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**Notes**

# New U–Pb SHRIMP ages from the Lubango region, SW Angola: insights into the Palaeoproterozoic evolution of the Angolan Shield, southern Congo Craton, Africa

S. McCOURT<sup>1</sup>, R. A. ARMSTRONG<sup>2</sup>, H. JELSMA<sup>3</sup> & R. B. M. MAPEO<sup>4</sup>

<sup>1</sup>*Geological Sciences, School of Agricultural, Earth and Environmental Sciences, University of KwaZulu-Natal, Durban, South Africa*

<sup>2</sup>*Research School of Earth Sciences, The Australian National University, Canberra, ACT, Australia*

<sup>3</sup>*De Beers Group Services, Southdale, Johannesburg, South Africa*

<sup>4</sup>*Department of Geology, University of Botswana, Gaborone, Botswana*

\*Corresponding author (e-mail: [mccourts@ukzn.ac.za](mailto:mccourts@ukzn.ac.za))

**Abstract:** In an attempt to better understand the tectonic evolution of the continental crust forming SW Angola, zircon grains from the principal Precambrian rock types exposed in the Lubango area have been analysed using the sensitive high-resolution ion microprobe method. U–Pb ages of  $2038 \pm 28$  Ma and  $1954 \pm 6$  Ma were obtained on weakly deformed granite samples from the basement below the Humpata Plateau. The Chela Group on the Humpata Plateau is a relatively undeformed Palaeoproterozoic supracrustal sequence with an eruptive age of  $1798 \pm 11$  Ma on ignimbrite of the Humpata Formation. The age of the northern part of the Kunene Complex is constrained by zircon data from a xenolith of basement gneiss and a mangerite dyke cutting anorthosite, which give an emplacement age of  $1385 \pm 7$  Ma. The c. 2.0 Ga granites below the Chela Group are part of a Palaeoproterozoic granitoid terrane that extends from north of Lubango in Angola into NW Namibia. This terrane is referred to as the Angolan Shield. Regionally, the Angolan Shield is interpreted to be part of a Palaeoproterozoic magmatic arc that extends NE from Angola and Namibia under Phanerozoic cover into NW Zambia. The resultant crustal terrane defined the southern margin of the developing Congo Craton at c.  $2.0 \pm 0.04$  Ga.

**Supplementary materials:** Tables summarizing the zircon U–Pb data are available at [www.geolsoc.org.uk/SUP18577](http://www.geolsoc.org.uk/SUP18577).

The Late Precambrian structural framework of southern and central Africa is dominated by the Kalahari and Congo cratons, which are crustal blocks that stabilized following Mesoproterozoic orogenesis (e.g. Hanson 2003). The Kalahari Craton (Fig. 1) comprises the Archaean Kaapvaal Craton, Limpopo Belt and Zimbabwe Craton, the Palaeoproterozoic Magondi–Gweta Belt and Rehoboth Block, and the Mesoproterozoic Namaqua–Natal Belt. The southwestern part of the Congo Craton comprising the Angolan Shield and contiguous Kasai Craton (Fig. 1) is presumed to preserve a record of crustal evolution similar to that of the Kalahari Craton but this is poorly documented. Regional geological and geochronological studies were carried out in southern Angola during the early 1970s (de Carvalho *et al.* 1987; de Carvalho & Alves 1993, and references therein) and identified the presence of widespread Palaeoproterozoic crust, dominated by granitoids, together with a limited amount of Archaean crust (for a summary, see de Carvalho *et al.* 2000). This basement terrane, which constitutes the Angolan Shield, is intruded by anorthosite of the Kunene Complex, a set of Mesoproterozoic (red) granites, and is unconformably overlain by supracrustal sequences that include the Chela Group. The Neoproterozoic Kaoko belt extends from the coast of Namibia northwestwards under the Phanerozoic cover into the southwestern corner of Angola where it is exposed as the Iona belt (de Carvalho *et al.* 2000) and along the coast further north as the ‘Angolan belt’ (Delor *et al.* 2006).

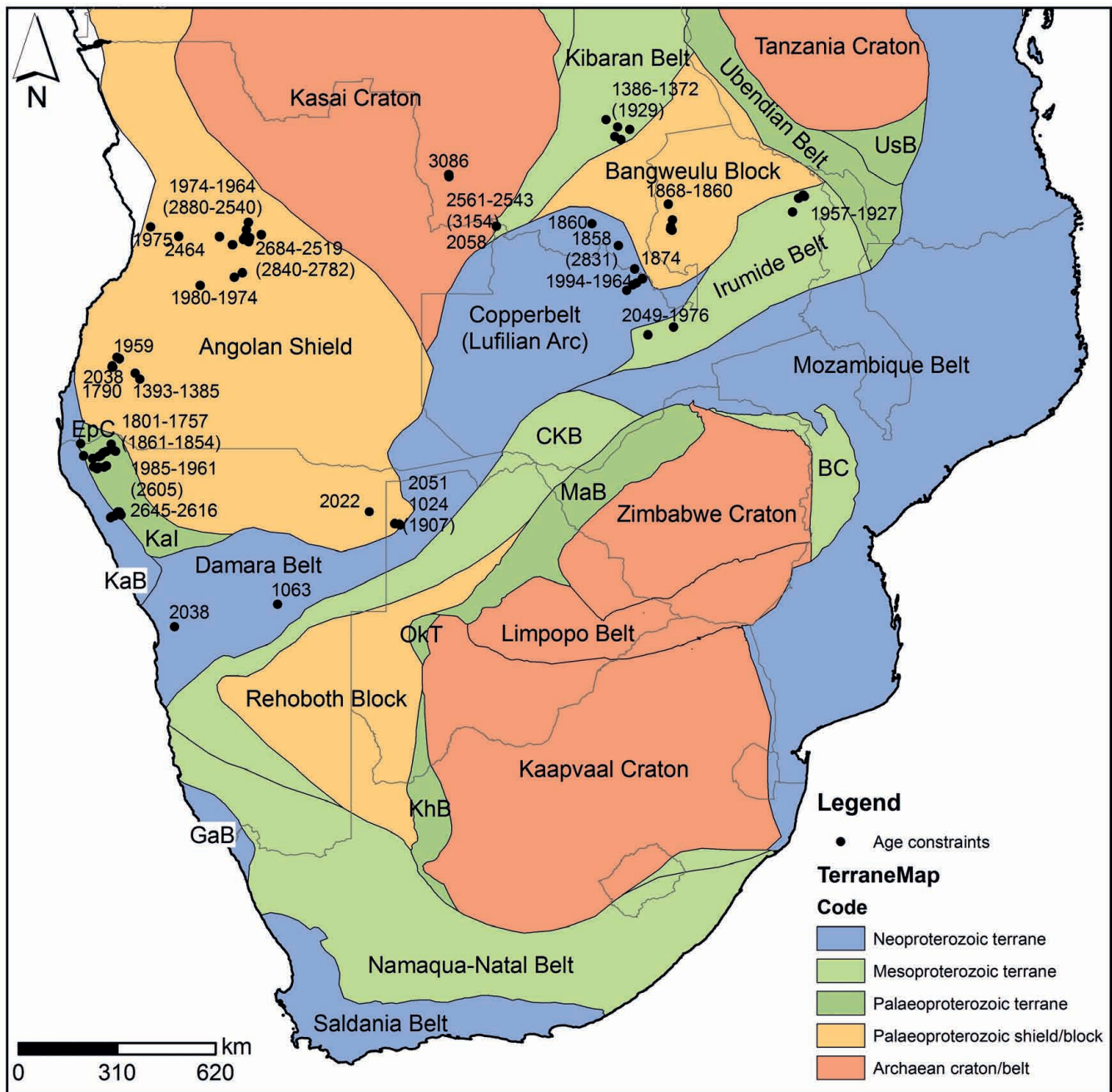
Following de Carvalho *et al.* (2000), Jelsma *et al.* (2011) recognized four broad tectonic domains within the Angolan Shield, comprising the Central Shield Zone and Cassinga Zone in the east and the Central Eburnean Zone and Lubango Zone in the west (Fig. 2) In this paper we report the results of precise U–Pb sensitive

high-resolution ion microprobe (SHRIMP) analysis of zircon grains from three important Precambrian rock units (basement granites, the Chela Group and the Kunene Complex) in the Lubango Zone. We use these new age data to place constraints on the tectonic evolution of the Angolan Shield and to evaluate suggested regional correlations. The study forms part of a regional project dealing with the Precambrian crustal evolution of southern and central Africa and is a contribution to IGCP 418 (The Kibaran of southwestern Africa).

## The geology of SW Angola

Recent accounts of the regional geology of SW Angola (here defined as the area south of  $13^\circ\text{S}$  and west of meridian  $18^\circ\text{E}$ ; Fig. 2) are based on field work prior to 1975 and best documented in publications by Cahen *et al.* (1984), de Carvalho *et al.* (1987) and in particular de Carvalho & Alves (1993). de Carvalho *et al.* (2000) provided a review of the Rb–Sr age data for western Angola whereas Mayer *et al.* (2004) reported Sm–Nd, Rb–Sr and U–Pb data for rocks of the Kunene Complex in Angola. Drüppel *et al.* (2007) documented new geochemistry and Nd, Sr and O isotope data for the anorthosites and associated felsic dykes from the southward extension of the Kunene Complex in NW Namibia together with a U–Pb zircon age for the emplacement of the felsic rocks. Delor *et al.* (2006) and Jelsma *et al.* (2011) reported as yet unpublished U–Pb zircon ages from the Central Shield Zone west of Andulo and the Central Eburnean Zone near Huambo (Fig. 2).

The regional geology of SW Angola is shown in Figure 2 and outlined briefly below. The main Precambrian lithostratigraphic units together with the most recently reported age data

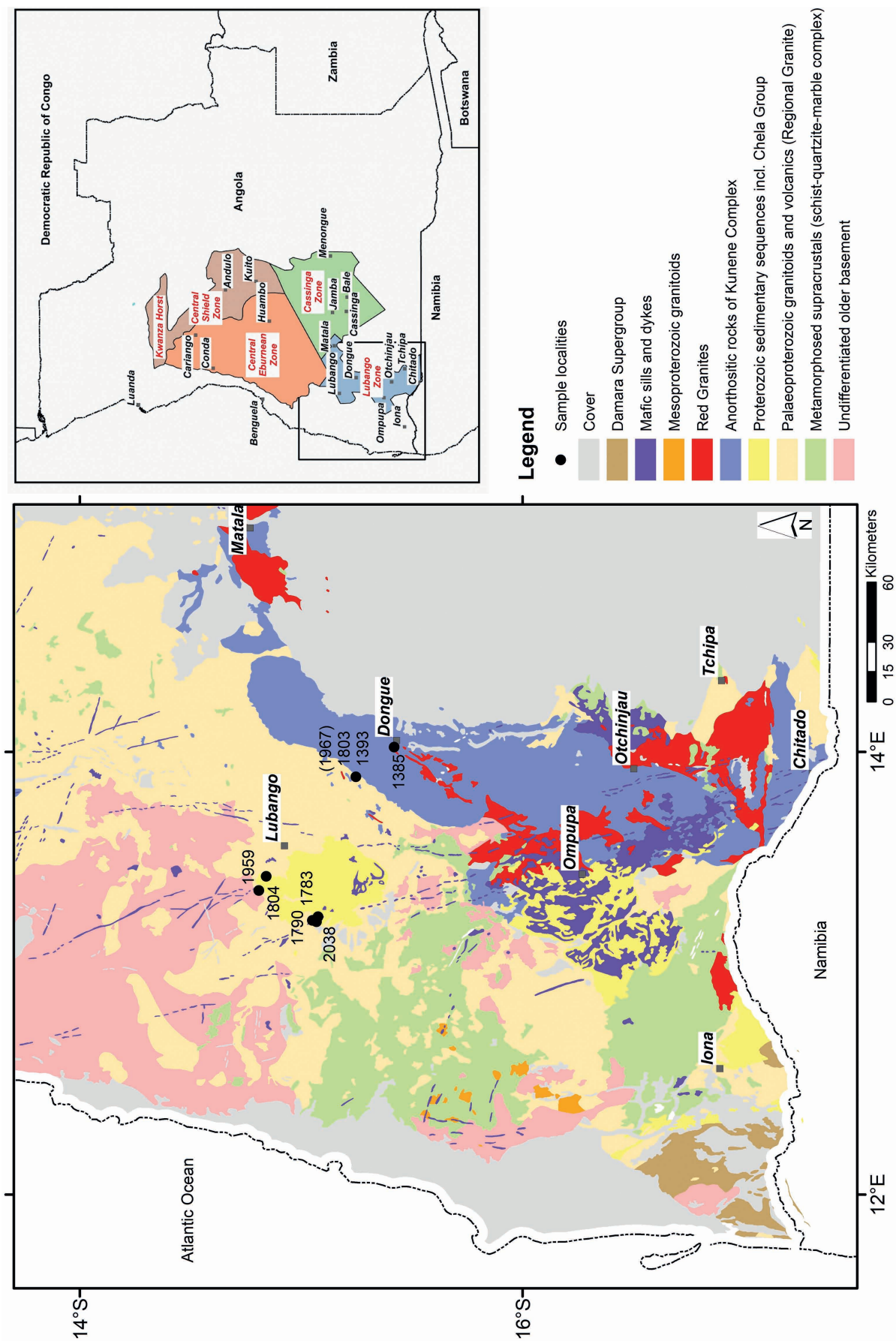


**Fig. 1.** Geographic information system (GIS)-based map showing the Precambrian tectonic framework of southern Africa, after Hanson (2003) and this study. Geochronological data shown are recently published U–Pb zircon ages and age ranges for granitoids and associated volcanic rocks along the southern margin of the Congo Craton as cited in the text; ages in parentheses are from zircon grains interpreted as xenocrysts. Epc, Epupa Complex; Kal, Kamanjab Inlier; KaB, Kaoka Belt; GaB, Gariiep Belt; KhB, Kheis Belt; OkT, Okwa Terrane; MaB, Magondi–Gweta Belt; CKB, Choma–Kaloma Block; BC, Barue Complex; UsB, Usagaran Belt. The Mesoproterozoic terranes labelled Namaqua–Natal Belt, Choma–Kaloma Belt (CKB) and Barue Complex (BC) define the margins of the Kalahari Craton.

for these rocks are summarized in Table 1 and the principal localities mentioned in the text are indicated on the inset map in Figure 2.

Polymetamorphic gneisses and migmatite cropping out to the south of Cariango, in the Andulo area, to the north of Matala and SE of Cassinga constitute the Archaean component of the Central Shield and Cassinga Zone (de Carvalho *et al.* 2000; Jelsma *et al.* 2011). Published ages (de Carvalho *et al.* 2000) are based predominantly on Rb–Sr whole-rock isochron data whereas those reported

by Delor *et al.* 2006 (2590–2520 Ma) and by Jelsma *et al.* 2011 (ages between 2682 and 2519 Ma) are based on U–Pb SHRIMP analyses of zircon. Field relationships of these Archaean gneisses are either as relicts or enclaves within the Eburnean (Palaeoproterozoic) Regional Granite (see below) or locally (e.g. near Andulo) the Regional Granite is intrusive into the gneisses (de Carvalho & Alves 1993; Jelsma *et al.* 2011). In addition to the granitoids de Carvalho & Alves (1993) described a greenstone-belt-like sequence resting unconformably on gneissic basement and intruded by



**Fig. 2.** GIS-based map showing the regional geology of SW Angola (after de Carvalho & Alves 1993) with several towns for reference. Age data refer to the samples analysed as part of the present study. Inset map shows the position of the main localities mentioned in the text and the tectonic domains of southern Angola as recognized by de Carvalho *et al.* (2000); box outlines area covered by the geological map.

**Table 1.** Precambrian lithostratigraphic units of SW Angola (after de Carvalho *et al.* (2000) and other references cited)

Lithostratigraphic unit	Principal rock types	Age (Ma)	Comment
<i>Neoproterozoic</i>			
Damara Supergroup	Quartzite, conglomerate, marble, amphibolite, schist	No published ages	Interpreted as an extension of the Nosib Group in northern Namibia
<i>Mesoproterozoic</i>			
Leba–Tchamalindi Formation	Stromatolitic dolomite, chert and anhydrite	No published ages	Unconformable on Chela Group (de Carvalho <i>et al.</i> 1987)
Chela Group	Conglomerate, quartzite, sandstone, felsic volcanic rocks, argillite	No published ages	Unconformable on Ompupa Red Granite (1407±26 Ma, Rb–Sr) intruded by norite sills, dykes dated at 1119±27 Ma (Rb–Sr)
Red Granite	Granite, granodiorite, syenite, rhyolitic porphyry	Otechinjau 1411±24 Ma; Ompupa 1407±26 Ma; Matala 1350±65 Ma; Rb–Sr ages	Intrusive into the anorthosite of the Kunene Complex and the supracrustal rocks of the Tchippia–Iona and Cahama–Otechinjau formations (de Carvalho <i>et al.</i> 1987)
Kunene Complex	Massive anorthosite, leucotroctolite, leucogabbro, mangerite, syenodiorite	c. 1385 Ma with felsic rocks at c. 1374 Ma	Ages from Mayer <i>et al.</i> (2004) and Drüppel <i>et al.</i> (2007), U–Pb zircon
<i>Palaeoproterozoic</i>			
Leucocratic Granite (Macota-type)	Fine- to medium-grained equigranular granite	1763±21 Ma whole-rock isochron	Late Eburnean granitoids linked to the ‘Namib’ thermotectonic event by de Carvalho <i>et al.</i> (2000)
Tchippia–Iona Formation	Quartzite, arkose, chert, rare marble; felsic volcanic rocks	No published ages	Correlated with the c. 1860 Ma Khoabendus Group, Namibia
Bale, Oendolongo Groups	Quartzite, conglomerate, shale, sandstone; felsic volcanic rocks	No published ages	Unconformable on the Chivanda and Jamba groups
Regional Granite	Biotite granite, granodiorite and tonalite	Quipungo 2191±60 Ma; Cela 2236± Ma (Rb–Sr); Lubango 2038±28 Ma (this study, U–Pb zircon); Huambo 1987±16 Ma (Delor <i>et al.</i> 2006; U–Pb zircon), 1967±5 Ma (Jelsma <i>et al.</i> 2011; U–Pb zircon)	Regionally dominant granitoid, intrusive into Archaean gneiss–migmatite complex; basement to Chela Group rocks
Chivanda Group	Quartzite, conglomerate, sandstone, pillow lava, felsic volcanic rocks, schist	Felsic schist 2149±83 Ma; black schist 1915±58 Ma (Rb–Sr ages)	Metamorphosed supracrustal sequences; intruded by the Regional Granite
Schist, quartzite amphibolite complex with marble	Chert, schist, quartzite, amphibolite, marble		
<i>Archaean</i>			
Jamba Group	Schist, greywacke, pillow lava, chert, felsic volcanic rocks, pelite	No published ages	Unconformable on gneissic basement, intruded by Regional Granite
Granite, gneiss and migmatite complex	Granitic, tonalitic gneiss and migmatite	Cariango 2522±108 Ma; Andulo 2520±36 Ma (Rb–Sr), 2533±11 Ma megacrystic gneiss, Andulo area (Jelsma <i>et al.</i> 2011; U–Pb age)	Neoproterozoic protoliths with xenocrysts back to 2782 Ma (Jelsma <i>et al.</i> 2011)

Palaeoproterozoic granite. They referred to this greenstone-like sequence as the Jamba Group and regarded it as Archaean in age although no age data are available.

Proterozoic granitoid rocks of SW Angola comprise the Palaeoproterozoic Regional Granite and the Mesoproterozoic Red Granite (de Carvalho & Alves 1993). Palaeoproterozoic granitoids are the dominant component of the Angola Shield. They occur in each of the tectonic zones recognized by de Carvalho *et al.* (2000) but are especially well developed in the Central Eburnean Zone and the Lubango Zone (Fig. 2). The Regional Granite is typically gneissic in character and although there are a large number of published ages for these intrusions they are exclusively Rb–Sr whole-rock isochron dates and their geological significance is unclear. Delor *et al.* (2006) reported as yet unpublished U–Pb ages of 1980±9 Ma and 1987±16 Ma for granite from the Huambo area, in agreement with ages of 1967±5 Ma and 1966±3 Ma (Jelsma *et al.* 2011) from west of Andulo (Figs 1 and 2)

The Red Granite (de Carvalho & Alves 1993) is well developed in the Matala region east of Lubango and the Ompupa–Otechinjau–Chitado region to the SE (Fig. 2). The granite occurs as elongate NE–SW-trending bodies intrusive into the anorthosite of the Kunene Complex and the supracrustal rocks of the Tchippia–Iona Formation (de Carvalho & Alves 1993; Table 1). In addition to granite, monzonite, syenite, charnockite, mangerite and rhyolitic porphyry have been documented. Rb–Sr ages for the Red Granite in SW Angola fall in the range 1300–1400 Ma (see Table 1) whereas in NW Namibia Seth *et al.* (2005) obtained a precise U–Pb SHRIMP age of 1374±5 Ma on zircon from a body of red granite intruding granitoid gneiss of the Epupa Metamorphic Complex (EpC in Fig. 1).

Demonstrable Palaeoproterozoic supracrustal rocks are restricted to the Chivanda Group (de Carvalho & Alves 1993). This is a metasedimentary sequence constrained internally by imprecise Rb–Sr ages between 2160 and 1915 Ma and intruded by the

Regional Granite (Table 1). The Bale Group rocks are unconformable on the Chivanda Group and therefore younger. The identical relationship holds for the rocks defining the Oendolongo Group. Both sequences are unmetamorphosed and subhorizontal and from the literature (e.g. de Carvalho & Alves 1993) are unconformable on the Regional Granite. There are however no direct age constraints on either sequence. The Mesoproterozoic (*c.* 1375 Ma) Red Granites are intrusive into the metasedimentary rocks of the Tchippia–Iona and Cahama–Otechinjau formations (Table 1) for which they provide minimum age constraints. The rocks of the Tchippia–Iona Formation are locally folded; de Carvalho & Alves (1993) regarded them as Palaeoproterozoic in age and suggested that the unit may be equivalent to the Khoabendus Group of NW Namibia. The rocks of the Khoabendus Group form part of the basement terrane to the Neoproterozoic Damara Belt and are exposed in the Kamanjab Inlier (KaI in Fig. 1). Quartz porphyry from near the top of the Khoabendus Group has a SHRIMP U–Pb zircon age of  $1862 \pm 6$  Ma (Steven & Armstrong 2002).

Mesoproterozoic supracrustal rocks in SW Angola are included in the Chela Supergroup (de Carvalho & Alves 1993), comprising the Chela Group and overlying Leba–Tchamalindi Formation. The type area for the Chela Group is the Humpata Plateau region near Lubango (Correia 1976) but it has also been documented from the Ompupa region, and to the east of Iona (de Carvalho & Alves 1993; Fig. 2). There are no direct age constraints on the Chela Group exposed on the Humpata Plateau but the sequence in the Ompupa region is unconformable on the  $1407 \pm 26$  Ma Ompupa Red Granite (Table 1), and is intruded by noritic sills with a Rb–Sr isochron age of  $1119 \pm 27$  Ma. Based on these age constraints, de Carvalho & Alves (1993) assigned the Chela Group to the Mesoproterozoic ‘Kibaran Cycle’. Kröner & Correia (1980) have suggested that the Chela Group is a correlative of the Neoproterozoic Nosib Group in Namibia.

The Kunene Complex of SW Angola and the neighbouring part of Namibia is one of the largest massif-type anorthosite bodies in the world (Ashwal & Twist 1994; Mayer *et al.* 2004; Drüppel *et al.* 2007). The complex intruded along the southern margin of the Congo Craton and, in Angola, defines a NNE–SSW-trending elongate shape that covers an area of *c.* 15000 km<sup>2</sup> (Ashwal & Twist 1994; Fig. 2). Country rocks exposed along the western margin of the Complex comprise a variety of metamorphic and igneous rocks that include the Regional Granite (de Carvalho & Alves 1990). In the east, Cenozoic-age sediments of the Kalahari Group cover the Kunene Complex, thus its full extent is unknown. The dominant rock type is a massive dark anorthosite followed by leucotroctolite, troctolite, leucogabbro and subordinate norite (de Carvalho & Alves 1990). Ultramafic rocks appear to be absent (Ashwal & Twist, 1994). Mayer *et al.* (2004) noted the presence of dolerite at the northwestern margin of the complex and based on mutually intrusive relationships suggested that the dolerite is cogenetic with the anorthosite. Mayer *et al.* (2004) further noted that in proximity to the Red Granite, the Kunene Complex is characterized by massive Fe–Ti ore bodies and again suggested a genetic link between anorthosite, Fe–Ti ore bodies and at least some of the Red Granite. In NW Namibia, the Kunene Complex has a pronounced east–west elongation and consists mainly of heavily tectonized and pervasively altered pale-coloured anorthosite (Drüppel *et al.* 2007). The white anorthosite of NW Namibia is intruded by sheet-like bodies of dark, weakly altered anorthosite to produce the Zebra Mountains (Drüppel *et al.* 2007).

The age of the Kunene Complex, previously a matter of some debate (see de Carvalho *et al.* 2000, and references therein), is now well constrained. Mayer *et al.* (2004) documented a near concordant upper intercept age of  $1371 \pm 2.5$  Ma based on conventional

multigrain analyses of zircon from a mangerite dyke cutting anorthosite at Dongue (Fig. 2) in the northern part of the Kunene Complex. This is supported by a U–Pb single zircon age of  $1385 \pm 25$  Ma obtained on a sample from the dark anorthosite suite in Namibia (Drüppel *et al.* 2007) and compatible with a U–Pb upper intercept zircon age of  $1376 \pm 2$  Ma for the emplacement of a syenodiorite dyke associated with the anorthosite (Drüppel *et al.* 2007).

## The present study

In an attempt to better understand the tectonic evolution of south-western Angola, zircons from the principal Precambrian rock types exposed in the Lubango area were analysed using the SHRIMP at The Australian National University in Canberra. Three samples are from the Chela Group on the Humpata Plateau, two from the Kunene Complex and two from the basement below the Chela Group. The GPS coordinates of the samples analysed are given in the data table for the sample and the localities are indicated in Figure 2.

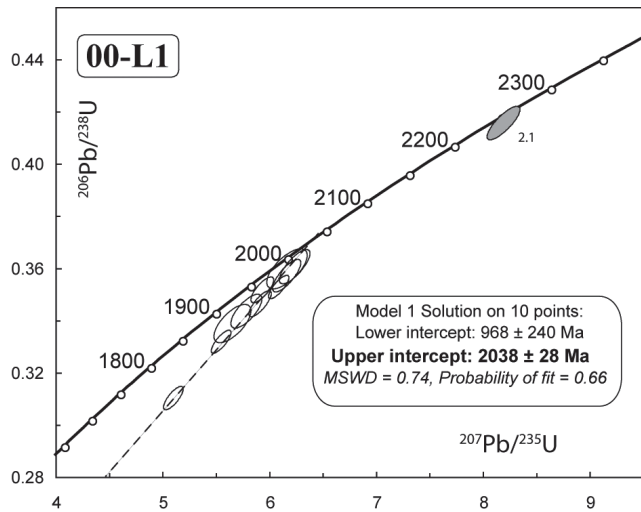
The granites (00-L1, 00-L10) were sampled in the same areas as the clastic rocks, and thus represent the immediately underlying basement to the Chela Group at both localities. Both granites were medium to coarse grained but they differed in texture. Sample 00-L1 was porphyritic and sample 00-L10 equigranular. The granites are not pervasively deformed but at both localities centimetre-scale high-strain zones, characterized by grain-size reduction and mineral alignment, are common.

The samples from the Chela Group consisted of siliceous volcanoclastic material from the Humpata Formation (00-L2), and two samples (00-L3, 00-L9) of quartz arenite from the Bruco Formation. Sample 00-L2 is from a fine-grained siliceous felsic rock with obvious shards, which we interpret as an ignimbrite. Sample 00-L3 was collected from the lower part of the Bruco Formation and comprised reddish cross-bedded sandstone with occasional well-rounded pebbles. Sample 00-L9 (cross-bedded quartzite) was collected from close to the top of the Bruco Formation.

The samples from the Kunene Complex are of a mangerite dyke (00-L4) intruding massive anorthosite and a xenolith of granitoid gneiss (CHN-1) collected by R.B.M.M. on an earlier visit to the complex. The mangerite was sampled near Dongue in the northern part of the Kunene Complex and thus probably represents the same material as analysed by Mayer *et al.* (2004). We agree with Mayer *et al.* (2004) that the lack of reaction rims, chilled margin and compositional zoning across the dyke suggest that the mangerite intruded while the anorthosite was still hot and may therefore be part of the complex. Taken together, the samples analysed provide minimum and maximum age constraints on the anorthosite of the Kunene Complex.

## Analytical techniques

The samples were crushed and the zircons were separated using standard magnetic and heavy liquid density separation techniques. The clean zircon separates were mounted in epoxy at the Research School of Earth Sciences (RSES), together with the RSES reference zircons AS3 and SL13. Zircons were handpicked under a binocular microscope (igneous rocks) or in the case of the detrital zircons, were scattered onto double-sided tape prior to encasing in epoxy to ensure a random selection of grains. Photomicrographs in transmitted and reflected light were taken of all zircons and these, together with SEM cathodoluminescence (CL) images, were used to decipher the internal structures of the sectioned grains and to select specific areas within the zircons for spot analysis. U–Pb analyses were carried out using SHRIMP I, SHRIMP II and



**Fig. 3.** Concordia plot showing zircon isotopic ratios and derived ages for basement granite sample 00-L1.

SHRIMP RG at the RSES. The data were reduced in a manner similar to that described by Williams (1998, and references therein), using the SQUID-1 Excel Macro of Ludwig (2000). For the zircon calibration the Pb/U ratios were normalized relative to a value of 0.1859 for the  $^{206}\text{Pb}/^{238}\text{U}$  ratio of AS3 reference zircons, equivalent to an age of 1099 Ma (Paces & Miller 1989). U and Th concentrations were determined relative to the SL13 standard.

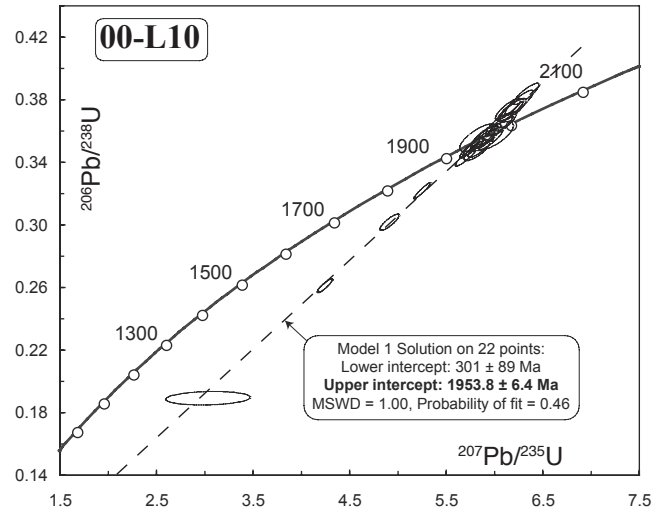
Uncertainties given for single analyses (ratios and ages) are at the  $1\sigma$  level, but uncertainties in any calculated weighted mean, concordia age (Ludwig 1998) or intercept age are reported as 95% confidence limits (unless indicated otherwise) and include the uncertainties in the standard calibrations where appropriate. Concordia plots, regressions and age calculations were carried out using Isoplot/Ex (Ludwig 1999) and SQUID-1 (Ludwig 2000).

#### Zircon morphology, SHRIMP results and interpretation

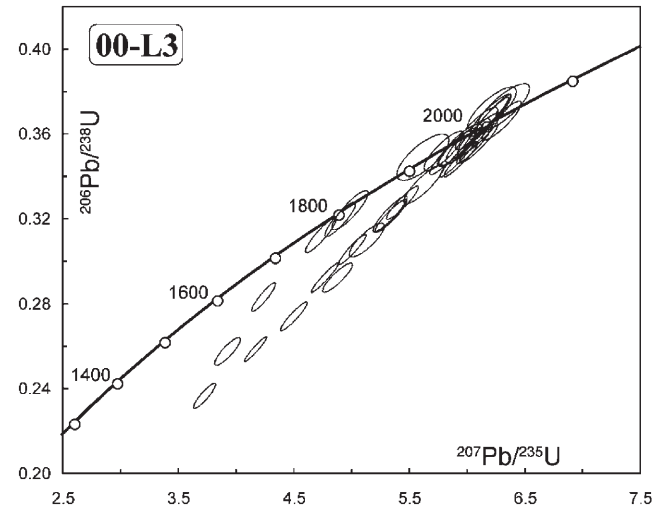
##### Basement granites

**Sample 00-L1.** The zircons from this granite are euhedral to subhedral with shapes ranging from squat and almost equidimensional to more elongate prismatic forms. All are brown and show well-developed oscillatory zoning. CL imaging reveals a number of cores. Ten of 11 spot analyses are for the zoned magmatic areas and these data plot along a discordia trend with an upper intercept age of  $2038 \pm 28$  Ma (Fig. 3) interpreted as the emplacement age of the granite. The calculated lower intercept age of  $968 \pm 240$  Ma suggests Pb loss as a consequence of a Mesoproterozoic event, but is too imprecise to place any meaningful interpretation on this date. A single analysis (spot 2.1) of an inherited core gave a near-concordant  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $2263 \pm 12$  Ma.

**Sample 00-L10.** The zircons from this granite are very similar in appearance to those of the previous sample, composed mainly of pink euhedral to subhedral grains, with oscillatory zoning of variable intensity. CL imaging shows that the zoning is progressively darker towards the grain margins and these areas of relatively elevated U (and common Pb) contents tend to yield discordant data. All 22 data points analysed combine to give an upper intercept age of  $1953.8 \pm 6.4$  Ma (Fig. 4) interpreted as the emplacement age of the granite. The lower intercept date is  $301 \pm 89$  Ma, very different from that of sample 00-L1.



**Fig. 4.** Concordia plot showing zircon isotopic ratios and derived ages for basement granite sample 00-L10.



**Fig. 5.** Concordia plot of the SHRIMP data for sample 00-L3 from the Bruco Formation, Chela Group.

##### Supracrustal rocks

**Samples 00-L3 and 00-L9.** Detrital zircon grains separated from two samples of quartz arenite from the Bruco Formation (Chela Group) were analysed, in an attempt to constrain the maximum age of sedimentation for the unit. A total of 74 zircon grains were analysed and the data are shown on two separate concordia plots (Figs 5 and 6). Considering the most concordant analyses only, the zircons from sample 00-L3 (34 grains) show a limited range in ages from  $1752 \pm 12$  Ma (spot 24.1) to  $2014 \pm 12$  Ma (spot 13.1), with the largest group of data clustering around concordia at about 1990 Ma. Most (37) of the zircon grains from quartzite sample 00-L9 are spread across a similar age range from  $1790 \pm 18$  Ma (spot 25.1) to  $2043 \pm 17$  Ma (spot 11.1), but include a number of older Palaeoproterozoic and Archaean grains with the oldest calculated ages at  $2577 \pm 15$  Ma,  $2608 \pm 21$  Ma and  $2977 \pm 16$  Ma (spots 4.1, 20.1 and 15.2).

The least discordant (<10% discordant)  $^{207}\text{Pb}/^{206}\text{Pb}$  ages from both samples have been assessed using the Kernel Density Estimate

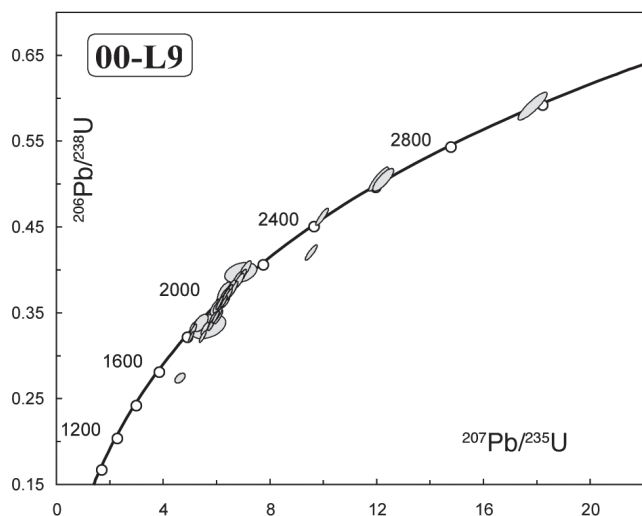


Fig. 6. Concordia plot of the SHRIMP data for sample 00-L9 from the Bruco Formation, Chela Group.

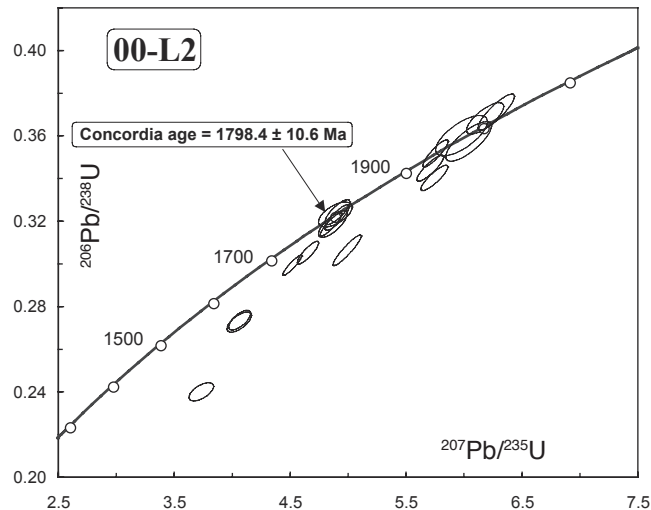


Fig. 8. Concordia plot showing zircon isotopic ratios and derived age for sample 00-L2, ignimbrite from the Humpata Formation, Chela Group.

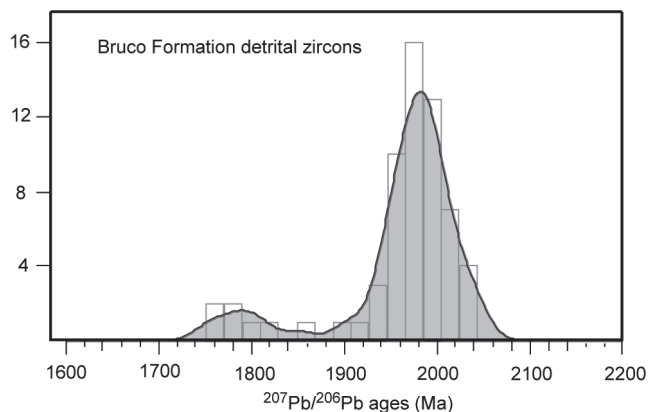


Fig. 7. Kernel Density Estimate (KDE) plot of  $^{207}\text{Pb}/^{206}\text{Pb}$  ages for the least discordant analyses of zircon grains from samples 00-L3 and 00-L9.

(KDE) statistical protocols of Vermeesch (2012) to identify age groups within this dataset. The great majority of the zircons are derived from sources ranging in age from 1750 to 2050 Ma. The KDE plot (Fig. 7) of the ages allows identification of two broad peaks with ages of  $1782 \pm 6$  Ma (11% of the data) and  $1985 \pm 2$  Ma (89% of the data). The zircon grains in these sediments were presumably locally derived from the Regional Granite and any volcanic equivalents, and have only minor contributions from older sources. A maximum age of sedimentation of  $1782 \pm 6$  Ma can be estimated from the youngest group of analyses calculated above.

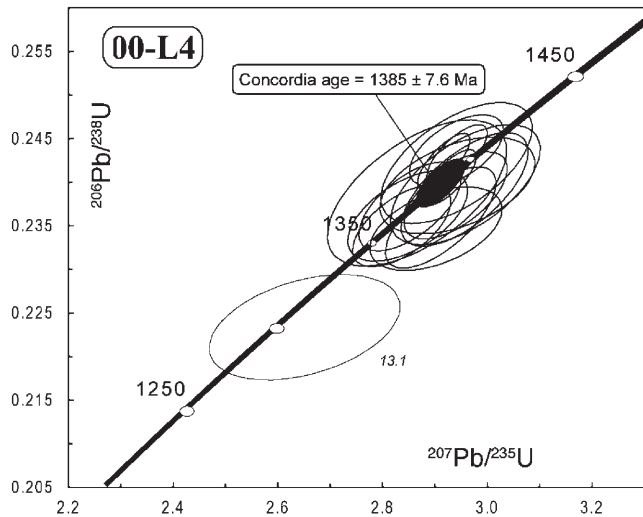
**Sample 00-L2.** This volcanoclastic sample yielded a mixture of zircons, but the majority are prismatic, pink to light brown and euhedral to anhedral, ranging in length from about 50 to 320  $\mu\text{m}$ . Most show no signs of abrasion and sharp pyramidal tips are preserved. The CL images of these grains tend to be dark, but typical igneous zoning is discernible. Many of the zircons from this sample contain high common Pb levels (up to 50% of the total  $^{206}\text{Pb}$  was measured as common  $^{206}\text{Pb}$  in one grain) and these analyses were rejected. The U–Pb data plot as two main groups (Fig. 8) with the older group (six grains) having a range of ages between

$1920 \pm 10$  Ma and  $1995 \pm 15$  Ma. The analyses from the younger concordant group (four grains) combine to yield a concordia age of  $1798.4 \pm 10.6$  Ma. The two main age groups identified in this volcanoclastic sample are similar to two of those identified in the detrital population described above. If the younger group is volcanic in origin (the preferred interpretation) then  $1798.4 \pm 10.6$  Ma is the absolute age of the ignimbrite. If these grains are inherited then  $1798.4 \pm 10.6$  Ma represents a maximum age for this volcanoclastic unit. The older zircon grains are inherited from the basement granites or local sediments.

#### Kunene Complex

**Mangerite dyke sample 00-L4.** This unusual rock type yielded a good crop of clear, light yellow to colourless zircons, which show a full range of forms from anhedral crystals to euhedral grains with square or rectangular cross-section and abbreviated pyramidal terminations. Internal structures as revealed by CL imaging are dominated by sector zoning grading into minor oscillatory zoning at the margins. A total of 16 grains were analysed; the analytical data are plotted in Figure 9. Fifteen of the 16 U/Pb analyses carried out on the zircon grains plot on concordia to give an age of  $1385 \pm 7.6$  Ma. This is considered to be the age of crystallization of these zircons, and thus represents either a minimum age for the host anorthosite or, if the mangerite is cogenetic with anorthosite as suggested by Mayer *et al.* (2004), is the best estimate of the age of the Kunene Complex.

**Xenolith sample CHN-1.** Most zircon grains from this xenolith are anhedral in shape, but occasional subhedral prismatic grains were also noted. A total of 17 grains were analysed and the resultant data plot as three groups on concordia (Fig. 10), defining three distinct ages. Group 1 is defined by the oldest zircon grains, which combine to give a weighted mean  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $1967 \pm 11$  Ma (MSWD=0.38). Most of the analyses fall into Group 2 and plot as a cluster on or around concordia, with 11 of the 13 analyses combining to give a weighted mean  $^{207}\text{Pb}/^{206}\text{Pb}$  age of  $1803.4 \pm 9.6$  Ma (MSWD=0.95). The two rejected analyses appear to be overcorrected for common Pb. The youngest group of data (Group 3) is defined by just two analyses (4.1 and 8.1) and combine to give a concordia age of  $1393 \pm 16$  Ma ( $2\sigma$ ). The oldest group of zircon grains are readily distinguishable by



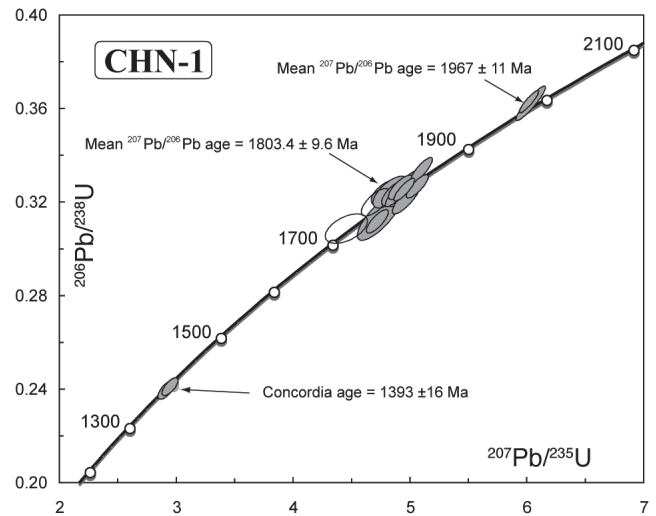
**Fig. 9.** Concordia plot showing zircon isotopic ratios and derived age for sample 00-L4, mangerite dyke from the Kunene Complex.

their strong prismatic habit and relatively well-developed oscillatory zoning, but the zircons from the other two groups show no clear differences in chemistry (Th/U) or form. Zircon grains from Groups 2 and 3 are generally anhedral (with some resorption), clear, and have only broad or poorly preserved zoning when viewed under CL. The data from the zircon grains in Groups 1 and 2 are interpreted to represent the original age of the rock forming the xenolith (1803 Ma) with *c.* 1967 Ma inheritance. The youngest group could have crystallized *in situ* from a partial melt (or micro-veining) within the Kunene intrusion, or could have lost all radiogenic Pb during incorporation, resulting in a total reset. The latter option is considered unlikely, as one would expect the other zircon grains to have undergone at least partial Pb loss and to define a continuous discordia between the protolith age and the age of the host magma, which is not the case.

## Discussion

The precise U–Pb zircon data generated during the present study allow us to comment on the following aspects of the Precambrian geology of SW Angola: (1) the age of the Chela Group rocks on the Humpata Plateau; (2) the suggested correlation between the Chela Group of Angola and the Nosib Group in Namibia; (3) the age of the Kunene Complex; (4) Proterozoic tectonics affecting the southern part of the Angola Shield. These points are discussed below.

The Chela Group rocks on the Humpata Plateau near Lubango (Fig. 2) have been correlated with the Nosib Group of Namibia (Kröner & Correia 1980). The Nosib Group contains rhyolites extruded during rifting and a thick succession of alkaline volcanic and intrusive rocks known as the Naaupoort Formation. Published age data (Hoffman *et al.* 1996) establish the age of the upper Naaupoort Formation as  $747 \pm 2$  Ma and that of the underlying basement as 1063–1115 Ma (Steven *et al.* 2000), identifying the Nosib Group as a Neoproterozoic sequence. The Chela Group is unconformable on the granites sampled as 00-L1 and 00-L10 in this study. The  $2038 \pm 28$  Ma and  $1953.8 \pm 6.4$  Ma U–Pb zircon ages obtained on these samples provide a maximum age for the deposition of the sedimentary sequence. This maximum age can be refined using the  $1782 \pm 6$  Ma peak on the KDE plot for samples 00-L3 and 00-L9. There is no indication in these samples of zircon grains from either the Kunene Complex or the Red Granite



**Fig. 10.** Concordia plot of the SHRIMP data for the zircon grains from sample CHN-1, xenolith of gneissic granitoid from the Kunene Complex.

implying that these units were either not exposed or had not yet intruded during the deposition of the sediment now exposed as the Bruco Formation. A minimum age constraint for the onset of Chela Group deposition is provided by the concordia age of  $1798.4 \pm 10.6$  Ma for sample 00-L2 if this is accepted as the eruptive age of the sample, an interpretation that is consistent with the morphology of the zircon grains collected from 00-L2. Based on these constraints we argue that the supracrustal rocks on the Humpata Plateau are part of a Palaeoproterozoic succession and that the Chela Group *sensu stricto* (Correia 1976) is significantly older than the Nosib Group of Namibia. There are no direct age constraints on the occurrences of ‘Chela Group’ rocks identified by de Carvalho & Alves (1993) in the Ompupa and Iona areas (Fig. 2).

The age of the anorthosite in the northern section of the Kunene Complex is constrained by the zircon data from the xenolith of granitoid gneiss sampled as CHN-1 and the mangerite dyke sampled as 00-L4 (see Fig. 2 for location), and is in agreement with recently published ages (Mayer *et al.* 2004; Drüppel *et al.* 2007). The zircons from CHN-1 give three ages of  $1967 \pm 11$  Ma,  $1803.4 \pm 9.6$  Ma and  $1393 \pm 16$  Ma. Our interpretation of these data is that the *c.* 1800 Ma age represents the crystallization age of the host rock to the Kunene Complex (the Regional Granite) and provides a maximum age for the anorthosite. A minimum age is provided by the concordia age of  $1385 \pm 7.6$  Ma for the mangerite dyke that intrudes the anorthosite. This age is statistically indistinguishable from the average of  $1393 \pm 16$  Ma for the two analyses defining the youngest peak in the dataset for CHN-1. We interpret these two zircon grains to be the product of partial melting of the xenolith during intrusion of the Kunene anorthosite. Based on this interpretation,  $1385 \pm 7.6$  Ma is thus a direct age constraint on the intrusion of the Kunene Complex. This age is older than, but compatible with, the  $1371 \pm 2.5$  Ma published by Mayer *et al.* (2004) and the  $1376 \pm 2$  Ma reported by Drüppel *et al.* (2007) for felsic rocks associated with the Kunene Complex, and supports the  $1385 \pm 25$  Ma age obtained on anorthosite from the extension of the Kunene Complex into Namibia (Drüppel *et al.* 2007). In addition to these U–Pb zircon ages, Mayer *et al.* (2004) reported a Sm–Nd mineral age of  $1319 \pm 13$  Ma on an anorthosite sample from Angola, interpreted as dating the end of magmatism, and Seth *et al.* (2005) documented a Pb–Pb age of  $1341 \pm 47$  Ma on garnet from a hornfels along the southeastern margin of the Kunene Complex in Namibia.

These age data establish the Kunene Complex as a product of Mesoproterozoic magmatism. The age data coupled with the areal extent of the Kunene Complex (Fig. 2) identify a period of significant crustal extension and associated magmatism along the SW margin of the Congo Craton starting at *c.* 1385 Ma. The cause of this extension, and thus the tectonic setting of the intrusion, has yet to be investigated in SW Angola, but interestingly the age of the Kunene magmatic event coincides with the *c.* 1375 Ma 'Kibaran' magmatic event documented by Tack *et al.* (2010) from the Karagwe–Ankole Belt (KAB, formerly NE Kibaran Belt) of Central Africa. The KAB magmatism is bimodal in character and is ascribed to regional-scale intra-cratonic (Congo Craton) extension resulting in the emplacement of mantle-derived mafic and ultramafic layered complexes, which then initiated partial melting of Palaeoproterozoic basement to produce coeval S-type granitoids (for details, see Tack *et al.* 2010). Mayer *et al.* (2004) argued for a genetic link between the anorthosite and Red Granite of the northern Kunene Complex whereas Drüppel *et al.* (2007), in their comprehensive account of the Kunene Complex in NW Namibia, concluded that whereas the anorthositic rocks were derived from partial melting of the upper mantle, the spatially and temporally associated felsic rocks were produced by anatexis of the lower crust, presumably in response to the emplacement of the anorthositic magma. Thus, although separated by over 2100 km, there are striking similarities between the Kunene and KAB magmatic events.

The Proterozoic geochronology and regional tectonic evolution of southern Africa was documented by Hanson (2003) and the Palaeoproterozoic record of the NE part of the Congo Craton has been discussed in more detail by Rainaud *et al.* (2005) and De Waele *et al.* (2008, 2009). In the section that follows we build on these earlier papers by outlining our understanding of the evolution of the continental crust forming the Palaeoproterozoic section of the southern Congo Craton (see the age data in Fig. 1).

The new precise U–Pb data obtained on samples 00-L1 and 00-L10 confirm that the granitic basement in the Lubango Zone is Palaeoproterozoic in age. Although no zircon grains of Archaean age were identified from either granite sample, detrital grains at  $2577 \pm 15$  Ma,  $2608 \pm 21$  Ma and  $2977 \pm 16$  Ma were present in sample 00-L9, indicating the presence of Archaean crust in the source area for the Bruno Formation. The age data on granites from the Lubango Zone are compatible with those from the Central Eburnean Zone ( $1987 \pm 16$  Ma and  $1980 \pm 9$  Ma; Delor *et al.* 2006) and the Central Shield ( $1967 \pm 5$  Ma and  $1966 \pm 3$  Ma; Jelsma *et al.* 2011) but significantly older than recently published U–Pb ages from the Epupa Metamorphic Complex in NW Namibia (Kröner *et al.* 2010), generally regarded as the southern extension of the Angolan Shield. Like the Regional Granite of SW Angola, the Epupa Metamorphic Complex is host to the 1385 Ma Kunene Complex, but the protoliths to the orthogneisses and migmatites that characterize the Epupa terrane were formed between 1801 and 1757 Ma (Kröner *et al.* 2010) and thus are some 200 Ma younger than the granite samples from the Lubango Zone. They are, however, very similar in age to sample CHN-1, the *c.* 1803 Ma gneissic xenolith in the Kunene Complex. Kröner *et al.* (2010) proposed a continental marginal arc setting for the formation of the precursor granitoids to the Epupa Metamorphic Complex.

Orthogneisses derived from protoliths similar in age to those of the Lubango granites have been reported from west of Sesfontein some 100 km south of the Epupa Metamorphic Complex, where Seth *et al.* (1998) recognized orthogneisses and granites of Archaean and Palaeoproterozoic age. The Archaean orthogneisses are exposed in the east of the study area and have U–Pb SHRIMP ages of  $2645 \pm 6$  Ma and  $2616 \pm 5$  Ma, with Sm–Nd isotope data indicating the involvement of still older crust (Seth *et al.* 1998).

The Palaeoproterozoic granitoids occur as deformed (gneissic) intrusions in the Archaean terrane and as orthogneisses tectonically intercalated with Neoproterozoic metasedimentary rocks of the Kaoko belt to the west. Zircon from the Palaeoproterozoic intrusions within the Archaean terrane yielded SHRIMP ages of  $1961 \pm 4$  Ma and  $1985 \pm 23$  Ma with xenocrysts at  $2605 \pm 11$  Ma and  $2287 \pm 10$  Ma. Orthogneiss cropping out as basement slices within the paragneisses of the Kaoko belt yielded a protolith age of  $1971 \pm 7$  Ma. The Archaean orthogneisses dated by Seth *et al.* (1998) are comparable in age with those reported from the Andulo area by Jelsma *et al.* (2011) and like them are intruded by Palaeoproterozoic granitoids of equivalent age. In addition, the Palaeoproterozoic granitoids from Andulo and the Sesfontein area carry Archaean xenocrysts of comparable age (Seth *et al.* 1998; H. Jelsma, unpubl. data) indicating that they were derived by reworking of Archaean basement of similar age. The possibility that the Archaean granitoids of SW Angola and NW Namibia are part of the same crustal block is strengthened by the recognition of a significant igneous event in both areas at  $2.0 \pm 0.04$  Ga and the occurrence of xenocrysts dated at  $2263 \pm 12$  Ma in sample 00-L1 from Lubango and  $2287 \pm 10$  Ma in sample BK5 of Seth *et al.* (1998). The proposed Archaean terrane is not reflected in the zircon signature of the Epupa Metamorphic Complex (Kröner *et al.* 2010) but if the interpretation of a continental marginal arc proposed by Kröner *et al.* (2010) is correct then that arc would have been built on older continental crust, which could have included, in part at least, Archaean crust similar in age to that identified to the north in Angola and/or to the south near Sesfontein. An alternative configuration would place the southern margin of the Angolan Shield along the position of the Epupa Metamorphic Complex at *c.* 2.0 Ga, with the Archaean and Palaeoproterozoic crust south of the Epupa complex (the Sesfontein terrane) representing a separate block that accreted along the 'Epupa arc'.

The geology to the south of Sesfontein is dominated by the Neoproterozoic Damara Belt, which formed in response to convergent tectonics between the Congo and Kalahari cratons. In the northern section of the Damara Belt, the Congo Craton is represented by a number of basement inliers that expose granitoid gneisses and more rarely volcanic rocks. This basement terrane is best exposed in the Kamanjab Inlier (KaI in Fig. 1) but has also been sampled in the Abbabis Inlier and from the Ida and Tumas basement domes. Age data for basement gneisses from these inliers (Rainaud *et al.* 2005, and references therein) include a precise SHRIMP zircon age of  $2038 \pm 5$  Ma (compare 00-L1) on augen gneiss from the Ida Dome (Tack *et al.* 2002), indicating that the basement to the northern and central parts of the Damara Belt is Palaeoproterozoic in age and the rocks defining this basement were formed during the same episode of granitoid magmatism recognized at Lubango and Sesfontein.

The Palaeoproterozoic granitoids defining the Angolan Shield and its extension into Namibia are covered to the east by Phanerozoic sediments of the Congo and Kalahari basins but reappear as isolated outcrops in the Tsumkwe inlier of NE Namibia (SHRIMP age of  $2022 \pm 15$  Ma from Hoal *et al.* 2000) and the Quangwadum region of NW Botswana (thermal ionization mass spectrometry age of 2051 Ma from Singletary *et al.* 2003). Still further to the east, Rainaud *et al.* (2005) have identified a Palaeoproterozoic basement in the Neoproterozoic Central African Copperbelt in NW Zambia (Fig. 1); a terrane they regarded as a continuation of the Kamanjab Inlier of Namibia and, by extension of the present study, the Angolan Shield. Rainaud *et al.* (2005) referred to the basement terrane in NW Zambia as the Lufubu Metamorphic Complex (LMC) and interpreted it to be part of a *c.* 2.05–1.85 Ga magmatic arc. The basement rocks of the LMC

continue eastwards as the granitoids and felsic volcanic rocks of the Bangweulu Block (Rainaud *et al.* 2005; De Waele *et al.* 2009), which forms the foreland to, and basement of, the Mesoproterozoic Irumide Belt (De Waele *et al.* 2006, 2009). The Bangweulu Block (Fig. 1) comprises granitoids dated by SHRIMP at  $1862 \pm 8$  Ma and rhyolite dated at  $1868 \pm 7$  Ma, which De Waele *et al.* (2006, 2009) interpreted as having formed in a continental arc related to the Palaeoproterozoic Ubendian belt (Fig. 1). The Mkushi Gneiss Complex represents the extension of the Bangweulu Block into the southwestern Irumide Belt and has a SHRIMP age of  $2049 \pm 6$  Ma (Rainaud *et al.* 2005). The Luwalizi granite in the northeastern part of the belt has U–Pb SHRIMP ages of  $1942 \pm 6$  Ma and  $1927 \pm 10$  Ma (De Waele *et al.* 2006) and is interpreted as a product of the Palaeoproterozoic magmatism exemplified by the Bangweulu Block.

To the west of the Copperbelt, orthogneisses and granite are exposed in The Domes area of NW Zambia, where Key *et al.* (2001) reported SHRIMP zircon ages of  $1940 \pm 3$  Ma and  $1934 \pm 6$  Ma for granite from the Kabompo Dome and  $2058 \pm 7$  Ma for granite from the Mwinilunga area along the border region with Angola and the DRC (Fig. 1); ages that are compatible with those from the LMC. In addition to the Palaeoproterozoic granite at  $2058 \pm 7$  Ma, Key *et al.* (2001) reported ages of  $2543 \pm 5$  Ma for granulitic gneiss,  $2561 \pm 10$  Ma for granite and  $2538 \pm 10$  Ma for foliated granite, and the data include zircon cores in the granite with ages of  $2839 \pm 22$  Ma and  $3154 \pm 16$  Ma, indicating the involvement of even older crust. The Archaean granites and associated gneiss sampled by Key *et al.* (2001) in the Zambezi valley near Mwinilunga are interpreted as an extension of the Kasai Craton into NW Zambia, which, together with the rocks of the Lufubu Metamorphic Complex and the Bangweulu Block, records the same Palaeoproterozoic magmatic history in the NE part of the Congo Craton as the Angolan Shield does in the SW section.

Based on the U–Pb age data discussed above and plotted in Figure 1, it is possible to identify a Palaeoproterozoic granitoid terrane that extends from the Central Shield of Angola, south through the Lubango Zone and into Namibia. This Palaeoproterozoic terrane, which includes older components of Neoproterozoic age, is best referred to as the Angolan Shield and defines the SW section of the Congo Craton. At present exposure levels the Angolan Shield is characterized by granitoid orthogneisses and granite formed between *c.* 2040 and 1960 Ma, and the great majority of spatially associated supracrustal rocks are unconformable on these granitoids. The Angolan Shield is interpreted as a Palaeoproterozoic magmatic arc terrane developed on older Archaean crust similar to that exposed in the Central Shield of Angola and the Sesfontein area of NW Namibia. In the Lubango Zone of SW Angola, the arc granitoids acted as basement for the *c.* 1798 Ma Chela Group and other, as yet undated, sedimentary sequences. Between *c.* 1800 and 1760 Ma the southern part of the Angolan Shield was affected by a high-temperature tectonometamorphic event that produced the orthogneisses and migmatite of the Epupa Metamorphic Complex. At an expanded regional scale published age data suggest that the granitoids forming the Angolan Shield extend NE under Phanerozoic cover into NW Zambia to form the basement granitoids of the Central African Copperbelt and the adjacent Bangweulu Block. If these correlations are correct, the resultant crustal terrane, which has a minimum surface area of  $1.5 \times 10^6$  km<sup>2</sup>, defined the southern margin of the proto-Congo Craton at *c.*  $2.0 \pm 0.04$  Ga.

Palaeoproterozoic crustal extension on the Angolan Shield as evidenced by the deposition of the Chela Group at 1798 Ma has recently been linked to the event responsible for the formation of the Espinhaço basins on the São Francisco Craton of South America (Pedreira & De Waele 2008). Continuity of these crustal blocks prior

to Gondwana breakup is supported by links between the Araçuaí belt of Brazil and the West Congo belt (de Waele *et al.* 2008). Coeval extension of this contiguous crust in the Palaeoproterozoic is indicated by age data from zircon in volcanic rocks from the Chela Group (this study) and the lower part of the Espinhaço Supergroup of eastern Brazil (Pedreira & de Waele, 2008). In the São João de Chapada Formation of the southern Espinhaço Range zircon ages of  $1715 \pm 12$  Ma and  $1710 \pm 12$  Ma have been reported (for details, see Pedreira & de Waele 2008) and in the Rio dos Remédios Group, rhyolite and dacite have yielded zircon with ages of  $1752 \pm 4$  Ma (Pedreira & de Waele, 2008, and references therein). These age data allow for a temporal link between the Chela basin in central Africa and the Espinhaço basins in eastern Brazil.

## Conclusions

The new data presented here support the following conclusions about the crustal evolution of SW Angola.

- (1) Granitic magmatism to generate samples 00-L1 and 00-L10 of this study occurred at *c.*  $2.0 \pm 0.04$  Ga. This magmatism forms part of a Palaeoproterozoic granitoid event recognized throughout much of southern Angola and was probably linked to an active continental margin of that age. The resultant crustal terrane is referred to as the Angolan Shield.
- (2) As evidenced by sample 00-L2, extension of the Angolan Shield occurred at *c.* 1800 Ma to accommodate the deposition of the Chela Group in a basin that received detritus from a provenance dominated by Palaeoproterozoic crust but also including Archaean rocks. The regional extension of this basin in southern Angola is unknown although a correlation between the rocks of the Chela Group as defined here and the Bale and Oendolongo Groups of de Carvalho & Alves (1993) is possible.
- (3) The depositional age of the Chela Group in the type area of the Humpata Plateau is constrained at  $1798.4 \pm 10.6$  Ma by sample 00-L2 and supported by the detrital zircon populations from samples 00-L3 and 00-L9.
- (4) The age data from the Chela Group on the Humpata Plateau do not allow a correlation with the Nosib Group of Namibia as previously suggested but it is possible to correlate the development of the Chela Group basin on the Angolan Shield (proto-Congo Craton) with the formation of the Espinhaço basins on the São Francisco Craton in Brazil.
- (5) The age data from samples 00-L4 and CHN-1 confirm that the Kunene Complex is a product of Mesoproterozoic magmatism.
- (6) The areal extent of the Kunene Complex indicates a period of significant crustal extension and associated magmatism along the southern margin of the Congo Craton at *c.* 1385 Ma that may be linked to the *c.* 1375 Ma magmatic event documented from the Karagwe–Ankole Belt of Central Africa.

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