky ridges in the Rio Mázoè area, where they are invariably associated with, and occasionally cut by dolerite dykes. The generally NW-trending dykes, called micrograntes by Barton *et al.* (1991) in the adjacent Nyamapanda area in Zimbabwe, occur as swarms of up to 30–50 m in width and zones of several kilometres in length, often rising several tens of meters above the surrounding landscape.

These massive, brick-red dykes are generally distinctly porphyritic with euhedral, often zoned feldspar phenocrysts up to 30–40 mm in size and small (< 4 mm), roundish quartz phenocrysts ‘floating’ in a microcrystalline quartzofeldspathic matrix (Fig. 24). Olivine and pyroxene phenocrysts as well as magnetite grains and basaltic enclaves are occasionally present.

Mafic intrusives

Mafic intrusives belonging to the Rukore Suite include a swarm of basalt dykes and sills, which intrude Proterozoic rocks and Phanerozoic strata up to early Cretaceous and extend from Rio Luenha in the south to the northern side of the Lake Cahora Bassa. Barton *et al.* (1991) reported rare picritic dykes from the Zimbabwean side of the border, and the Sm-Nd isotopic data obtained from the prominent Moeza dyke also connect the emplacement of this dyke to the Karoo magmatic event.

Where basaltic dykes with microgabbroic texture occur as NW-trending dyke swarms or as small, elongated microgabbro stocks, it implies association of Karoo related magmatic activity and zones of crustal weaknesses. At places where the dolerite dykes invade coal seams within Karoo sedimentary strata, they may cause cokefication.

Where the enclosing country rocks have a low magnetic susceptibility, dolerite sills and dykes can be easily identified as strong anomalies on aeromagnetic maps, even when covered by sediments. Generally basaltic dykes stand out as small hills or ridges or, when weathered, betray their presence by chocolate-brown soils. In places, microgabbro dykes exhibit a clear fabric.

The 40–50 m thick mafic Moeza dyke, occurring in the Tete Province, can be followed in N-S direction on the aeromagnetic map for more than 150 km. In the coarse-grained dyke plagioclase ± clinopyroxene ± olivine are the major constituents, hornblende, biotite, chlorite and serpentine being retrograde minerals.

INTRUSIVE SUITES OF KAROO AGE; GORONGOSA

Introduction

In the Sofala Province, the Serra da Gorongosa Mountain dominates the surrounding plateau with its 1862 m high Gogogo peak by some 1200 metres. The mountainous zone corresponds to an oval-shaped intrusive complex (JrGg, JrGb), measuring 30 km N-S by 25 km E-W.

Lithology

According to Hunting (1984), the complex consists of a felsic core surrounded by mafic igneous rocks. Core rock types comprise micropegmatite-granite, which has intruded a mafic intrusion, composed of tholeiitic gabbro, some norite, and olivine gabbro. Quartzose hornfelses and pyroxene-amphibole hornfelses have been found in the Báruè Complex host rocks at the contact with intrusive granitic and gabbroic rocks, respectively.

The felsic and mafic intrusive bodies are readily distinguished in the ternary radiometric images, where a lighter core, dominated by low to medium K- and Th-signatures, is surrounded by a dark, very low-KThU ''aureole''. The aeromagnetic data clearly define the outline of the suite and show that it is laterally restricted to the outcrop area.

Gabbro

Dark green, fine- to medium-grained gabbro of the Gorongosa Suite intrudes micaceous gneisses and calc-silicate gneisses of the Báruè Complex in the NE contact of the suite. Medium-grained, massive gabbro is also exposed on the south-western slope of the Gorongosa Mountain.

Granite

Pinkish, medium-grained, massive granite forms the core of Serra da Gorongosa Mountain, intruding gabbroic rocks of the suite. The major mineralogy of alkalifeldspar granite comprises albite, orthoclase, quartz, clinopyroxene, and hornblende.

Gorongosa fault/fracture corridor and dyke swarm

The Gorongosa Suite is associated with a large swarm of NNE-SSW trending felsic and mafic dykes that radiate north and south of the Serra da Gorongosa, and stand out in relief as narrow, sharp ridges over distances of up to 50 km. The intrusive material fills a set of subvertical fault and fracture planes that appear to pre-date the emplacement of the main Gorongosa intrusive bodies. Notwithstanding their length, the majority of these fractures reveal very little apparent lateral displacement. A few major fault zones, however, extend from 70 km south of the Gorongosa Suite to 50 km north of it and are associated with apparent lateral displacements of close to 10 km. This indicates (1) that extensive block faulting with significant vertical movement has taken place on some of the faults and (2) that the facies interfaces in the Báruè Complex are gently dipping overall.

GEOCHEMISTRY OF KAROO-RELATED VOLCANIC ROCKS

Whole-rock geochemical data for 47 samples representing Karoo-related volcanic and intrusive rocks in southern and central Mozambique are listed in App. 1. The analyses have been performed at the Geochemical Laboratory, Geological Survey of Finland. Five samples representing the Movene Formation have been analysed at the Department of Geology, University of Helsinki.

The rocks are predominantly subalkaline (Fig. 25). SiO_2 ranges from ~45 to ~78 wt. % and shows a bimodal distribution into mafic and silicic rocks; intermediate compositions are relatively rare and are treated here together with the mafic rocks. Two samples from the Movene Formation exhibit strongly alkaline compositions and will be treated separately.

Mafic rocks

General characteristics

The mafic rocks are mainly subalkaline basalts and basaltic andesites (SiO_2 = 46 to 62 wt. %; TA = 1.5 to 7 wt. %) (Fig. 25). Four mafic to intermediate lavas from the Bangomateta and Rio Mázoè Formations show affinities to basaltic trachyandesite, trachyandesite, and andesite. Classification based on the immobile trace element ratios Nb/Y and Zr/TiO_2 (Winchester and Floyd 1977) confirms the predominance of subalkaline compositions (Fig. 26). The intermediate samples from the Bangomatete and Rio Mázoè Formations plot within the field of trachyandesite due to exceptionally high Nb/Y and Zr/TiO$_2$ values, and one relatively primitive basalt from the Rio Mázoè Formation has affinity to alkali basalt. The geochemical data thus suggest mild alkaline affinities in the mafic lavas of the Lupata region (Fig. 17). All samples show tholeiitic affinity on the basis of abundant normative hypersthene, however.

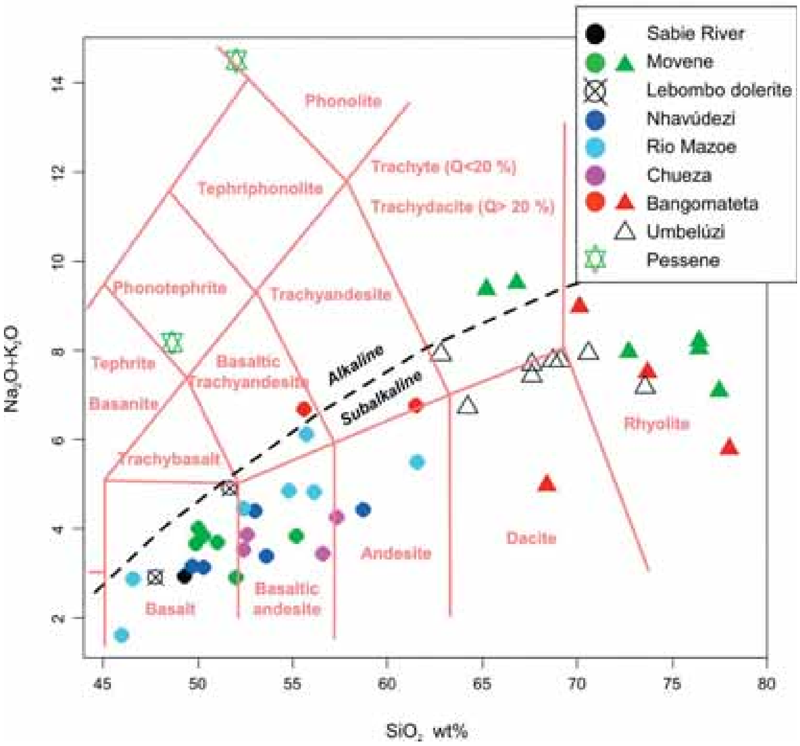

Fig. 25. Geochemical classification of Karoo-related lavas and dykes in southern and central Mozambique using total alkalis vs. silica diagram (LeMaitre *et al.*1989). Division into alkaline and subalkaline compositions is according to Irvine and Baragar (1971).

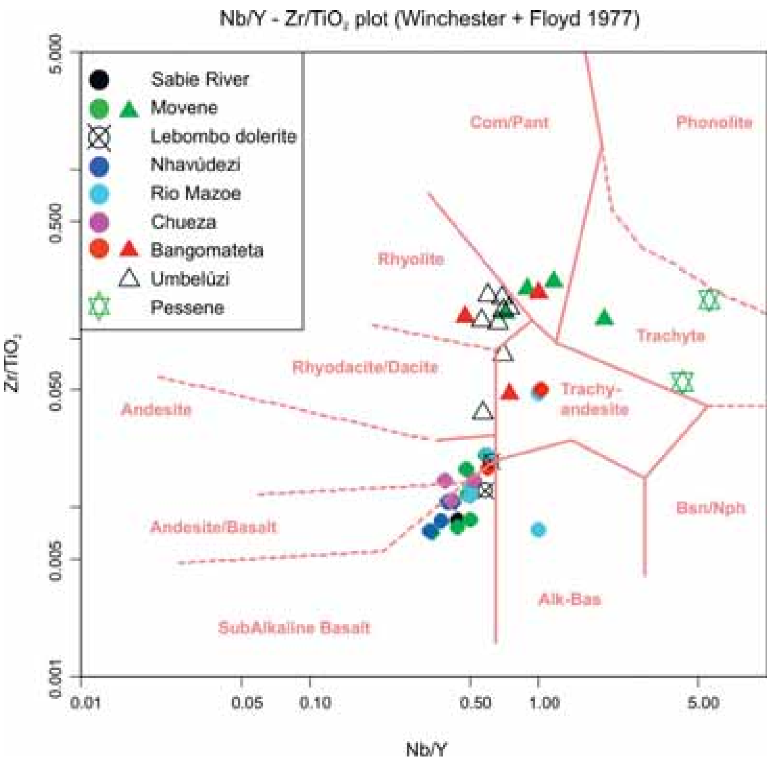

Fig. 26. Geochemical classification of Karoo-related lavas and dykes, southern and central Mozambique, using Nb/Y vs. Zr/TiO$_2$ diagram (Winchester & Floyd 1977).

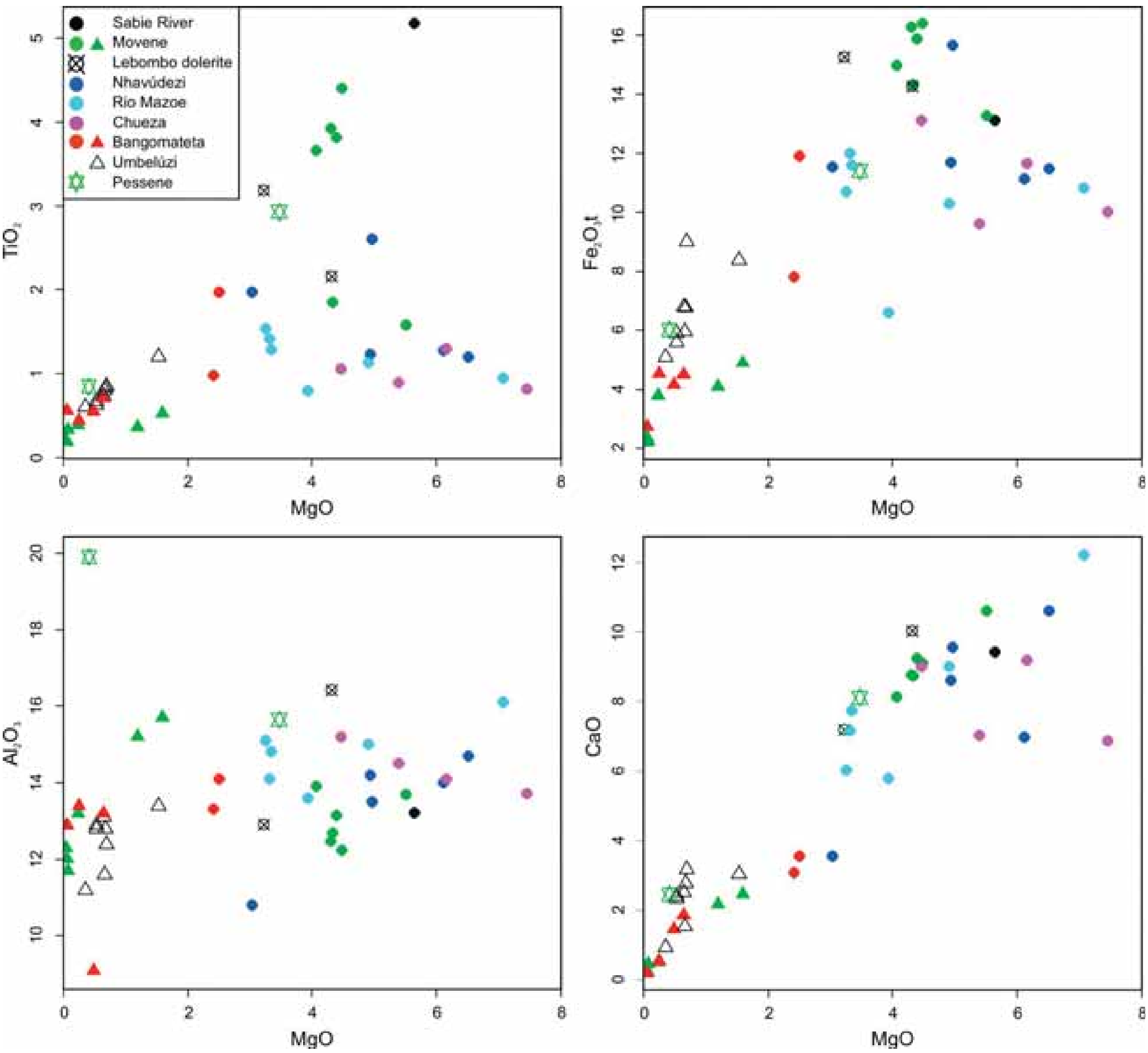

Fig. 27. Variations of TiO_2, Fe_2O_3t, Al_2O_3, and CaO vs. MgO (wt. %) for Karoo-related lavas and dykes from southern and central Mozambique.

Variations of major and trace elements are illustrated in Figs 27 and 28. Overall, the data show large scatter, which probably reflects the small number of analyses. The dataset is dominated by evolved compositions with MgO generally below 8 wt. % and typically below 5 wt. %. One sample from the Rio Mázoè Formation has markedly high contents of MgO (20 wt. %), Ni (820 ppm), and Cr (2080 ppm), and probably represents an olivine cumulate. This is not shown in the figures. Concentrations of K_2O and most of the trace elements show markedly wide ranges (e.g., Zr 50–800 ppm) and correlate negatively with MgO (Fig. 28). Typical of tholeiitic magma systems, the concentration trend of Fe_2O_3t shows enrichment when MgO decreases from ~8 wt. %, an inflection point at MgO of ~4 wt. %, and subsequent depletion (Fig. 27). Concentrations of TiO_2 show a broadly similar pattern.

Grouping

Similar to Karoo lava suites in South Africa and Botswana, the mafic lavas and dykes in Mozambique can be grouped into geochemical types using concentrations and ratios of the high field strength elements, specifically Ti, P, Zr, and Y (cf. Erlank *et al.* 1988, Sweeney *et al.* 1994, Marsh *et al.* 1997, Jourdan *et al.* 2007a). The mafic rocks mainly show relatively low TiO_2 (<2.5 wt. %) and Zr (<250 ppm) contents, and Zr/Y values (<6) typical of low-Ti tholeiites, but samples with high-Ti characteristics are also fairly abundant (Fig. 29). Generalizing, the mafic rocks from the Lupata region, Rio Mázoè, Chueza, and Bangomatete Formations, are low-Ti type lavas: however, some evolved samples show unusually high Zr contents and Zr/Y values. Representative samples of the Nhavúdezi Formation are also low-Ti lavas. The high-Ti samples are associated with the Lebombo Monocline; most of them, including one dolerite sample, are from the Movene Formation in central Lebombo. The single sample representing the Sabie River Basalt Formation in northern Lebombo and the spatially associated dolerite sample also belong to the high-Ti category.

Geochemical comparison of mafic lavas from different formations demonstrates their broadly uniform characteristics (Figs 27–29). The high-Ti rocks along the Lobombo Monocline exhibit relatively high Fe_2O_3t and Y at given MgO, and the geochemically fairly similar Rio Mázoè and Bangomateta Formations include samples with mild alkaline affinities.

Alkaline rocks of the Pessene region

Geochemically, the Pessene alkaline lava may be classified as phonotephrite, and it is distinguished from the stratigraphically older Movene basalts by notably higher K_2O (2.3 %) and Na_2O (5.9 %) at SiO_2 of 49 %. It is further characterized by high TiO_2 (2.9 wt. %) and notably high concentrations of P_2O_5 (1.3 wt. %), Zr (1620 ppm), and Nb (350 ppm) (Fig. 28).

The nepheline syenite of Pessene falls in the phonolite field of the TAS classification and, similar to the Pessene alkaline lava, a trachytic composition based on Zr/TiO_2 vs. Nb/Y –classification (Figs 25–26). The nepheline syenite of Pessene has high Zr, Ba and Sr contents (1440 ppm, 2447 ppm, 3127 ppm) (Appendix 1). Markedly high Al_2O_3, K_2O, and Rb may indicate accumulation of alkali feldspar

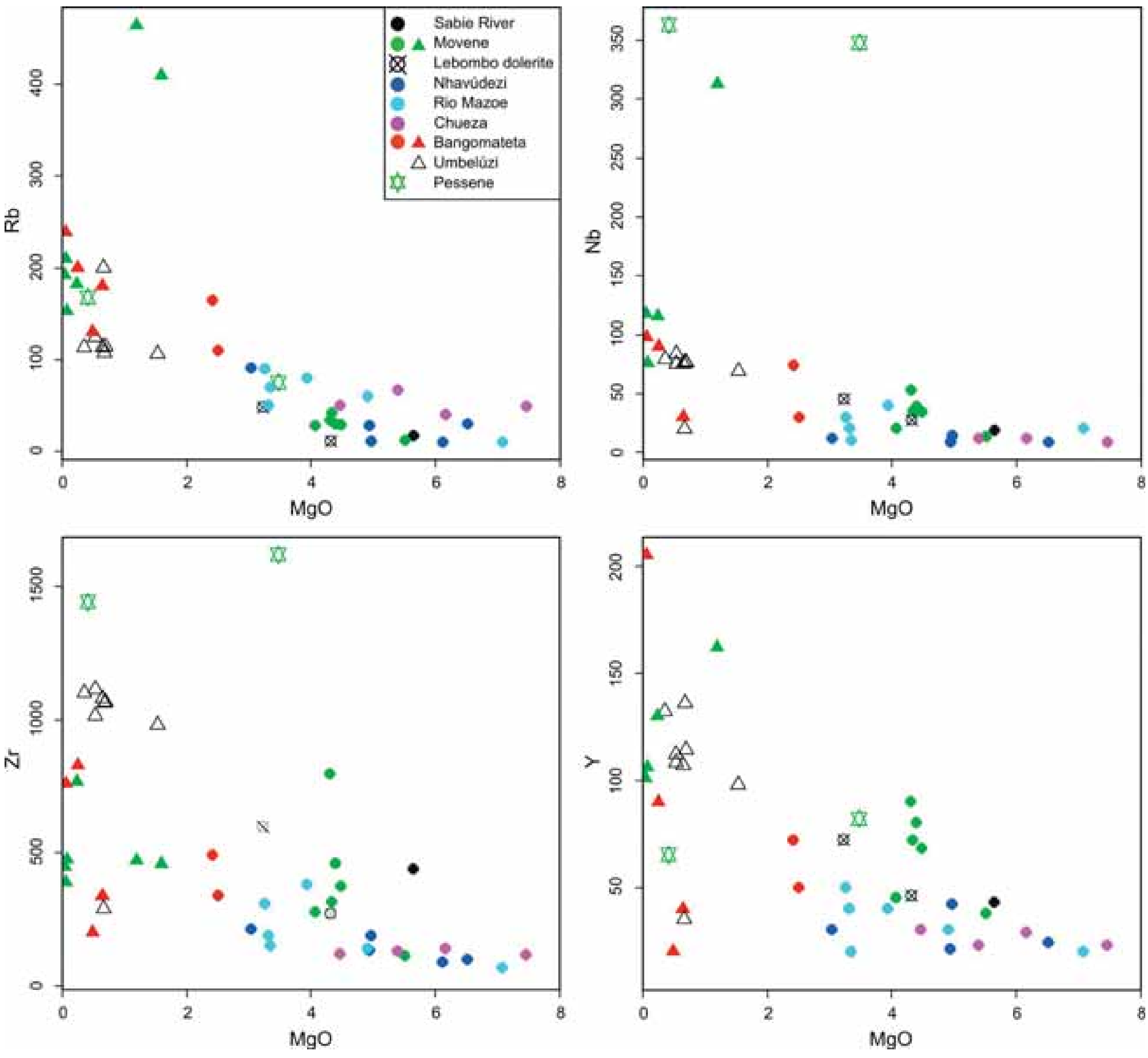

Fig. 28. Variations of Rb, Nb, Zr and Y (ppm) vs. MgO (wt. %) for Karoo-related lavas and dykes from southern and central Mozambique.

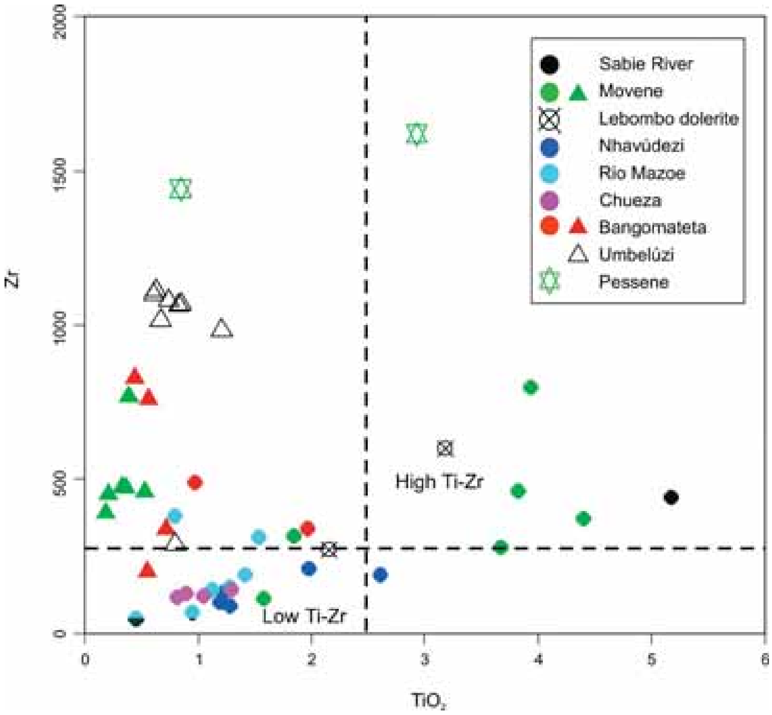

Fig. 29. Variations of Zr (ppm) vs. TiO_2 (wt. %) for Karoo-related lavas and dykes in southern and central Mozambique. Dash lines indicate critical values for low-Ti vs. high-Ti classification (Erlank *et al.* 1988).

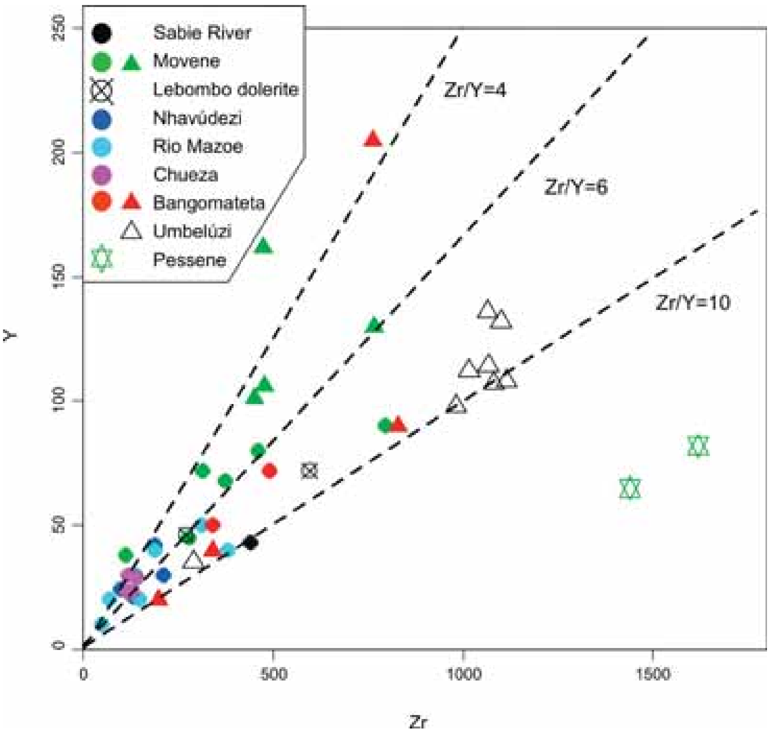

Fig. 30. Variations of Y vs. Zr (ppm) for Karoo-related lavas and dykes in southern and central Mozambique.

phenocrysts in the analysed sample. Based on broad geochemical similarities and similar ratios of TiO_2, Zr, Nb, and Y in particular, the alkaline lava and the nepheline syenite could represent extrusive and intrusive parts of the same alkaline magma system.

Felsic rocks

Geochemical data for representative samples of felsic lavas are listed in App. 1. The Karoo-related felsic rocks of southern and central Mozambique range from dacite to rhyolite (SiO_2 = 63–78 wt. %). They mainly plot within the field of subalkaline lavas in the TAS diagram, whereas the banded felsic volcanites of the Movene Formation can be classified as trachyte and a dacitic sample belonging to the Umbelúzi Formation is classified as trachydacite on the basis of normative Q/(An+Ab+Or). The banded felsic volcanites plot within the field of trachyte also in the Zr/TiO_2 vs. Nb/Y diagram (Fig. 26). The felsic rocks further exhibit peraluminous ($Al_2O_3 > Na_2O + K_2O + CaO$) and high-K geochemical characteristics (Fig. 31). Generalizing, the felsic rocks show A-type geochemical affinities: FeOt/ (FeOt+MgO) and Zr+Nb+Ce+Y values are relatively high (0.83–0.98 and mainly > 1000 ppm, respectively). The banded felsic volcanites of the Movene Formation have lower FeOt/(FeOt+MgO) values of 0.71–0.76.

Comparison of rhyolites belonging to the Umbelúzi and Movene Formations indicates the following differences: the stratigraphically older Umbelúzi Formation is typified by (1) relatively lower SiO_2 contents (mainly below 70 wt. %) (Fig. 25), (2) higher Zr at a given TiO_2, MgO, and Y content (Figs 28–30), (3) higher Fe_2O_3t and lower Al_2O_3 at a given MgO (Fig. 27). The felsic rocks from the Bangomateta Formation are geochemically quite similar to those belonging to the Movene Formation.

DISCUSSION

Geochemical provinciality of Karoo province

The Karoo large igneous province exhibits pronounced compositional heterogeneity that results from subsolidus alteration, crystallization and melting processes, contamination, and magma source heterogeneity. Rigorous geochemical grouping of the magmatic successions is fundamentally important in identifying magmatic lineages, addressing process- and source-dependent variations and un-

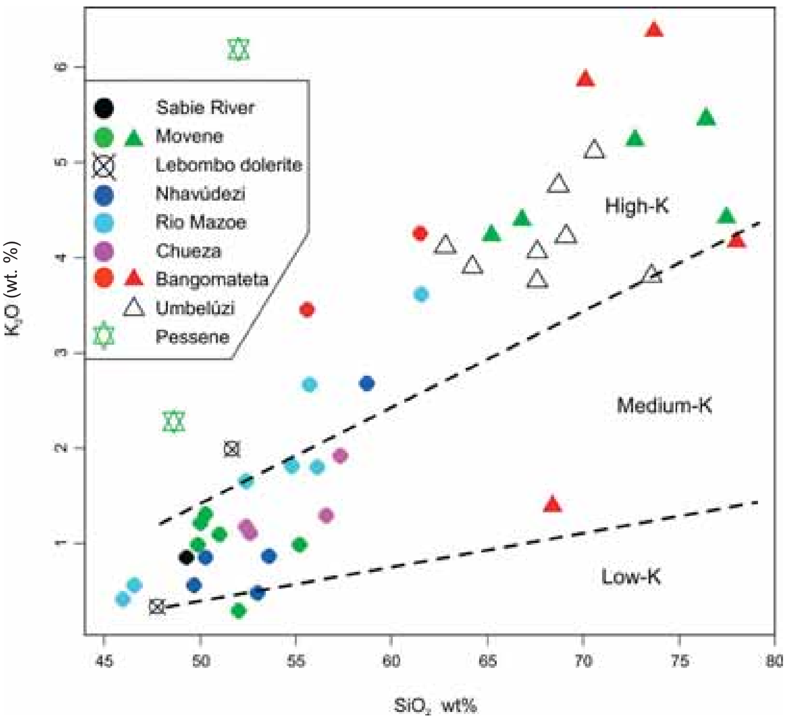

Fig. 31. Classification of Karoo-related subalkaline rocks from southern and central Mozambique into low-K, medium-K, and high-K types (LeMaitre *et al.* 1989).

derstanding the temporal and spatial evolution of the magmatic system. Geochemical and volcanological data for Mozambique are pivotal in this research: the volcanic rocks represent relatively little-studied parts of the province and probably include the youngest presently exposed volcanic rocks in the province.

Geochemical studies of mafic rocks belonging to the Karoo province in southern Africa and the western Dronning Maud Land, Antarctica, have demonstrated association of high-Ti lavas within or close to the purported Limpopo triple junction (Burke & Dewey 1973) and imply distribution of low-Ti magmas around the central area of high-Ti lavas.

Lebombo Monocline

Generalizing, the geochemical characteristic of mafic volcanic rocks and intrusive rocks in Mozambique are compatible with the previously outlined distribution pattern of low-Ti and high-Ti rocks. Sweeney *et al.* (1994) documented a narrow ~60 km zone between the northern high-Ti province and southern low-Ti province within the Sabie River Formation. Low-Ti type lavas are not found north of Sabie River and high-Ti type lavas south of Komati River; in between, both lava types are stratigraphically intercalated. The northern part of the Movene Formation is located to the east of this transition zone. Our geochemical data indicate continuation of penecontemporaneous high-Ti and low-Ti magmatism after the interlude of predominantly felsic eruptions represented by the Umbeluzi rhyolites. Specifically, the high-Ti basalts of Movene Formation and the spatially associated dolerite samples are tentatively correlated with the 'high-Fe' subtype of high-Ti basalts in the Sabie River Formation on the basis similar of Zr/Y values (~6) and TiO_2 (~4 wt. %) and Fe_2O_3t contents (~16 wt. %) (cf., Sweeney *et al.* 1994). It should be emphasized that the "high-Fe" basalts are confined to the uppermost part of the Sabie River Formation, which lends support to the proposed correlation. The single Sabie River basalt sample analysed in this study is a likely correlate of the "high Ti-Zr" subtype of high-Ti basalts. These lavas are characterised by markedly high Zr/Y (~10) and Fe_2O_3t (~12–13 wt. %) and become increasingly abundant in the northern part of the Sabie River Formation (Sweeney *et al.* 1994). In the same way, the low-Ti lavas of the Movene Formation are quite similar to the low-Ti basalts of the Sabie River Formation. They exhibit low Zr/Y (~4) and "intermediate" Fe_2O_3t (~14 wt. %) compared to the high-Ti subtypes (cf. Sweeney *et al.* 2004).

Nuanetsi-Sabi volcanic flexure

To our knowledge, our samples from the Rio Nhavúdezi Formation are the first geochemically analysed rocks from the Nunaetsi-Sabi flexure. These data imply preponderance of low-Ti lavas in the Rio Nhavúdezi Formation. The samples are broadly similar to the low-Ti basalts of the Movene Formation with relatively low Zr/Y (4–6) values and intermediate Fe_2O_3t (11–12 wt. %). One sample has fairly high TiO_2 (~2.6 wt. %), Fe_2O_3t (~16 wt. %), and Ti/Y (~400), typical of high-Ti lavas, but low Zr/Y (~4.5) values render high-Ti vs. low-Ti classification ambiguous. Overall, the geochemical data indicate similarity between the Nuanetsi-Sabi flexure, the Lebombo Monocline, and the Tuli syncline (cf. Sweeney *et al.* 1994, Jourdan *et al.* 2007) and lend further support to the view that these volcanic suites represent genetically related magmatism associated with the Limpopo triple junction structure.

Lupata trough and Moatize-Luia graben

Mafic and intermediate rocks belonging to the Cheza Formation, Rio Mázoè Formation, and Bangomateta Formation range from low-Ti basalt to low-Ti andesite. In addition to relatively low TiO_2, these lavas have low Fe_2O_3t contents and Zr/Y and Ti/Y values. Generalizing, they are quite similar to the low-Ti lavas that are associated with the Lebombo Monocline and the Nuanetsi-Sabi flexure, i.e. the Limpopo structure. A more detailed inspection of the geochemical traits of these rocks indicates some differences that may be significant in terms of correlation and genetic relationships. Compared to the Limpopo structure, lavas from the Cheza Formation, Rio Mázoè Formation, and Bangomateta Formation tend to have lower TiO_2 and Zr and Zr/Y at given MgO content. It may be significant that the low-Ti lavas from Botswana (Jourdan *et al.* 2007a), Springbok Flats, Lesotho (Marsh *et al.* 1997), and Kirwanveggen (Dronning Maud Land, Antarctica; Harris *et al.* 1990) can be similarly distinguished from the low-Ti lavas associated with the Limpopo structure (Luttinen & Leat 2007). Overall, the mafic lavas from the Lupata trough and the Moatize-Luia graben and those from the Lebombo Monocline and the Nuanetsi-Sabi flexure may represent geochemically and petrogenetically distinctive groups of magmas.

Karoo-related plutons and pre-break-up reconstructions of Gondwana

Mozambique

Pluton-size intrusive manifestations of Karoo magmatism are quite rare. The plutons provide insights into intratelluric magmatic processes, but most significantly, they typically contain minerals suitable for high-precision dating of magmatic events. In comparison, dating of volcanic rocks is frequently hampered by secondary alteration and/or lack of ample zircon/baddeleyite.

In conjunction with the mapping programme, the Consortium sampled several inadequately dated Precambrian and Phanerozoic plutons for geochronological studies. The results for three intrusions, the Moeza mafic dyke, the Rukore granite and the Gorongosa gabbro-syenite in the central Mozambique mapping area suggest Mesozoic emplacement (GTK Consortium 2006b).

The Rukore granite and the Gorongosa gabbro-syenite are readily associated with Karoo magmatism. The Rukore granite represents a felsic component of a complex intrusive suite that also includes mafic sills, dyke swarms and small microgabbroic stocks (Barton *et al.* 1991). Intrusive rocks that belong to this group cut the Proterozoic basement and sedimentary rocks of the Karoo Supergroup relatively close to the outer limit of the Archaean Zimbabwe craton. Dating of the granite yielded U-Pb ages within the range 195–180 Ma (GTK Consortium 2006b). This result is in accordance with contemporaneous emplacement of the Rukore intrusive suite during the peak of Karoo magmatism at ~180 Ma (e.g., Encarnación *et al.* 1996).

The intrusive rocks of the Gorongosa Complex cut the Proterozoic basement and are found in the central part of a ~100 km long swarm of N-S trending felsic and mafic dykes. The emplacement of these dykes is considered to manifest a presence of N-S trending system of faults and fractures, some of which can be followed laterally up ~120 km distance (GTK Consortium 2006b). These tectonic structures are associated with marked lateral displacements of up to 10 km. Zircon fractions from a syenitic sample from the felsic core of a gabbro-syenite part of the complex yielded an age of 181±2 Ma that is clearly equivalent to the peak of the Karoo magmatism (Encarnación *et al.* 1996).

The Moeza dyke is at least 150 km long, N-S trending mafic intrusion that crosscuts Proterozoic basement in the Tete Province (Fig. 1). A robust Sm-Nd age of 180±43 Ma (GTK Consortium 2006b) shows it to represent one of the largest intrusive manifestations of Mesozoic magmatism in southern Africa and tentatively associates it with Karoo magmatism. The emplacement of the gigantic Moeza dyke may well indicate a large-scale lithospheric fault or lineament associated with or precursory to Gondwana break-up magmatism.

South Africa and Dronning Maud Land

Several Karoo-related gabbroic intrusions have been reported in southern Africa: the Birds River intrusion in North-Eastern Cape (Eales 1990), the Komatipoort complex in central Lebombo (Saggersson & Logan 1970), the Mount Arthur complex ~150 km SW of Leshoto (Polderwaart 1946), and the New Amalfi sheet and the Insizwa complex in Kwa Zulu-Natal area < 100 km SE of Leshoto (e.g., Polderwaart 1944, Lightfoot *et al.* 1987). These intrusions typically are shallow-seated, sill-like mafic plutons that may represent the feeder system of Karoo basalts (cf. Allsopp *et al.* 1984, Saggersson & Logan 1970, Poldervaart 1944, 1946, Lightfoot *et al.* 1987). Whereas the Komatipoort complex is bounded by Karoo basalts, the other plutons are intruding sedimentary rocks of the Karoo Supergroup.

Karoo-related pluton-size intrusions have also been reported from western Dronning Maud Land, Antarctica. The ~1000 m-thick lava sequence of Vestfjella is cut by three gabbroic plutons: Utpostane, West-Muren, and East-Muren (Vuori & Luttinen 2003, Vuori 2004). U-Pb-dating of these intrusions at 182–180 Ma correlates them with the main peak of Karoo-magmatism (Vuori 2004, Encarnazión *et al.*1996). Whereas the two intrusions at Muren have a dyke-like character, the Utpostane pluton is composed of olivine-rich cumulate rocks and has been considered to represent a feeder system for Karoo lavas (Vuori & Luttinen 2003). The Sistefjell syenite has been intruded into metamorphic Proterozoic rocks of the Maud Belt (Harris & Grantham 1993). The age of intrusion is somewhat lower (173±2 Ma, Harris *et al.* 2002) than the main peak of Karoo magmatism, but it overlaps with the emplacement ages of Karoo-related dolerite dykes along the Lebombo Monocline (Jourdan *et al.* 2007).

Tectonic implications

The pluton-size intrusions of the Karoo province typically are located close to Archaean–Proterozoic lithospheric boundaries in southern Africa and western Dronning Maud Land, Antarctica (Fig. 32) and many of them can be associated with large-scale tectonic structures. Here we examine possible tectonic implications revealed by geochronological data and the distribution pattern of the plutons.

We have assembled an "ultra-tight" Gondwana reconstruction to highlight some potentially significant aspects. Our reconstruction illustrates that: (1) The mafic plutons are mainly associated with the present continental margins, i.e. those tectonic zones that finally developed into oceanic spreading systems. The Lebombo Monocline in Africa and the Vestfjella mountains in the Antarctica represent thick successions of seaward-dipping lava flows. We associate the emplacement of these voluminous lavas, and the spatially and temporally associated large plutons (e.g. Utpostane and Insizwa) in particular, with a position of these rocks directly over regions of mantle melting; (2) The Rukore and Gorongosa complexes and the Moeza dyke, central Mozambique, and the alkaline intrusions of western Dronning Maud Land define a broadly linear tectono-magmatic feature, possibly representing a major (~2000 km) lithospheric lineament. This purported lineament transects one of the rift arms of the Limpopo structure, the Mozambique zone of lithospheric thinning (Cox 1992), is associated with termination of the Nunaetsi-Sabi flexure, and may have been developed in response to tectonism and relatively small-scale melting along the Archaean–Proterozoic boundary (Fig. 32). We suggest that these felsic-alkaline plutons may manifest igneous activity in an aborted zone of lithospheric thinning away from the most active areas of rifting.

The position of the unexposed Archaean–Proterozoic lithospheric boundary is not firmly established in the strongly tectonized region to the east of the Lebombo Monocline and to the west of the Jutulstraumen zone (Fig. 32). Previous geophysical surveys have been interpreted to locate the boundary in northern Vestfjella (Corner 1994) and beneath the sedimentary plains of southern Mozambique (Lächelt 2004) (Fig. 33). These interpretations have been supported in the Antarctica by evidence for Archaean contaminants of basalts in northern Vestfjella (Luttinen & Furnes 2000). Rather similarly, the recent geochronological studies of the Pessene alkaline intrusion provide evidence for involvement of Archaean material in the petrogenesis of these rocks (GTK Consortium 2006a). Specifically, U-Pb dating of zircon separates of a Pessene nepheline syenite revealed anomalous old zircon fractions that have been probably derived from both Proterozoic

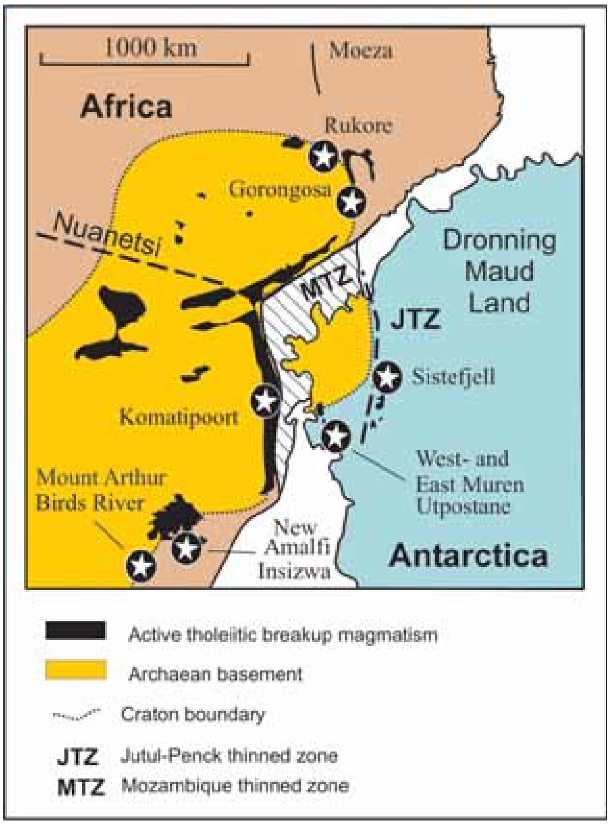

Fig. 32. Distribution of ~180 Ma gabbroic and felsic-alkaline pluton-size intrusives (stars) and major tectonic zones in a tight reconstruction of Karoo LIP. The ~N-S and ~NW-SE trending dykes and faulting in Moeza, Gorongosa, and Rukore extend towards the Jutul-Penck zone of western Dronning Maud Land, Antarctica.

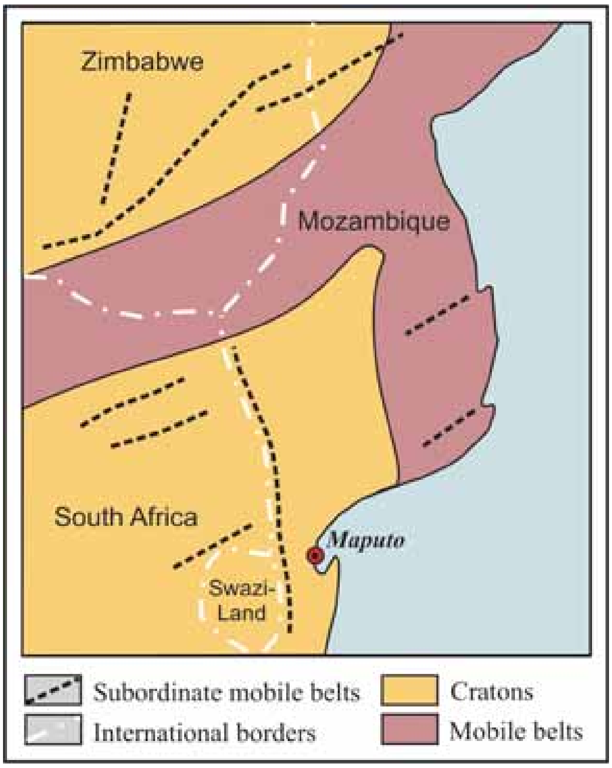

Fig. 33. Purported extensions of Archaean cratons and Proterozoic mobile belts in southern Mozambique (modified from Lächelt 2004).

and Archaean material in sedimentary rocks, crystalline basement, or both (GTK Consortium 2006b). Although we cannot positively identify the source of the inherited zircons, their presence is compatible with extension of the Archaean craton beneath the Movene Basalt Formation (Lächelt 2004).

A model of post-volcanic tectonic movements in the Movene Formation

The break-up of Gondwana and the emplacement of the Karoo province was associated with and followed by complex tectonic events including extension, transtension, and faulting (GTK Consortium 2006a, b). Coast-parallel dolerite dyke swarms have been frequently associated with extension tectonics, but the emplacement of the late-stage Rooi Rand dykes in southern Lebombo at 174–172 Ma (Jourdan *et al.* 2007b) may have been related to continent-scale strike-slip faulting along the Gastre Fault (Watkeys & Sokoutis 1998). Further evidence of marked syn-magmatic and post-magmatic N-S faulting and lateral displacement of lithospheric blocks can be observed in the area of Gorongosa pluton, central Mozambique (GTK Consortium 2006b). These displacements can be also associated with the N-S trending Moeza dyke that extends further North to the Zambia.

The plains of southern Mozambique and the coastal area of western Dronning Maud Land are of key importance to pre-break-up Gondwana reconstructions (e.g., Lavwer *et al.* 1992). Both regions probably represent areas of strongly tectonized and thinned lithosphere, but the tectonic movements are difficult to define due to poor exposure of bedrock. Aeromagnetic data and field observations may facilitate reconstruction of the post-volcanic tectonic evolution of the Movene Formation, however. Here we present a schematic tectonic model that has resonance for the stratigraphy of the Karoo-related lavas and the late-stage tectonic events related to Gondwana break-up.

Karoo-related lavas are commonly continuous and elongated subhorizontal sheets. The Pequenos Libombos rhyolites in the Movene Formation form discontinuous ridges, however, and these may indicate tectonic activity and displacement of crustal blocks. In recently published geological maps, the Pequenos Libombos rhyolites are divided into two units separated by a narrow zone of Movene basalts and crosscutting SW-NE trending dolerites (Fig. 34a). The facing edges of the rhyolite units strike NW-SE (Fig. 34a); the overall appearance of the units raises the question whether they could represent displaced pieces of an originally continuous rhyolite unit. This possibility is illustrated in Fig. 34 and discussed below.

The model stems from the hypothesis that the Pequenos Libombos rhyolites initially constituted a single, gently eastward dipping unit broadly parallel to Umbelúzi rhyolites (Fig. 34b). As the first post-magmatic tectonic event, the Movene Forma-

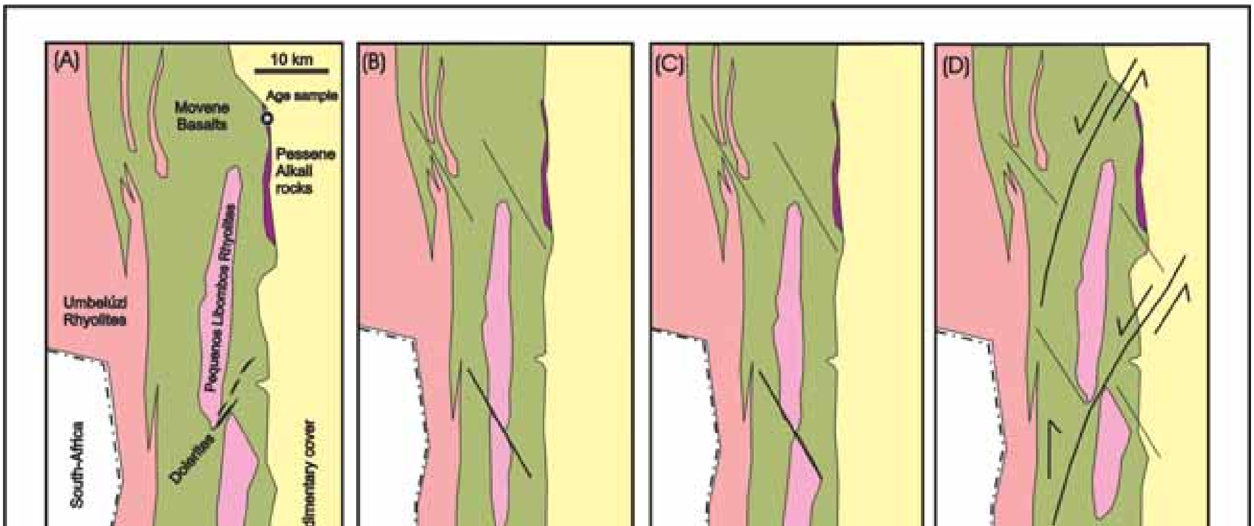

Fig. 34. Geological map of the Pequenos Libombos area (a) and its possible tectonic evolution: from suggested original situation (b) via faulting and movements (c, d) to current day configuration (a). See text for further details.

tion and the Pequenos Libombos rhyolites were cut by NW-SE-trending faults that are broadly parallel to the Botswana dyke swarm (Fig. 34b; Reeves 1978). Subsequently, the Pequenos Libombos unit was split in two parts that were sinistrally displaced along the NW-SE-trending faults (Fig. 34c). Given that the Umbelúzi rhyolites do not show evidence of similar displacement, the displacement within the Movene Formation probably was associated with rotation that led to relative uplift of the southern part of Pequenos Libombos. The rotation axis probably was close to the surface of the Umbelúzi rhyolites. The third tectonic event in this model involves NE-trending sinistral strike-slips (Fig. 34d), possibly associated with large-scale N-S movements that are observed also in central Mozambique. The intrusion of SW-NE-trending dolerites between the two parts of Pequenos Libombos may have been related to this event. We emphasize the speculative nature of the tectonic model. However, the 3-stage model illustrates possible tectonic discontinuities that may complicate stratigraphic studies of the Movene Formation. The model is compatible with the current distribution of Pequenos Libombos rhyolites and the occurrence of basalts and dolerites between the rhyolitic units, and it is also accordant with our observations in the central part of Mozambique, where N-S-trending structures are associated with Karoo-related extrusive and intrusive rocks.

CONCLUSIVE REMARKS

1. The Karoo-related volcanic rocks of southern and central Mozambique have mainly subalkaline affinities and include mafic, intermediate, and felsic varieties – intermediate compositions are relatively rare. The mafic rocks are lava flows that typically exhibit characteristic features of ropy lava. The felsic rocks are mainly ash-flow tuffs and ignimbrites.
2. The Movene Formation represents the capping unit of the Lebombo volcanic succession, but the exact age relationship between the ~182 Ma volcanic rocks in South Africa and the Movene basalts is unknown. Volcanic rocks belonging to the Nuanetsi-Sabi flexure in central Mozambique probably correlate with the ~182 Ma Sabie River Formation on the basis of geochemical similarity. Basalts and rhyolites in the Tete Province show affinities to Karoo lavas in Bostwana and Lesotho areas and presumably also erupted during the main-stage of magmatism at ~182 Ma.
3. The margins of Archaean cratons were associated with both felsic-alkaline and mafic igneous activity during the break-up of Gondwana. This is manifested by the new age data that delineates ~2000 km long chain of pluton-size intrusives both in southern Africa and in Antarctica.
4. The N-S trending structures associated with the Gorongosa and Rukore intrusive complexes and the Moeza dyke in central Mozambique may indicate large-scale lineaments and possible zones of crustal thinning. Magmatism and tectonism along this structure may correlate with Karoo-related alkaline intrusive activity within the Jutul-Penck tectonic zone in western Dronning Maud Land, Antarctica. Tectonic processes probably caused sinistral crustal dislocations during and/or after the emplacement of intrusive and extrusive Karoo magmas.
5. Inherited Archaean zircons in Pessene nepheline syenite imply extension of the Kaapvaal craton beneath the Mozambique Basin.

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Appendix 1. Chemical compositions of the Karoo volcanic rocks. The analyses are divided to the three locations shown in Figure 2. XRF analyses are made in the Chemical laboratory of GTK except rocks samples marked by *, which are analysed in the laboratory of the Department of Geology at the University of Helsinki. b.d.= below detection limit, ** = iron as FeOt

Location	Lebombo monocline																	
Formation	Sabie River	Umbelúzi							Movene									
Code	JrSba	JrUt	JrUt	JrUt	JrUr	JrUg	JrUr	JrUt	JrM	JrM	JrM	JrM	JrM	JrM	JrMq	JrMq	JrMfr	JrMr
Rock type	Basalt	Trachy-dacite	Dacite	Trachy-dacite	Rhyolite	Micro-granite	Rhyolite	Rhyolite	Basalt	Basalt	Basalt*	Basalt*	Basalt*	Basalt*	Quartz latite*	Quartz latite	Rhyolite	Rhyolite
SiO_2 wt%	49,3	67,6	64,2	62,8	73,6	67,6	68,7	69,1	50,0	52,05	50,29	49,92	55,21	51,00	65,2	66,8	77,5	72,7
TiO_2	5,18	0,83	0,85	1,21	0,60	0,73	0,67	0,63	3,67	1,58	4,40	3,82	1,85	3,93	0,53	0,36	0,33	0,39
Al_2O_3	13,2	12,8	12,4	13,4	11,2	13,1	12,9	12,8	13,9	13,69	12,24	13,14	12,69	12,46	15,7	15,2	11,7	13,2
Fe_2O_3t	13,12	6,77	9,00	8,39	5,09	6,82	5,60	5,92	14,97	13,26	14.74**	14.27**	12.87**	14.63**	4.41**	4,11	2,25	3,81
MnO	0,15	0,22	0,16	0,16	0,12	0,14	0,13	0,14	0,21	0,25	0,21	0,23	0,22	0,26	0,13	0,11	0,01	0,02
MgO	5,65	0,68	0,69	1,53	0,35	0,65	0,53	0,53	4,06	5,51	4,48	4,39	4,33	4,30	1,59	1,19	0,07	0,24
CaO	9,40	2,77	3,17	3,04	0,94	2,51	2,41	2,32	8,13	10,59	9,11	9,24	8,73	8,75	2,46	2,18	0,46	0,52
Na_2O	2,08	3,67	2,81	3,78	3,35	3,62	2,99	3,53	2,81	2,63	2,52	2,68	2,86	2,60	5,14	5,12	2,67	2,71
K_2O	0,85	3,76	3,90	4,12	3,81	4,07	4,76	4,23	1,21	0,29	1,31	0,99	0,99	1,09	4,24	4,39	4,42	5,24
P_2O_5	0,60	0,25	0,31	0,34	0,16	0,23	0,20	0,17	0,44	0,16	0,69	1,32	0,23	0,99	0,12	0,08	0,04	0,09
Total	99,52	99,35	97,50	98,76	99,22	99,47	98,87	99,36	99,39	100,01	99,99	100,00	99,98	100,01	99,51	99,54	99,46	98,92
Cr ppm	115	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	36	62	80	28	16	12	b.d.	b.d.	b.d.	b.d.
Ni	110	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	30	47	50	21	28	20	30	b.d.	b.d.	b.d.
Sc	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	34	45	36	34	44	39	b.d.	b.d.	b.d.	b.d.
V	442	34	43	97	30	b.d.	36	b.d.	487	400	404	279	381	255	70	40	b.d.	b.d.
Zr	440	1063	1066	982	1099	1081	1016	1114	279	113	374	460	315	796	460	474	476	767
La	34	107	97	94	113	98	123	104	b.d.	22	16	41	40	55	60	58	116	178
Ce	98	207	199	200	180	219	247	207	75	37	81	115	93	152	160	145	220	298
Ba	380	1350	1078	1342	3218	1221	1715	1196	523	164	336	519	369	812	260	167	690	2693
Sr	980	197	199	280	113	208	190	181	371	170	263	320	134	372	160	106	51	107
Rb	17	107	114	106	113	113	124	124	28	12	29	30	42	34	410	465	153	182
Y	43	136	114	98	132	107	112	108	45	38	68	80	72	90	0	162	106	130
Nb	19	77	76	69	79	75	84	75	20	13	34	39	35	53	0	313	76	116
Th	b.d.	15	12	13	13	17	16	16	b.d.	3	5	4	7	5	30	38	17	20
S	b.d.	b.d.	88	b.d.	520	b.d.	164	b.d.	106	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	520
Fe#	0,70	0,91	0,93	0,85	0,94	0,91	0,91	0,92	0,79	0,71	0,77	0,76	0,75	0,77	0,74	0,78	0,97	0,94
Obs. no	23602	23184	23476-A	23571	17478	23621	23472	23522	23473	19441	19435	23342	17397-B1	19443	mzm3.1.05	23213	23147	17438
Easting	351766	402172	361577	376439	401822	342890	366027	358099	367891	418269	408155	411494	417399	413976	428131	428363	427827	423881
Northing	7412661	7127735	7414939	7361656	7152039	7467720	7412481	7421612	7412946	7175937	7185158	7257363	7047351	7176600	7123596	7123749	7085816	7099640

Appendix 1. Continues

Location	Lebombo Monocline						Nuanetsi-Sabie volcanic flexure				Lupata trough and Moatize-Luia graben							
Formation	Umbeluzi		Pessene	Pessene	Upper Karoo Dykes		Rio Nhavúdezi				Rio Nhavúd.	Rio Mazoe						
Member	JrMr	JrMr	JrPal	JrPns			JrN	JrN	JrN	JrN	JrN	JrIb	JrIb	JrIb	JrIb	JrIa	JrIa	JrIa
Rock	Rhyolite	Rhyolite	Alkaline lava	Nepheline syenite	Dolerite	Dolerite	Basaltic andesite	Basalt	Basalt	Basalt	Andesite	Basalt	Basalt	Basalt	Basalt	Basaltic andesite	Basaltic andesite	Andesite
SiO_2 wt%	76,4	76,4	48,65	52,0	51,7	47,8	53,0	49,70	50,30	53,60	58,70	46,00	46,60	52,40	54,80	55,70	56,10	61,60
TiO_2	0,21	0,19	2,93	0,85	3,19	2,16	1,28	2,61	1,19	1,23	1,97	0,45	0,95	1,13	1,28	1,53	1,41	0,79
Al_2O_3	12,3	12,0	15,65	19,9	12,9	16,4	14,0	13,50	14,70	14,20	10,80	10,50	16,10	15,00	14,80	15,10	14,10	13,60
Fe_2O_3t	2,21	2,37	11,39	6,02	15,25	14,27	11,1	15,64	11,48	11,67	11,53	11,80	10,80	10,30	11,60	10,70	12,00	6,60
MnO	0,01	0,03	0,37	0,38	0,20	0,14	0,14	0,22	0,14	0,16	0,10	0,16	0,14	0,17	0,11	0,10	0,17	0,11
MgO	0,04	0,06	3,47	0,41	3,22	4,32	6,12	4,96	6,52	4,94	3,03	20,20	7,08	4,91	3,34	3,25	3,31	3,94
CaO	0,20	0,26	8,11	2,45	7,18	10,02	6,96	9,55	10,60	8,59	3,55	6,35	12,20	8,99	7,74	6,03	7,14	5,78
Na_2O	2,57	2,77	5,89	8,29	2,90	2,57	3,91	2,60	2,27	2,53	1,74	1,21	2,33	2,80	3,03	3,45	3,02	1,90
K_2O	5,47	5,45	2,28	6,19	1,99	0,33	0,49	0,56	0,85	0,87	2,69	0,42	0,56	1,66	1,82	2,67	1,80	3,61
P_2O_5	0,02	0,01	1,27	0,11	0,99	0,41	0,13	0,27	0,14	0,17	0,47	0,08	0,25	0,18	0,22	0,35	0,27	0,13
Total	99,42	99,54	100,01	96,61	99,52	98,42	97,14	99,61	98,19	97,95	94,58	97,17	97,01	97,54	98,75	98,88	99,32	98,07
Cr ppm	b.d.	b.d.	22	b.d.	b.d.	166	220	70	508	98	b.d.	2080	230	270	110	40	40	230
Ni	b.d.	b.d.	b.d.	b.d.	b.d.	114	130	33	215	61	b.d.	820	130	90	70	20	b.d.	70
Sc	b.d.	b.d.	6	b.d.	34	33	b.d.	41	b.d.	b.d.	b.d.	b.d.	40	30	b.d.	b.d.	40	b.d.
V	b.d.	b.d.	b.d.	60	283	340	260	434	293	295	264	160	260	250	290	240	300	150
Zr	450	390	1618	1440	598	270	90	190	100	133	212	50	70	140	150	310	190	380
La	b.d.	b.d.	274	186	62	34	b.d.	b.d.	b.d.	b.d.	36	0	b.d.	30	40	40	30	70
Ce	113	240	540	276	154	74	b.d.	47	36	52	72	30	40	60	60	90	70	130
Ba	466	420	1262	2447	679	313	140	155	259	410	544	160	380	560	530	600	580	860
Sr	20	20	1977	3127	355	395	220	220	195	267	57	110	340	220	220	220	230	220
Rb	192	210	75	168	48	11	10	11	30	28	91	20	10	60	70	90	50	80
Y	101	0	82	65	72	46	0	42	24	21	30	10	20	30	20	50	40	40
Nb	118	0	348	363	45	27	b.d.	14	9	9	12	b.d.	20	b.d.	10	30	20	40
Th	22	20	36	26	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	10
S	b.d.	b.d.	b.d.	160	436	b.d.	b.d.	336	60	193	358	b.d.	b.d.	100	b.d.	b.d.	60	60
Fe#	0,98	0,98	0,77	0,94	0,83	0,77	0,65	0,76	0,64	0,70	0,79	0,37	0,60	0,68	0,78	0,77	0,78	0,63
Obs. no	23194-A	mzm3.2.05	19445-A	17441	23476-B	23642	24781	10705,1	10707	10704	34481	14076	14264	14249	15082	14103	14101	14252
Easting	422028	428189	430758	431268	361577	430808	473912	608534	612002	609263	635136	414913	531390	540611	535036	398662	396767	538770
Northing	7119151	7121897	7157784	7150430	7414939	7113337	7708061	7842728	7849038	7843748	8017203	8220669	8171272	8170894	8138896	8197345	8194082	8170546

Appendix 1. Continues

Location	**Lupata trough and Moatize-Luia graben**										
Formation	**Chueza**				**Bangomateta**						**Serra Bombue**
Member	JrC	JrC	JrC	JrC	JrBb	JrBb	JrBr	JrBr	JrBr	JrBr	JrSb
Rock	Basalt	Mafic dyke	Basaltic andesite	Andesite	Basaltic andesite	Andesite	Dacite	Rhyolite	Rhyolite	Rhyolite	Rhyolite
SiO_2 wt%	52,40	52,60	56,60	57,30	55,60	61,50	68,40	70,10	73,70	78,00	70,60
TiO_2	1,29	1,05	0,81	0,89	1,97	0,98	0,72	0,44	0,56	0,55	0,80
Al_2O_3	14,10	15,20	13,70	14,50	14,10	13,30	13,20	13,40	12,90	9,10	11,60
Fe_2O_3t	11,64	13,10	10,01	9,61	11,90	7,82	4,52	4,53	2,74	4,17	5,97
MnO	0,22	0,20	0,14	0,13	0,09	0,12	0,07	0,07	b.d.	0,03	0,08
MgO	6,16	4,46	7,46	5,40	2,51	2,42	0,64	0,25	0,06	0,48	0,66
CaO	9,18	8,99	6,85	7,03	3,54	3,07	1,86	0,54	0,19	1,46	1,53
Na_2O	2,36	2,76	2,16	2,35	3,22	2,52	3,59	3,09	1,12	1,62	2,81
K_2O	1,17	1,10	1,29	1,92	3,46	4,26	1,39	5,87	6,38	4,17	5,11
P_2O_5	0,18	0,21	0,12	0,14	0,62	0,21	0,18	0,05	0,08	0,12	0,18
Total	98,69	99,67	99,14	99,27	97,02	96,18	94,57	98,34	97,74	99,71	99,35
Cr ppm	300	40	417	251	b.d.	b.d.	50	b.d.	b.d.	70	b.d.
Ni	74	70	74	52	b.d.	b.d.	30	b.d.	b.d.	30	b.d.
Sc	32	40	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.	b.d.
V	301	330	224	212	220	121	70	0	0	60	77
Zr	142	120	117	130	340	490	340	830	761	200	290
La	b.d.	b.d.	b.d.	32	50	81	50	160	127	30	61
Ce	38	50	55	58	100	169	100	260	255	50	99
Ba	434	340	409	559	750	792	820	1140	1195	640	1244
Sr	169	170	198	205	200	155	130	60	48	100	119
Rb	40	50	49	67	110	165	180	200	239	130	200
Y	29	30	23	23	50	72	40	90	205	20	35
Nb	12	b.d.	9	12	30	74	30	90	98	b.d.	20
Th	b.d.	b.d.	b.d.	b.d.	b.d.	20	20	30	29	b.d.	24
S	b.d.	120	b.d.	b.d.	b.d.	622	600	b.d.	499	b.d.	94
Fe#	0,65	0,75	0,57	0,64	0,83	0,76	0,88	0,95	0,98	0,90	0,90
Obs. no	14734	15065	17211	17214	14071	17198	14114	14260	14503,2	14087	34490
Easting	624901	597229	628949	629546	420215	521520	405729	535392	524478	409038	636880
Northing	8092174	8169736	8073975	8074634	8227326	8175109	8207966	8169354	8168964	8212677	8016042