Available online at www.sciencedirect.com
ScienceDirect
Precambrian Research 158 (2007) 79–92
Precambrian Research
www.elsevier.com/locate/precamres

Ion-probe dating of 1.2 Ga collision and crustal architecture in the Namaqua-Natal Province of southern Africa

Åsa Pettersson[a,*], David H. Cornell[a], Henri F.G. Moen[b], Steven Reddy[c], David Evans[d]

[a] Earth Sciences Centre, Göteborg University, Box 460, SE-405 30 Göteborg, Sweden
[b] Council for Geoscience, PO Box 775, Upington 8800, South Africa
[c] Department of Applied Geology, Curtin University, Bentley, GPO Box U 1987, Perth, Western Australia 6845, Australia
[d] Geology and Geophysics Department, Yale University, PO Box 208109, New Haven, CT 06520-8109, USA

Received 2 February 2006; received in revised form 3 April 2007; accepted 25 April 2007

Abstract

The Namaqua-Natal Province of southern Africa formed a part of the Kalahari craton, possibly linked to the ~1.0 Ga supercontinent Rodinia, but the timing of assembly and its positioning relation to other components is still debated. Thorough ion-probe zircon dating combined with strategic field observations in the tectonic front of a metamorphic belt can clarify some of these issues. In this study, the age of two "pretectonic" units, constrains the timing of collision and clarifies the role of the Koras Group as a tectonostratigraphic marker. The volcanosedimentary Wilgenhoutsdrif Group contains Archaean and Paleoproterozoic material, showing that it probably formed in a continental rift or a passive margin setting, before its involvement in the Namaqua collision event. At 1241 ± 12 Ma the Areachap island arc magmatism was in progress, followed by a collision event around 1200 Ma which at 1165 ± 10 Ma gave rise to migmatites in the island arc terrane. At the same time (1173 ± 12 Ma) in the adjoining Kaaien terrane the first sequence of Koras Group bimodal magmatism formed in a fault basin, invalidating the concept that this Group is a tectonostratigraphic marker of the end of tectonism in the whole Namaqua Province. A time of little activity followed, with yet another pulse of magmatism at 1100–1090 Ma, giving rise to a second sequence of sedimentation and volcanism in the Koras Group, as well as correlated intrusive rocks. This second pulse is not related to any significant regional deformation and may have been thermally induced. It is in part coeval with the Umkundo large igneous province of the Kaapvaal and Zimbabwe Cratons. These formations preserve an important record for reconstructing Rodinia and our 1093 ± 7 Ma U–Pb age of the uppermost volcanic formation of the Koras Group, should be used as the age for the Kalkpunt formation, frequently cited as a Kalahari Craton paleopole.

Keywords: Namaqua-Natal Province; Rodinia; U–Pb zircon; Ion-probe dating; Koras Group; Kalahari craton

1. Introduction

Collision events in the Namaqua sector have been assigned ages between 1.28 Ga (Frimmel, 2004) and 0.9 Ga (Hoal, 1993), with many authors citing 1100 Ma (Thomas et al., 1996) and most paleomagnetic syntheses start at 1100 Ma. The mid-Proterozoic supercontinent Rodinia (Dalziel et al., 2000) included many ~1.0 Ga components now distributed over the globe. The Namaqua sector of the Namaqua-Natal Province of Southern Africa (Fig. 1) is one such fragment, in which the timing of collision and subsequent events is poorly constrained. Several workers (Humphreys and Van Bever

* Corresponding author. Tel.: +46 317862800; fax: +46 317862849.
E-mail addresses: asap@gvc.gu.se (Å. Pettersson), cornell@gvc.gu.se (D.H. Cornell).

0301-9268/$ – see front matter © 2007 Elsevier B.V. All rights reserved.
doi:10.1016/j.precamres.2007.04.006

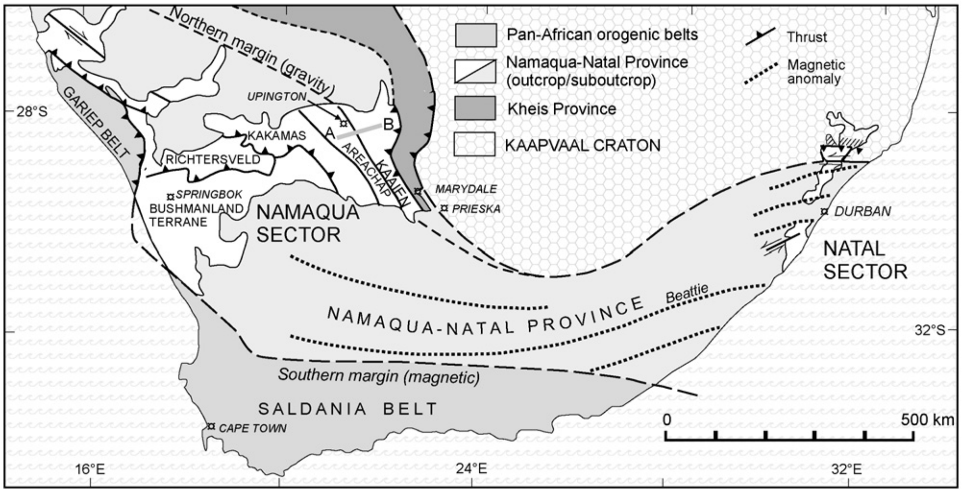

Fig. 1. Map of southern Africa. Modified after Cornell et al. (2006). Shows the spatial relationship of the ∼1.0 Ga Namaqua Province to the Kaapvaal Craton. The clearly defined geophysical boundary runs northwestward along the tectonic front zone, but departs from the craton margin at Marydale, where the ∼1.8 Ga Kheis Province is interposed between them.

Donker, 1987; Stowe, 1986; van Zyl, 1981) concluded that the north eastern part of the Namaqua sector is a structurally complex area with at least one deformational phase prior to terrane assembly, and that several fold phases developed in relation to Namaquan collision events, with the main event, here termed NF2. This is evident in both the Areachap and Kaaien terranes. Stowe (1986) considered the area we refer to as the Kaaien Terrane as a part of the Kgalagadi Province. Note that in Fig. 2 we follow Thomas et al. (1994b) and Cornell et al. (2006), restricting the Kheis Province to east of the Dabep thrust, following geochronological evidence that the main foliation in the region between the Dabep thrust and Trooilopspan Shear Zone (here called the Kaaien Terrane) is related to the Namaqua Orogeny.

The ion-probe technique of zircon dating enables precise age determinations of rock-forming events in complex metamorphic areas such as the Namaqua-Natal Province. Using backscattered electron and cathodoluminescent images of zircon, distinct age domains such as xenocrystic cores, oscillatory zoned magmatic areas and metamorphic rims can be identified and metamict zones avoided by the ∼30 μm ion beam. In this work we present a number of precise ion-probe dates for key formations and events in the NE marginal areas of the Namaqua sector, which allow us to clarify the history before, during and after collision. We show that the main collision event in this part of the Namaqua sector occurred after 1230 Ma and before 1165 Ma.

The volcanosedimentary Koras Group in the Kaaien Terrane near Upington (Figs. 1–3) has been considered important due to its stratigraphic position in the Namaqua Front, being regarded as undeformed and overlying highly deformed rocks of the Namaqua Province. These relationships suggest that the Koras Group is younger than all deformation in the collisional orogeny, possibly related to the formation of Rodinia (Gutzmer et al., 2000). This concept led to the Koras Group being chosen as defining the top of the Mokolian Erathem of the South African Committee for Stratigraphy (SACS) (1980), so that its age, although variously defined at 1080, 1180 or 1123 Ma, is used as a chronostratigraphic boundary in maps of the South African Geological Survey. Previous investigations include geochemistry and several imprecise and contradictory whole rock or bulk zircon model age determinations from 1.2 to 1.0 Ga, including 1.9 Ga xenocrysts (Table 1). Gutzmer et al. (2000) summarised the earlier work and claimed that their precise 1171 ± 7 Ma ion-probe Pb–Pb zircon age for a Koras rhyolite resolved this topic. Palaeomagnetic data from the Koras Group provide important points on apparent polar wander paths (Briden et al., 1979), but the precise age of the formations sampled was not well known. In this work we confirm the age for one Koras rhyolite, but also show that the Group represents at least 80 Ma of stratigraphic history. We also demonstrate that the tectonostratigraphic relationships defining the end of Namaqua deformation are valid only in the Kaaien Terrane, not in the terranes further west.

2. Methods

Zircons were separated from about 2 kg of each sample. The samples were crushed using a swing mill and

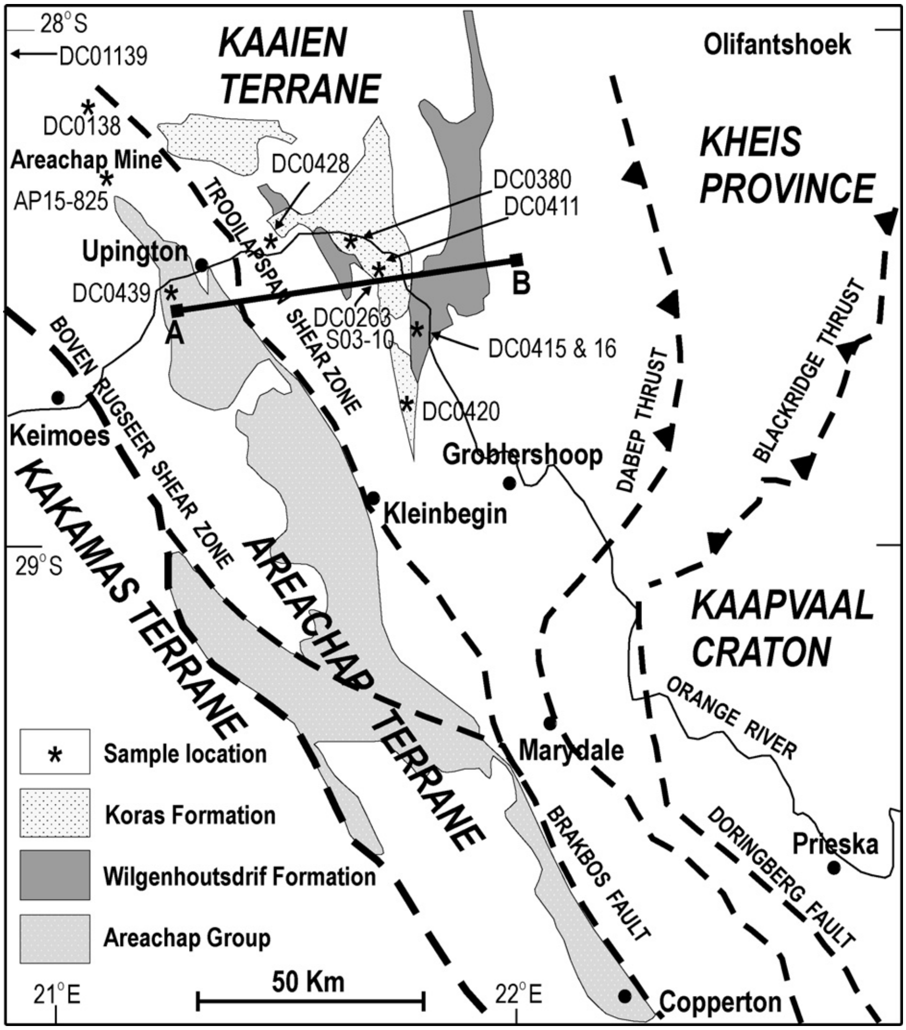

Fig. 2. Map of the investigated area. Sample locations are shown as asterisks except for DC01139 that crop out off the map to the NW. Outcrops patterns of the Koras Group, the Wilgenhoutsdrif Group and the Areachap Group are shown, as well as major shear zones.

then sieved through 400 μm. This material was panned by hand, heavy minerals were dried and zircons were hand picked, mounted in epoxy and polished. Cathodoluminescence and backscattered images were obtained for the individual zircon grains, to identify age domains and to avoid cracks and metamict zones. All imaging for samples with prefix DC was done using a Zeiss DSM 940 electron microscope at Gothenburg University. A Cameca 1270 ion-probe was used for U–Pb dating at the Nordsim facility in the Swedish Natural History Museum in Stockholm, as described by Whitehouse et al. (1997, 1999). A ∼30 μm oxygen ion beam was used and the NIST 91500 zircon standard was used for calibration. Common Pb corrections samples run at Nordsim (prefix DC) assume a present day Stacey and Kramers (1975) model average terrestrial Pb composition, based on the observation that most common Pb is due to laboratory contamination. Sample S03-10 was analysed with a SHRIMP instrument at Curtin University, Perth, Australia according to (Nelson, 1997) using standard CZ3, common Pb correction with a Broken Hill type of composition (Cummings and Richards, 1975) and cathodoluminescence imaging done at Curtin University. Age calculations were made using the Isoplot 3 programme of Ludwig (1991, 1998). Uncertainties of age calculations are all given at the 2σ level, ignoring decay constant errors. Unless stated otherwise, all the dates reported in this work are ion-probe zircon U–Pb data.

The results are given in Table 2 and raw data in the supplementary data.

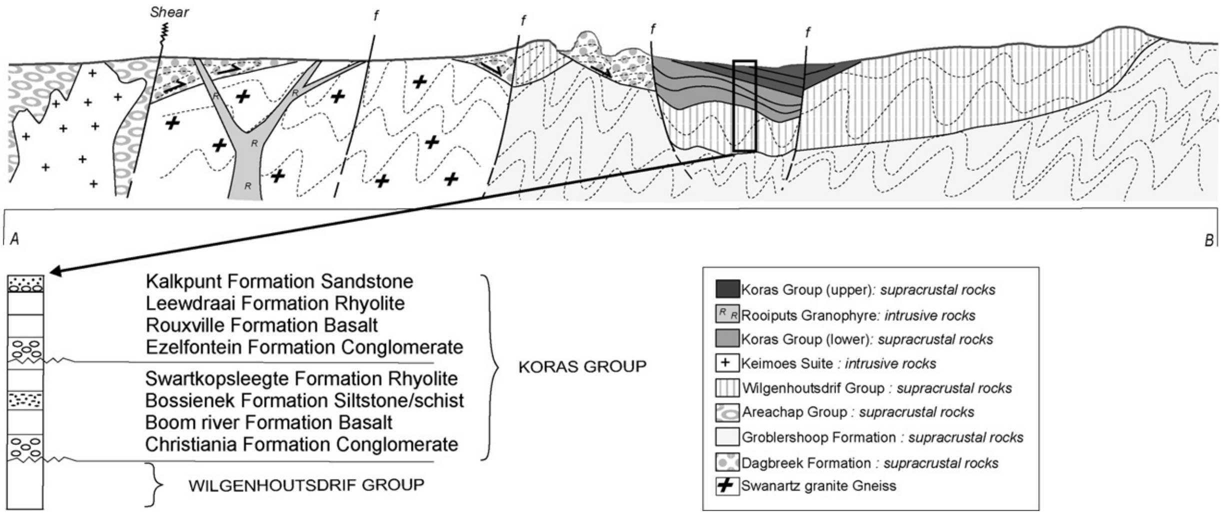

Fig. 3. A generalised section A–B showing the Koras Group and its tectonostratigraphic context. The profile A–B is shown in Fig 2. Longitude and latitude for A = 28′38 400, 21′18 100, B = 28′22 000, 21′57 800. The section is drawn through the Central Domain of the Koras Group. Drawn from the SA Council for Geoscience 1:250 000 geological map 2820 Upington, stratigraphic nomenclature following (Moen, in preparation), for earlier names used for palaeomagnetism see Table 1. Thicknesses are not to scale, and the dips of faults and shears are schematic.

Mineral analysis of hornblende in DC0439, see Table 3, were done at Gothenburg University on a Hitachi S-3400N Scanning electron microscope with an Oxford EDS system, and pressure calculations in the programme by Tindle and Webb (1994).

3. Results

3.1. Wilgenhoutsdrif Group

The upper part of the Wilgenhoutsdrif Group is made up of basaltic volcanic rocks which contain preserved

Table 1
Literature age compilation

	Rock type	Age ± 2σ (Ma)	Method, initial ratio	Reference
Koras Group extrusives				
Leeuwdraai formation	Qtz porphyry lavas	1180 ± 74	Discordia, 3 conventional U–Pb zircon samples	Botha et al. (1979)
Swartkopsleegte formation	Qtz porphyry lavas	1171 ± 7	Weighted mean ion-probe zircon Pb–Pb	Gutzmer et al. (2000)
Swartkopsleegte formation	Qtz porphyry lavas	1966 ± 7	Ion-probe zircon Pb–Pb one xenocryst in above sample	Gutzmer et al. (2000)
Boom River formation, formerly Florida formation[a]	Basalts	1157 ± 44 replaces 1176 ± 18	Rb–Sr isochron, 7 points, MSWD 1.2, 0.7060 ± 4	Recalculated data of Kröner (1977)
Koras intrusives				
Ezelfontein intrusion	Syenite	1076 ± 52	Rb–Sr isochron 0.7065	Barton and Burger (1983)
Uitkoms dyke	Quartz porphyry	1032 and 1049	2 discordant conventional U–Pb zircon samples	Barton and Burger (1983)
Wilgenhoutsdrif Gp				
	Metabasic lava	1331 ± 100	Rb–Sr isochron 0.7026	Barton and Burger (1983)
	Metabasic lava	1125 ± 20	Rb–Sr errorchron 0.7017	Cornell 1975, in Cahen and Snelling (1984)
	Acid lava	1336 and 1287	2 discordant conventional U–Pb zircon samples	Barton and Burger (1983)
Areachap Group				
Copperton formation	Metadacite	1285 ± 14	Kober method zircon Pb–Pb	Cornell et al. (1990)
Jannelsepan formation	Amphibolite	1300–1100	Imprecise Rb–Sr, Pb–Pb and Th–Pb data	Barton and Burger (1983)

[a] The Florida formation paleomagnetic pole (Briden et al., 1979), was derived from outcrops of the present Boom River formation.

Table 2
Age calculations for U–Pb ion-probe zircon data, unless otherwise stated, used in this work

Sample	Formation, rock type	Age (Ma)	Type of grain	Spots used	Isoplot regression	MSWD	Th/U ratio	Lower intercept (Ma)	Location	
									S	E
Koras Group										
DC0411	Kalkpunt, Sandstone	1116 ± 16	Detrital	1	Concordia	0.19	–		28°27.322′	21°40.348′
		1120–1196	Detrital	5	Pb–Pb ages	–	–			
		1290	Detrital	1	Pb–Pb ages	–	–			
		1824 and 1896	Detrital	2	Pb–Pb ages	–	–			
DC0263	Leeuwdraai, Rhyolite	1092 ± 9	Magmatic	14	Concordia	0.47	>0.8		28°27.800′	21°40.800′
S03-10	Leeuwdraai, Rhyolite	1095 ± 10	Magmatic	20	Concordia	0.74	>0.8		28°28.204′	21°41.664′
DC0420	Rhyodacite at Ezelfontein	1104 ± 8	Magmatic	9	Concordia	1.9	>0.7		28°37.894′	21°42.113′
	(mapped as Swartkopsleegte)	1182–1204	Xenocrysts	3	Pb–Pb ages	–	–			
		1341	Xenocryst	1	Pb–Pb age	–	–			
		1814–2117	Xenocrysts	4	Pb–Pb ages	–	–			
DC0380	Swartkopsleegte, Rhyolite	1173 ± 12*	Magmatic	9	Concordia	0.75	0.08–0.57		28°24.878′	21°36.364′
		1163 ± 12	Magmatic	21	Discordia	1.6		328 ± 25		
Wilgenhoutsdrif Group										
DC0415	Leerkrans, Sandstone	2016–2760	Detrital	9	Pb–Pb ages	–	–		28°29.757′	21°42.723′
DC0416	Leerkrans, Conglomerate	1337–2864	Detrital	13	Pb–Pb ages	–	–		28°29.757′	21°42.723′
Areachap Group										
DC0439	Jannelsepan, Migmatite	1241 ± 12	Magmatic	5	Concordia	0.65	>0.75		28°30.279′	21°12.378′
		1165 ± 10*	Metamorphic rim	5	Concordia	0.67	<0.09			
AP15825	Jannelsepan, Biotite Gneiss	1192 ± 14	Metamorphic	3	Concordia	< 0.01	0.15–0.28		28°17.970′	21°02.500′
		1158 ± 12	Metamorphic rim	3	Concordia	1.7	<0.01			
		1142 ± 12	Monazites	2	Wtd mean Pb–Pb	2.6	–			
Unit not assigned to a group or suite										
DC0428	Swanartz Granite Gneiss	1371 ± 9	Magmatic	8	Concordia	0.12	>0.46		28°24.794′	21°25.900′
		1364 ± 13	Magmatic	11	Discordia	0.93		428 ± 120		
DC01139	Blauwbosch Granite	1093 ± 11	Magmatic	4	Concordia	1	>0.46		28°05.740′	20°49.044′
		1093 ± 11	Magmatic	14	Discordia	1.3		250 ± 39		
DC01138	Rooiputs Granophyre	1093 ± 10	Magmatic	10	Concordia;	0.16	>0.2		28°08.891′	21°01.888′
		1818 and 1742	Xenocrysts	2	Pb–Pb ages	–	–			
		1187 ± 14	Xenocrysts	4	Concordia	0.24	<0.06			

Errors are given at 2σ level, except where indicated by * (at 95% confidence level) and calculations ignoring decay constant errors. For full data see supplementary data and for concordia plots, see Figs. 4–6

Table 3
SEM-EDS analysis of hornblende in the Jannelsepan migmatite, Areachap Terrane (DC0439) thin section, for Al in hornblende barometry (see text)

Formula	Number of ions	Oxide %	Oxide % sigma
Analysis 1—hornblende in DC0439			
Na_2O	0.45	1.48	0.07
MgO	1.79	7.62	0.10
Al_2O_3	1.96	10.54	0.11
SiO_2	6.35	40.36	0.19
K_2O	0.28	1.42	0.04
CaO	1.92	11.38	0.10
TiO_2	0.15	1.28	0.07
MnO	0.13	1.01	0.06
FeO	2.85	21.66	0.17
O	23		
Total		96.75	
Analysis 2—hornblende in DC0439			
Na_2O	0.43	1.41	0.07
MgO	1.8	7.69	0.10
Al_2O_3	1.95	10.49	0.11
SiO_2	6.35	40.34	0.19
K_2O	0.27	1.37	0.04
CaO	1.89	11.23	0.10
TiO_2	0.16	1.36	0.07
MnO	0.13	0.99	0.06
FeO	2.88	21.92	0.18
O	23		
Total		96.8	
Analysis 3—hornblende in DC0439			
Na_2O	0.42	1.36	0.07
MgO	1.78	7.6	0.10
Al_2O_3	1.96	10.57	0.11
SiO_2	6.36	40.48	0.19
K_2O	0.29	1.43	0.04
CaO	1.92	11.43	0.10
TiO_2	0.15	1.28	0.07
MnO	0.14	1.03	0.06
FeO	2.86	21.79	0.18
O	23		
Total		96.97	

hyaloclastites and pillow lavas, with interbedded rhyolites, sandstones, conglomerates, shales, and minor calcsilicates (Figs. 2 and 3). The group overlies the Groblershoop formation, a thrust package of metasedimentary quartz-mica schists which may be as old as 1900 Ma (Theart et al., 1989) that probably represents a passive margin shelf sequence on the western margin of the Kaapvaal Craton formed before the Kheis tectonism. The Wilgenhoutsdrift Group is severely deformed and metamorphosed in the greenschist facies. It shows two phases of deformation which according to Moen (1987, 1999), record the Namaqua deformation history in this area. Geochemical data suggests that the metabasites are alkali-basalts, which may have originated in either a rift setting or as oceanic islands (Stenberg, 2005). Unlike many other mafic rocks from southern Africa, the Wilgenhoutsdrif shows no geochemical subduction signature. The mafic and at least partly submarine volcanism, together with the presence of minor serpentinites in the sequence leads to the suggestion of an oceanic tectonic setting prior to its involvement in the Namaqua collision. We analysed detrital zircons to investigate if the sediments had a juvenile character, reflecting an oceanic setting, or formed close to an old crustal source.

Although ascribed by most workers to the early stages of the Namaqua Wilson Cycle, previous dates for the Wilgenhoutsdrif Group, summarised in Table 1 have not been consistent. A felsic volcanic rock dated at

1290 ± 8 Ma (Moen, unpublished data) in Cornell et al. (2006), establishes an age for the volcanism in this Group.

Two samples were analysed from sedimentary units within the Wilgenhoutsdrif Group. The outcrop displayed quartzite and calcsilicate layers interbedded with conglomerate. The U–Pb data for these detrital zircons are concordant (Fig. 4b), and shown as Pb–Pb data in a probability density plot in Fig. 4a, range between 1770 and 2864 Ma, with the major population between 1800 and 2200 Ma.

3.2. Koras Group

The Koras Group (Fig. 2) overlies highly deformed units, including the Wilgenhoutsdrif Group. As shown in Fig. 3, it is made up of two bimodal volcanic sequences comprising basalt, rhyolite and sediments like conglomerate and sandstone. Each sequence represents a cycle of bimodal volcanism and sedimentation. It is situated in fault basins and considered to be related to a trans-tensional setting (Grobler et al., 1977), developed during late to post-collision. The Koras Group is usually described as undeformed, although in many samples greenschist facies mineral assemblages pseudomorph the magmatic minerals. Most previous workers agreed that the entire Koras Group postdated Namaqua deformation in the entire region. However, Sanderson-Damstra (1982) documented deformation fabrics in the Bossienek Formation, meter-scale folds as well as slickenside striations in outcrops of micaceous sandstone, which we also observed. His mapping also established the existence of gentle folding in the lower Swartkopsleegte rhyolites, identified two phases parallel to the regional FN2 and FN3 (FN3 crosscutting FN2) respectively and an angular unconformity between them and the overlying Rouxville basalts on the farm Karos Settlement. In this work four different units were sampled within the Koras Group. They are described in stratigraphic order from base to top. The Swartkopsleegte rhyolite is from the first cycle and recently yielded an ion-probe Pb–Pb age of 1171 ± 7 Ma (Gutzmer et al., 2000). Our sample contained a small number of zircons, which for 21 spots yield a discordia upper intercept age of 1163 ± 12, and for the nine concordant grains a concordia age at 1173 ± 12 Ma (Table 2, Fig. 5a). The concordia age is interpreted as the age of extrusion. The lower intercept of 328 ± 25 Ma reflects an ancient lead loss event during the Carboniferous, possibly corresponding to the Dwyka glaciation in the Gondwana continent. Much of the present land surface in this area is an exhumed Dwyka surface and tillite occurences are common.

Two rhyolitic lava samples were taken from the Leeuwdraai Formation in the upper volcanic cycle, which overlies the unconformity. The massive appearance of this formation led to its interpretation as an intrusion by some workers. However, the occurrence of horizons of welded tuff and layers with quartz-filled vesicles leave no doubt that it is an extrusive unit. These two samples yielded plentiful zircon and concordia ages of 1095 ± 10 Ma by SHRIMP, and 1092 ± 9 Ma by Nordsim respectively (Table 2, Fig. 5b and c). The mean of these two ages, which overlap statistically, is 1093 ± 7 Ma.

A unit regarded as a Swartkopsleegte correlate on the farm Ezelfontein in the southern domain, 20 km south of the type area, was dated. This yielded a date of 1104 ± 8 Ma (Table 2, Fig. 5d), showing that it is actually a Leeuwdraai correlate. Xenocrystic zircon cores in this sample (DC0420) yield Pb–Pb ages from 1182 Ma to 2116 Ma old. Concerning the correlations in the Koras

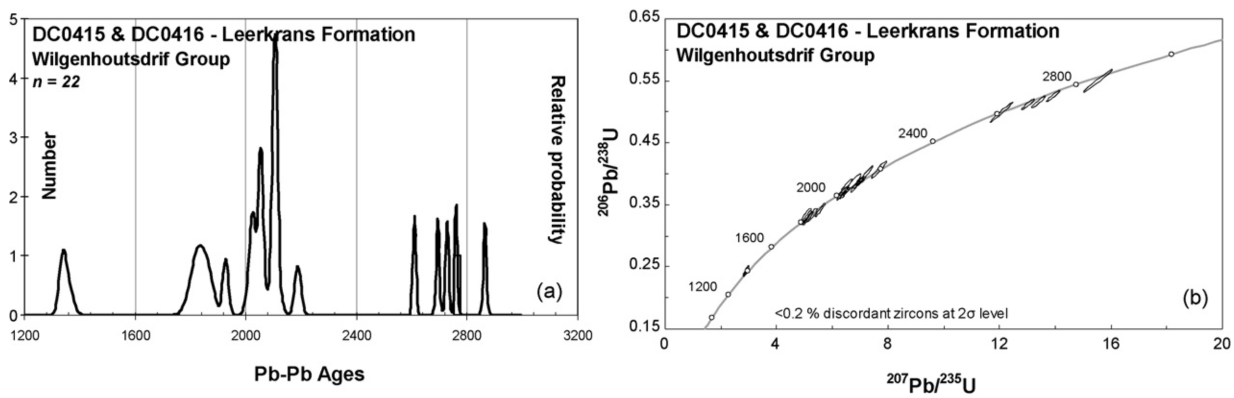

Fig. 4. Provenance age plot. (a) Detrital zircon ages (in Ma) in two metasedimentary samples of the Wilgenhoutsdrif Group shown as a probability density plot. Number of spots are 22 (n = 22) in 22 zircons. (b) Concordia plot of data in (a).

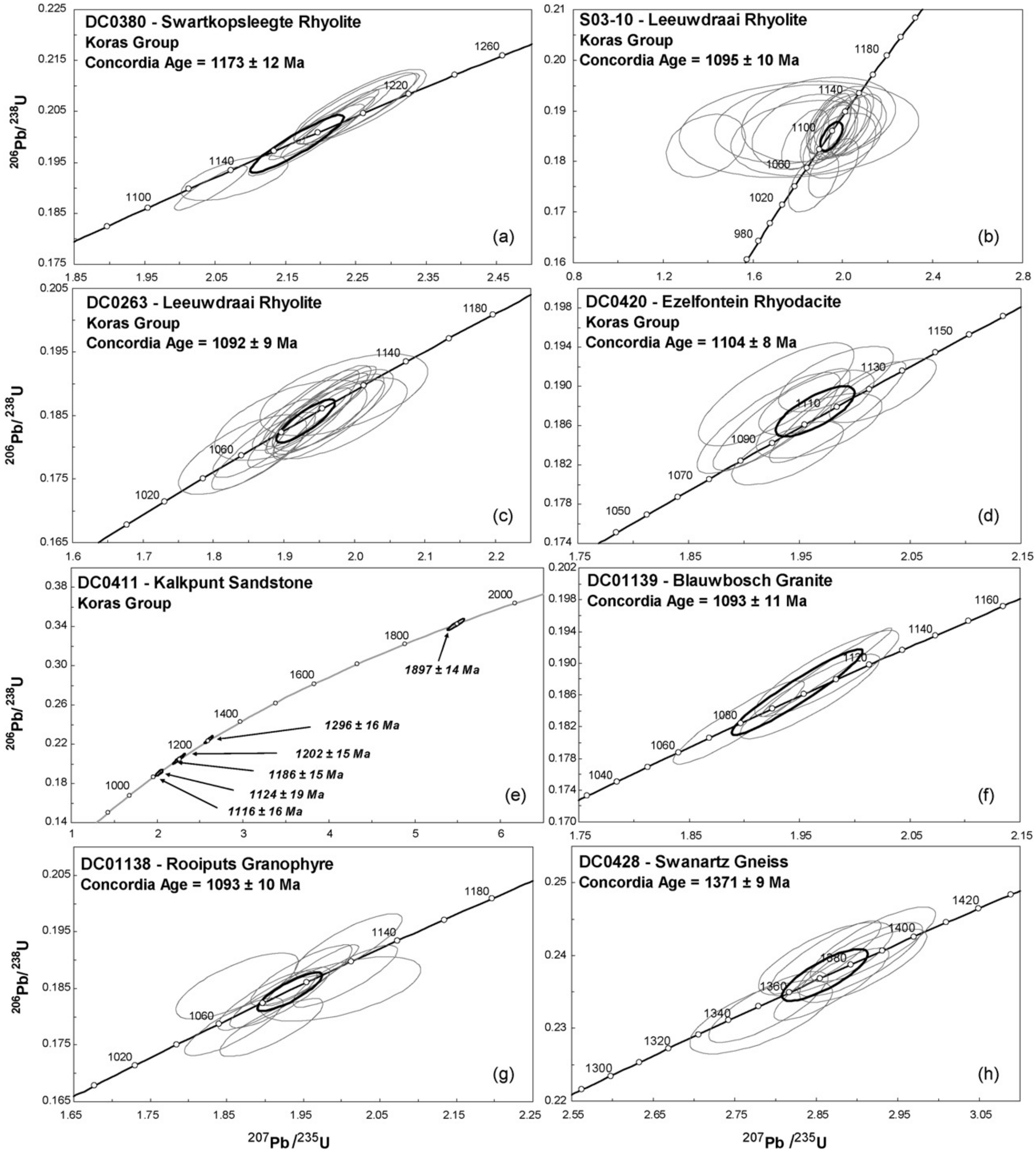

Fig. 5. Concordia diagrams of (a) DC0380, (b) S03-10, (c) DC0263, (d) DC0420, (e) DC0411, (f) DC01139, (g) DC01138 and (h) DC0428.

Group, our sample is not the same as the Ezelfontein Formation palaeomagnetic sample of Briden et al. (1979). Their sample is from a basaltic unit today referred to as Boom River Formation.

The uppermost Kalkpunt Formation red sandstone sample gave a wide range of detrital zircon U–Pb ages from 1116 up to 1897 Ma (Table 2, Fig. 5e). This reflects the ages in the provenance area towards the end of Koras volcanism. It suggests that the volcanism was not so extensive that it covered the whole area, although it is possible that the 1900 Ma grains were xenocrysts in Koras lavas. This sandstone has been used to define a paleomagnetic pole with age given as 800–1050 Ma (Briden et al., 1979) and taken as 1065 Ma (Weil et al., 1998). Field relationships suggest that the volcanic rubble which forms the base of this sedimentary unit was deposited soon after the 1093 ± 7 Ma Leeuwdraai Formation volcanism ceased, thereby establishing a maximum and probably true age for the Kalkpunt Sandstone Formation.

3.3. Blauwbosch and Rooiputs intrusives

The Blauwbosch granite and the Rooiputs granophyre have been interpreted as intrusive and extrusive or subvolcanic equivalents of the Koras Group respectively, based on their lack of deformation and the similarity in geochemical signatures (Geringer and Botha, 1976; Moen, 1987). They crop out 50 and 38 km NW of Upington, respectively (Figs. 1 and 2). The coarse-grained, two-feldspar Blauwbosch granite yielded a concordia age of 1093 ± 11 Ma (Table 2, Fig. 5f). The Rooiputs granophyre is characterized by large numbers of mafic xenoliths, reflecting bimodal magmatism, and gave a concordia age of 1093 ± 10 Ma (Table 2, Fig. 5g). These ages confirm the correlation, but only with the upper part of the Koras Group. Two xenocrystic zircons in the Rooiputs granophyre yield Pb–Pb minimum ages of 1818 and 1742 Ma, possibly reflecting Kheis Province rocks at depth. Three other xenocrysts have low Th/U ratios that probably indicate metamorphic zircon (Schersten et al., 2000) which yield a concordia age of 1187 ± 11 Ma.

This corresponds to the first Koras volcanic cycle and might reflect a metamorphic event in the bedrock at that time. Similar ages have been reported further west in the Namaqua Province (Raith et al., 2003) and as shown in the following section.

3.4. Areachap Group

The Areachap Terrane lies west of the Kaaien Terrane (Figs. 1 and 2), comprising a package of predominantly mafic to minor felsic metavolcanic rocks and metasediments which have the geochemical signature of a subduction-related arc complex (Geringer et al., 1994). This terrane has an amphibolite to granulite facies metamorphic overprint, which is generally much higher grade than those to the east. However, the amphibolite grade stretches into the westernmost quartzites of the Kaaien Terrane and their deformational histories are commonly correlated (Stowe, 1986; van Zyl, 1981).

The Areachap Group is defined by Geringer et al. (1994). It was conceived as a group of subduction-related formations which were accreted to the Kalahari Craton during the Namaqua orogeny (Fig. 2). Common features are the rock assemblages dominated by mafic and intermediate metavolcanics and their erosion products, the geochemical subduction signatures of the Copperton, Boksputs and Jannelsepan mafic rocks and Besshi-type Cu–Zn mineralization which has very similar Pb and S isotope signatures at Copperton and Areachap Mines (Voet and King, 1986; Theart et al., 1989).

Its juvenile character was established by a Kober method zircon date of 1285 ± 14 Ma (Cornell et al., 1990) at Copperton, 200 km south of Upington (Table 1). Views on this correlation are not unanimous, some workers consider the Boven Rugseer Shear Zone (Fig. 2), which transects the two areas, a major terrane boundary which prohibits them from correlating across it. Several strong geochemical similarities, Pb and S isotopes, Sm–Nd model ages and zircon ages as well as lithology need to be explained if they are not correlated. For further discussion see Cornell et al. (2006).

The narrow juvenile Areachap terrane seems to be unique in the Namaqua sector, but has similar age and origin to the juvenile terranes in the Natal sector of the Province (Thomas et al., 1994a). In this work, a metadacite was dated to establish ages for its origin and metamorphism, as was a cordierite-biotite-quartz-sphalerite gneiss from the Areachap Mine, close to Upington. The metadacite occurs as a thick migmatitic unit exposed in a quarry in the largely metabasic Jannelsepan formation. It contains extensive locally derived leucosome lenses and is also cut by tonalitic dykes which were folded after intrusion, showing that FN2 deformation accompanied migmatization. Conditions for performing hornblende barometry based on the Al content were met, melt and fluid were present as were phases of K-feldspar, titanite, plagioclase, magnetite, biotite, quartz and hornblende. The aluminium in hornblende geobarometer gives pressures of 5–6 kbar (Tindle and Webb, 1994), corresponding to 15–18 km depth for the migmatite (Table 3). Differences are due to different calibrations of the barometer, the calibration of Schmidt (1992), gave 6.1–6.3 kbar.

Zircons from this sample (DC0439), seen in backscattered electron images, exhibit oscillatory-zoned magmatic cores related to the origin of the protolith. Most grains also have thick rims or truncating overgrowths, which are ascribed to recrystallisation during migmatization. The magmatic zircon gave a concordia age of 1241 ± 12 Ma (Table 2 and Fig. 6a) and the overgrowths, which have low (<0.1) Th/U ratios indicative of metamorphic zircon gave a concordia age of 1165 ± 10 Ma (Table 2 and Fig. 6a). A borehole sample

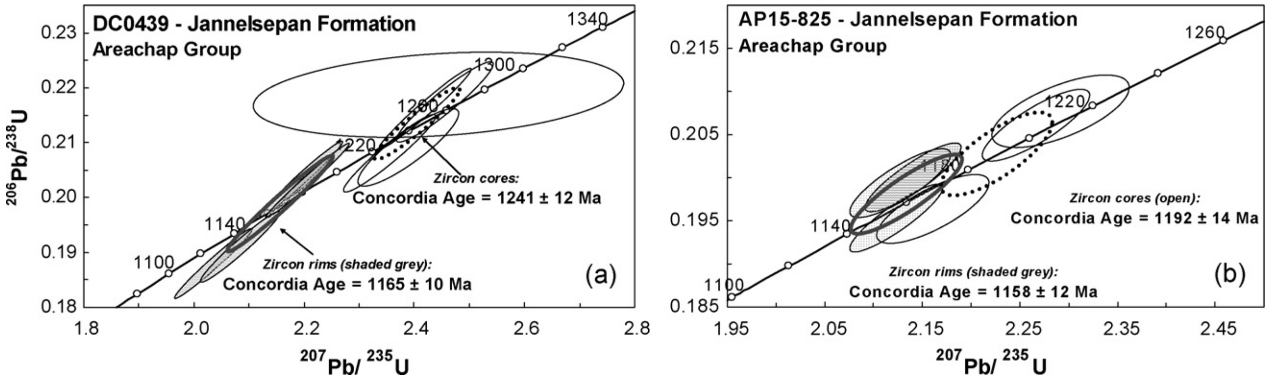

Fig. 6. (a). Concordia diagram of sample DC0439, Jannelsepan formation, Areachap Group. Displays two age groups, of magmatic and metamorphic origin. (b) Concordia diagram of sample AP15-825, Jannelsepan formation, Areachap Group.

(AP15-825), a cordierite-biotite-quartz-sphalerite gneiss from Areachap Mine north of the Orange river, further confirms the regional extent of this metamorphic event. The sample has rare zircons with metamorphic overgrowths yielding a concordia age of 1158 ± 12 Ma (Fig. 6b) as well as monazites giving a mean Pb–Pb age of 1148 ± 12 Ma (Table 2).

3.5. Swanartz gneiss

This granitic gneiss intervenes between the Areachap and the Wilgenhoutsdrif Group (Figs. 2 and 3). It is a generally coarse grained granitic gneiss with abundant biotite and hornblende as well as K-feldspar porphyroblasts. It shows intrusive but generally bedding parallel relationships to the surrounding schist of the Dagbreek formation, although cross-cutting contacts occur, with continuous structural fabric over them. Like many other granites in the region, it is deformed and was thus classified as a pre- or syntectonic granite. It is also cut by many bimodal Koras dykes. Its abundant zircon yields a concordia age of 1371 ± 9 Ma (Table 2, Fig. 5h), establishing that it formed early in the tectonic cycle and before the Wilgenhoutsdrif Group was deposited.

4. Discussion

4.1. Wilgenhoutsdrif Group

The detrital zircon from metasedimentary samples of the Wilgenhoutsdrif Group shows that most of the sediment was derived from an old provenance area. The 2.5–3.2 Ga zircons were probably derived from the Kaapvaal Craton, but the main body of 1800–2100 grains is more likely derived from the Kheis Province (Fig. 1) although the Craton does contain some rocks of this age. Hills of sandstone and micaceous quartzite occur and the Hartley lava horizon in the Kheis Front is dated at 1928 ± 4 Ma (Cornell et al., 1998). The Kheis Front is a west-verging thrust package ramped over the Kaapvaal Craton (Stowe, 1986), which may reflect the closure of an ocean basin at the end of a 1.9–1.7 Ga Wilson cycle (Cornell et al., 1998). As Eglington and Armstrong (2004) point out, the geochronological evidence for such a tectonic cycle is fragmentary, however it seems to be the best explanation for the geological relationships in the Kheis Province as shown in Fig. 2, which suggest a passive margin development at 1.9 Ga and require a thrusting event before 1.7 Ga (Tinker et al., 2002). Detrital zircons in the quartzites (Dagbreek formation and Groblershoop formation) to the east and around the Koras and Wilgenhoutsdrif exposures also have ages that agree with the dominating 1900–2200 Ma range, as well as a few older ages (Moen, unpublished data), in Cornell et al. (2006).

The chemical alteration trends and pillow structures in the mafic rocks together with the occurrence of serpentinites and calcsilicate rocks in the Wilgenhoutsdrif Group point to an oceanic setting. Together with the geochemical interpretation of an alkaline basalt protolith (Stenberg, 2005), these data indicate that the Wilgenhoutsdrif Group originated in a continental rift, accompanied by immature and locally shallow-water shelf sediments.

4.2. Subduction and collision

Some time after the onset of Wilgenhoutsdrif basin development, a subduction zone was active in an ocean basin to the west, leading to arc magmatism in which Areachap mafic to intermediate volcanic rocks formed between 1285 (Copperton formation) and 1240 Ma (Jannelsepan formation). The geometry suggests that the Wilgenhoutsdrif Group formed in a back-arc basin environment with the "Swanartz crustal block" on the outboard side. The ocean basin closed and the terranes of the Namaqua Province were assembled by a series of collisions, resulting in thickened crust and an extensive mountain belt across most of the Province. The Areachap Terrane was thus juxtaposed onto the Kaaien Terrane and the Wilgenhoutsdrif depositional basin was closed. This collision event was accompanied by isoclinal deformation in rocks of both terranes, referred to as the main Namaqua deformation event, FN2 (Humphreys and Van Bever Donker, 1987). After most orogenic deformation was complete in the Kaaien Terrane, trans-tensional stress opened up a new basin much as proposed by Jacobs et al. (1993), but much earlier than the 1070 Ma they suggested, leading to the first Koras bimodal volcanism at 1173 Ma.

4.3. Age of the collision from different terranes

In the Kaaien Terrane the collision-related orogeny is bracketed between the age of the Wilgenhoutsdrif Group at 1290 Ma and the oldest Koras Group rhyolites at 1173 Ma. However, the 1173 Ma rhyolites show traces of folding as pointed out by Sanderson-Damstra (1982) and so the FN2 deformation probably still affected this area to some extent, during the first Koras volcanism. The collision event and subsequent deformation must have proceeded for some tens of millions of years before deformation rates approached zero, thus the collision probably began before 1200 Ma.

In the adjacent Areachap Terrane, arc-magmatic processes were active at 1240 Ma, but migmatization at 15–18 km depth following the collision was in progress at 1165 Ma. At least 20 Ma was required for the build-up of heat, so the collision should have begun before 1185 Ma. Considering both terranes, the collision began after 1240 Ma and probably just before or around 1200 Ma.

4.4. End of tectonism in different terranes

Our dating shows that while the lower Koras Group was being deposited in the Kaaien Terrane at 1173 ± 12 Ma, the Jannelsepan Formation of the Areachap Group, today less than 12 km to the west, was subjected to migmatization and deformation in the Areachap Terrane (1165 ± 10 Ma) in a syntectonic setting. This can be explained by the 15–18 km difference in depth between the two localities, which prevailed at that time, according to our hornblende barometry. The long-held concept that the Koras postdates all tectonism in the Namaqua Sector of the Province (Barton and Burger, 1983; Gutzmer et al., 2000) must therefore be laid to rest.

Four ion-probe dates for Koras Group rhyolites suggest that there were two discrete pulses of magmatism at 1173 and 1093 Ma. Both intrusive equivalents which we dated fall in the latter group. We cannot exclude the possibility that all the zircons found in the two Swartkopsleegte samples thus far dated by ion-probe are actually xenocrysts. However, we have had no evidence to support this idea and consider it less likely.

The unconformity between the first and second volcanic cycles, recognised by Du Toit (1965) and documented by Sanderson-Damstra (1982) is now shown to represent an interval of some 80 Ma (1173–1093). After 1093 Ma there is no sign of folding in the Koras Group, although tilting continued. The Koras dykes and correlated intrusions which cut the Areachap Terrane are also undeformed, which shows that tectonism in the Areachap Terrane had waned by 1093 Ma. It seems likely that by this time the Areachap Terrane had been exhumed from the mid-crustal depths envisaged during the migmatization process.

In the broader context (Raith et al., 2003) documented high grade metamorphism at 1187 Ma in the Bushmanland Terrane, associated with extensive granite magmatism of the 1210–1180 Little Namaqualand Suite (Clifford et al., 2004; Robb et al., 1999). These rocks crop out around 300–400 km west of the area we investigated and correlations of tectonic events has not yet been established.

4.5. Magmatic event around 1100 Ma

Geochemical work has shown (Geringer and Botha, 1976; Moen, 1987) that rhyolite of the Koras Group and the intrusive Blaauwbosch granite and the Rooiputs granophyre are related and display a potassium-enriched calc-alkaline trend. Our zircon data now confirms that these intrusives are linked to the Koras Group, but only to the second volcanic pulse, around 1093 Ma. Moreover, these intrusive and extrusive rocks together suggest a 'post tectonic' bimodal magmatic event at 1093 Ma in the eastern Namaqua Sector. To the west (1087 Ma charnockite date, Barton and Burger, 1983) and south (Copperton) (Cornell et al., 1992), magmatic intrusions such as charnockites, and low-P, high-T metamorphic events have been dated around 1080 Ma, which reflect the same regional thermal pulse. This may be broadly related to the 1106 ± 2 Ma Umkundo Igneous Province (Hanson et al., 2004), defined by a large number of mafic intrusions on the otherwise undeformed Kaapvaal and Zimbabwe Cratons. 1109 Ma magmatism has also been recognised near the west coast by (Raith et al., 2003). A mantle process of continental scale seems to have happened at this time. This might be related to either a superplume (Hanson et al., 2004) or to mantle delamination suggested by Gibson et al. (1996) which could explain the changes in age, down to 1040 Ma in western Namaqualand.

4.6. Evidence for 1.9 Ga Kheis Province crust at depth

The xenocrysts in the Rooiputs granophyre and some of the extrusive rocks of the Koras Group are thought to be derived from deeper in the crust. These range in age from 2.1 to 1.74 Ga, similar to the main group of Wilgenhoutsdrif detrital zircons which are considered to be derived from the Kheis Province. It thus seems likely that the Kheis Province extends beneath the Kaaien Terrane, which was thrust onto it during the Namaqua collision. This is consistent with the gravity-defined boundary of the Namaqua Province lying west of the Kaaien Terrane (Fig. 1). Both xenocrystic and detrital zircons in and around the Koras basin reflect Palaeoproterozoic crustal growth, possibly in the Kheis Province. These crustal events are too young to reflect basement of the Kaapvaal Craton to the east, and too old to belong to the Areachap juvenile island arcs further west.

The Swanartz gneiss is wedged between faults in the Kaaien terrane and its 1371 Ma age predates all other basement rocks reported so far in eastern Namaqualand. Comparable ages are known from 1350 Ma granulites near Marydale (Humphreys and Cornell, 1989) and from the Awasib Mountain land, Namibia (Hoal and Heaman, 1995). They probably all reflect passive margin processes at the beginning of the Namaqua Wilson cycle.

5. Conclusions

1. Two “pretectonic” units have been dated, which formed before the Namaqua Province was assembled by collisions. These are the 1371 ± 9 Ma Swanartz Gneiss in the Kaaien Terrane and the 1241 ± 12 Ma Jannelsepan Formation in the Areachap Terrane.
2. The Wilgenhoutsdrif Group sediments were strongly influenced by older continental material, derived mainly from the Kheis Province. The bimodal character of the volcanic rocks likewise indicates significant crustal input during their generation. The Wilgenhoutsdrif Group probably formed in a continental back arc rift before becoming involved in Namaqua collisions.
3. The collision event which assembled terranes in the eastern Namaqua Sector started some time after 1230 Ma to allow for the formation of the Jannelsepan Formation at 1241 ± 12 Ma and probably around 1200 Ma to allow for pressure and heat build up to result in migmatization at 1165 ± 10 Ma in the Jannelsepan Formation of the Areachap Terrane.
4. Ages of two discrete bimodal volcanic cycles in the Koras Group and their related intrusive equivalents, the Blauwbosch Granite and the Rooiputs Granophyre have been determined. These rocks, which range from slightly folded to undeformed, overlie and intrude highly folded rocks in the Namaqua Front.
5. The 1173 Ma date for the first Koras volcanic pulse marks the end of all but gentle FN2 folding in the Kaaien Terrane. However the nearby Areachap Terrane was experiencing migmatization and severe FN2 deformation at around that time. Thus the regional tectonostratigraphic implications of a long-sought after “correct” date for the Koras Group are much less profound than has been envisaged.
6. The two cycles in the Koras Group may have different origins, considering the 80 Ma time gap. The early sequence probably originated in a pull-apart basin due to post-collision strike-slip movements. The late cycle reflects a continental-scale thermal process in the mantle such as a superplume or lithospheric delamination process.
7. An issue raised with the new chronostratigraphy of the Koras Group is the importance of complementing stratigraphic mapping with additional dating. A consequence is that the integrity of the Koras Group might be questioned. The 80 Ma time gap and unconformity between the pulses of magmatism in the Koras Group might invalidate its definition as a Group.
8. Paleoproterozoic zircon xenocrysts found in the Koras extrusives and correlated intrusives reflect a 1.8–2.0 Ma crust-forming event. They probably originate from sediments or tectonic basement which formed on the margin of the Kaapvaal Craton during the Kheis tectonic cycle and was overridden by the Kaaien terrane during the Namaquan collision.
9. By determining the age of the last volcanic cycle in the Koras Group, the Leeuwdraai rhyolite at 1093 ± 7 Ma, we have also established the maximum age of the sedimentation in the Kalkpunt sandstone. This constrains the age of the paleopole taken from this formation at younger than but close to 1093 Ma (we propose 1090 ± 5 Ma). These new data will con-

tribute to the refinement of palaeomagnetic data for other formations of the Koras Group, and more importantly to Apparent Polar Wander curves for the Kalahari Craton in paleomagnetic reconstructions.

Acknowledgments

The unpublished thesis of Sanderson-Damstra (1982) provided an invaluable basis for our fieldwork. The authors would also like to thank two reviewers for comments that greatly improved the manuscript. Martin Whitehouse and the Nordsim team are gratefully acknowledged. The NordSIM facility is supported by the research councils in Denmark Norway and Sweden and the Geological Survey of Finland, together with the Swedish Museum of Natural History. This is Nordsim contribution no. 183. The work of ÅP and DHC was supported by Swedish Research Council Grant 621-2003-4274 to DHC. This paper is TIGeR publication no. 15.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.precamres.2007.04.006.

References

Barton, E.S., Burger, A.J., 1983. Reconnaissance isotopic investigations in the Namaqua mobile belt and implications for Proterozoic crustal evolution—Upinton geotraverse. In: Botha, B.J.V. (Ed.), Geological Society of South Africa, vol. 10. Marshalltown. Spec. Publ., pp. 173–191.

Botha, B.J.V., Grobler, N.J., Burger, A.J., 1979. New U–Pb age-measurements on the Koras Group. Cape Province and its significance as a time-reference horizon in eastern Namaqualand. Trans. Geol. Soc. S. Afr. 82, 1–5.

Briden, J.C., Duff, B.A., Kroener, A., 1979. Palaeomagnetism of the Koras Group, northern Cape Province, South Africa. Precambrian Res. 10, 43–57.

Cahen, L., Snelling, N.J., 1984. The Geochronology and Evolution of Africa. Oxford University Press, Oxford, pp. 512.

Clifford, T.N., Barton, E.S., Stern, R.A., Duchesne, J.C., 2004. U–Pb zircon calendar Namaquan (Grenville) crustal events in the granulite-facies terrane of the O'okiep copper district of South Africa. J. Petrol. 45, 669–691.

Cornell, D.H., Armstrong, R.A., Walraven, F., 1998. Geochronology of the Proterozoic Hartley basalt formation, South Africa; Constraints on the Kheis tectogenesis and the Kaapvaal Craton's earliest Wilson cycle, Aspects of tensional magmatism, vol. 26. Pergamon, London-New York International, pp. 5–27.

Cornell, D.H., Humphreys, H., Theart, H.F.J., Scheepers, D.J., 1992. A collision-related pressure-temperature-time path for Prieska copper mine, Namaqua-Natal tectonic province, South Africa. Precambrian Res. 59, 43–71.

Cornell, D.H., Kroener, A., Humphreys, H., Griffin, G., 1990. Age of origin of the polymetamorphosed Copperton formation, Namaqua-Natal Province, determined by single grain zircon Pb–Pb dating. S. Afr. J. Geol. 93, 709–716.

Cornell, D.H., Thomas, R.J., Gibson, R., Moen, H.F.G., Moore, J.M., Reid, D.L., 2006. Namaqua-Natal Province. In: Johnson, M.R., Anhauesser, C.R., Thomas, R.J. (Eds.), Geology of South Africa. Geol. Soc. S. Afr. and Council Geoscience, Pretoria, pp. 325–379.

Cummings, G.L., Richards, J.R., 1975. Ore lead ratios in a continuously changing Earth. Earth Planet. Sci. Lett. 28, 155–171.

Dalziel, I.W.D., Mosher, S., Gahagan, L.M., 2000. Laurentia–Kalahari collision and the assembly of Rodinia. J. Geol. 108, 499–513.

Du Toit, M.C., 1965. Koras formation. Unpublished MSc Thesis, University of Orange Free State, South Africa, Bloemfontein, pp. 110.

Eglington, B.M., Armstrong, R.A., 2004. The Kaapvaal Craton and adjacent orogens. In: Southern Africa; A Geochronological Database and Overview of the Geological Development of the Craton. Kaapvaal Craton. Bureau for Scientific Publications, Pretoria, South Africa, pp. 13–32.

Frimmel, H.E., 2004. Formation of a late mesoproterozoic supercontinent: the South Africa–East Antarctica connection. In: Eriksson, P.G. (Ed.), The Precambrian Earth: Tempos and Events. Elsevier, pp. 240–254.

Geringer, G.J., Botha, B.J.V., 1976. The quartz porphyry-granite relation in rocks of the Koras formation west of Upington in the Gordonia district. Trans. Geol. Soc. S. Afr. 79, 58–60.

Geringer, G.J., Humphreys, H.C., Scheepers, D.J., 1994. Lithostratigraphy, protolithology, and tectonic setting of the Areachap Group along the eastern margin of the Namaqua mobile belt, South Africa. S. Afr. J. Geol. 97, 78–100.

Gibson, R.L., Robb, L.J., Kisters, A.F., Cawthorn, R.G., 1996. Regional setting and geological evolution of the Okiep Copper District, Namaqualand, South Africa. S. Afr. J. Geol. 99, 107–120.

Grobler, N.J., Botha, B.J.V., Smit, C.A., 1977. The tectonic setting of the Koras Group. Trans. Geol. Soc. S. Afr. 80, 167–175.

Gutzmer, J., Beukes, N.J., Pickard, A., Barley, M.E., 2000. 1170 Ma SHRIMP age for Koras Group bimodal volcanism, Northern Cape Province. S. Afr. J. Geol. 103, 32–37.

Hanson, R.E., Crowley, James, L., Bowring, S.A., Ramezani, J., Gose, W.A., Dalziel, I.W.D., Pancake, J.A., Siedel, E.K., Blenkinsop, T.G., Mukwakwami, J., 2004. Coeval large-scale magmatism in the Kalahari and Laurentian Cratons during Rodinia assembly. Science 304, 1126–1129.

Hoal, B.G., 1993. The proterozoic sinclair sequence in southern Namibia; intracratonic rift or active continental margin setting? Precambrian Res. 63, 143–162.

Hoal, B.G., Heaman, L.M., 1995. The Sinclair sequence: U–Pb age constraints from the Awasib Mountain area. Commun. Geol. Surv. South West Africa/Namibia 10, 83–91.

Humphreys, H.C., Cornell, D.H., 1989. Petrology and geochronology of low-pressure mafic granulites in the Marydale Group, South Africa. Lithos 22, 287–303.

Humphreys, H.C., Van Bever Donker, J.M., 1987. Aspects of deformation along the Namaqua Province eastern boundary, Kenhardt district, South Africa. Precambrian Res. 36, 39–63.

Jacobs, J., Thomas, R.J., Weber, K., 1993. Accretion and indentation tectonics at the southern edge of the Kaapvaal Craton during the Kibaran (Grenville) Orogeny. Geology 21, 203–206.

Kröner, A., 1977. The Sinclair aulacogen—a late proterozoic volcano-sedimentary association along the Namib desert of Southern

Namibia (SWA). In: Proceedings of the 9th Colloquium on African Geology, Göttingen, pp. 127–129.

Ludwig, K.R., 1991. Isoplot: a plotting and regression program for radiogenic-isotope data.

Ludwig, K.R., 1998. On the treatment of concordant uranium-lead ages. Geochimica et Cosmochimica Acta 62, 665–676.

Moen, H.F.G., 1987. The Koras Group and related intrusives north of Upington; a reinvestigation. Geological Survey of South Africa, Pretoria, South Africa Bulletin 85, 20 pp.

Moen, H.F.G., 1999. The Kheis tectonic subprovince, Southern Africa; a lithostratigraphic perspective. S. Afr. J. Geol. 102, 27–42.

Nelson, D.R., 1997. Compilation of SHRIMP U–Pb zircon geochronological data, record. Western Aust. Geol. Surv., 189.

Raith, J.G., Cornell, D.H., Frimmel, H.E., De Beer, C.H., 2003. New insights into the geology of the Namaqua tectonic province, South Africa, from ion-probe dating of detrital and metamorphic zircon. J. Geol. 111, 347–366.

Robb, L.J., Armstrong, R.A., Waters, D.J., 1999. The history of granulite-facies metamorphism and crustal growth from single zircon U–Pb geochronology, Namaqualand, South Africa. J. Petrol. 40, 1747–1770.

SACS, South African Committee for Stratigraphy, 1980. Stratigraphy of South Africa. Part 1. Lithostratigraphy of the republic of South Africa, South West Africa/Namibia, and the Republics of Bophuthatswana, Transkei and Venda. Handbook 8. Geological Survey of South Africa, p. 690.

Sanderson-Damstra, C.G., 1982. Geology of the central and southern domains of the Koras Group, Northern Cape Province. Unpublished MSc Thesis. Rhodes University, Grahamstown, 163 pp.

Schersten, A., Årebäck, H., Cornell, D., Hoskin, P., Åberg, A., Armstrong, R., 2000. Dating mafic-ultramafic intrusions by ion-microprobing contact-melt zircon; examples from SW Sweden. Contrib. Mineral. Petrol. 139, 115–125.

Schmidt, M.W., 1992. Amphibole composition in tonalite as a function of pressure; an experimental calibration of the Al-in-hornblende barometer. Contrib. Mineral. Petrol. 110, 304–310.

Stacey, J.S., Kramers, J.D., 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. Earth Planet. Sci. Lett. 26, 207–221.

Stenberg, S., 2005. The tectonic setting of the Namaqua sector rocks in the Upington area, South Africa: A geochemical study. Earth Sciences Centre B469. MSc. Thesis. Gothenburg University, Gothenburg. 40 pp.

Stowe, C.W., 1986. Synthesis and interpretation of structures along the north-eastern boundary of the Namaqua tectonic province, South Africa. Trans. Geol. Soc. S. Afr. 89, 185–198.

Theart, H.F.J., Cornell, D.H., Schade, J., 1989. Geochemistry and metamorphism of the Prieska Zn–Cu deposit, South Africa. Econ. Geol. Bull. Soc. Econ. Geol. 84, 34–48.

Thomas, R.J., Agenbacht, A.L.D., Cornell, D.H., Moore, J.M., 1994a. The Kibaran of Southern Africa: tectonic evolution and metallogeny. Ore Geol. Rev. 9, 131–160.

Thomas, R.J., Cornell, D.H., Moore, J.M., Jacobs, J., 1994b. Crustal evolution of the Namaqua-Natal metamorphic province, Southern Africa. S. Afr. J. Geol. 97, 8–14.

Thomas, R.J., de Beer, C.H., Bowring, S.A., 1996. A Comparative Study of the Mesoproterozoic Late Orogenic Porphyritic Granitoids of Southwest Namaqualand and Natal, South Africa, IGCP 348 (Mozambique and related belts). Pergamon, London-New York International, pp. 485–508.

Tindle, A.-G., Webb, P.-C., 1994. PROBE-AMPH; a spreadsheet program to classify microprobe-derived amphibole analysis. Comput. Geosci. 20, 1201–1228.

Tinker, J., de, W.M.J., Grotzinger, J., 2002. Seismic stratigraphic constraints on Neoarchean-Paleoproterozoic evolution of the western margin of the Kaapvaal Craton, South Africa. S. Afr. J. Geol. 105, 107–134.

van Zyl, C.Z., 1981. Structural and metamorphic evolution in the transitional zone between craton and mobile belt, Upington Geotraverse. Ph.D. Thesis. University of Cape Town, Cape Town, 243 pp.

Voet, H.W., King, B.H., 1986. The Areachap copper–zinc deposit, Gordonia District. In: Annhaeusser, C.R., Maske, S. (Eds.), Mineral Deposits of Southern Africa. Geological Society of South Africa, pp. 1529–1538.

Weil, A.B., Van der Voo, R., Mac Niocaill, C., Meert, J.G., 1998. The proterozoic supercontinent rodinia; paleomagnetically derived reconstructions for 1100–800 Ma. Earth Planet. Sci. Lett. 154, 13–24.

Whitehouse, M.J., Claesson, S., Sunde, T., Vestin, J., 1997. Ion microprobe U–Pb zircon geochronology and correlation of Archaean gneisses from the Lewisian complex of Gruinard Bay, Northwestern Scotland. Geochimica et Cosmochimica Acta 61, 4429–4438.

Whitehouse, M.J., Kamber, B.S., Moorbath, S., 1999. Age significance of U–Th–Pb zircon data from early Archaean rocks of west Greenland; a reassessment based on combined ion-microprobe and imaging studies. Chem. Geol. 160, 201–224.

Sample/ spot	[U] ppm	[Th] ppm	Th/U meas.	f_{206}%	$^{207}Pb/^{235}U$	±1_ error	$^{206}Pb/^{238}U$	±1_ error	Error corr.	Discordance (%)	$^{207}Pb/^{206}Pb$ ±1_(Ma)	$^{206}Pb/^{238}U$ ±1_ (Ma)
DC01138 - Rooiputs Granophyre												
10a	132	114	0.869	0.71	1.8634 ±	2.8398	0.18549 ±	2.0720	0.73	9.4	1010 ± 39	1097 ± 21
10b	145	137	0.943	{0.08}	2.0085 ±	2.3101	0.19261 ±	1.9214	0.83	5.1	1085 ± 26	1136 ± 20
10c	137	123	0.895	{0.09}	2.0047 ±	2.2601	0.18717 ±	1.9109	0.85	-3.1	1139 ± 24	1106 ± 19
10d	139	124	0.889	0.16	1.9477 ±	2.2511	0.18731 ±	1.8968	0.84	2.7	1080 ± 24	1107 ± 19
17b	158	59	0.378	3.43	1.9978 ±	3.4824	0.18492 ±	2.0333	0.58	-5.8	1156 ± 55	1094 ± 20
20a	112	77	0.685	{0.17}	1.9027 ±	2.2390	0.18293 ±	1.8952	0.85	0.3	1080 ± 24	1083 ± 19
20b	113	77	0.689	{0.13}	1.9193 ±	2.2377	0.18340 ±	1.9264	0.86	-0.7	1092 ± 23	1086 ± 19
24a	103	67	0.655	{0.07}	1.9086 ±	2.3284	0.17811 ±	1.8956	0.81	-7.9	1140 ± 27	1057 ± 19
24b	106	70	0.664	{0.07}	1.8591 ±	2.2776	0.17821 ±	1.8953	0.83	-2.9	1086 ± 25	1057 ± 19
61a	349	72	0.207	{0.04}	1.9616 ±	2.0452	0.18733 ±	1.8955	0.93	1.3	1094 ± 15	1107 ± 19
17a*	462	27	0.058	0.06	2.2398 ±	1.9748	0.20443 ±	1.8987	0.96	1.4	**1184** ± 11	1199 ± 21
64a*	391	23	0.059	{0.03}	2.2176 ±	1.7809	0.20223 ±	1.6486	0.93	0.2	**1185** ± 13	1187 ± 18
~~62a~~	1075	6	0.005	2.89	1.5560 ±	2.2956	0.15061 ±	1.9055	0.83	-16.3	1067 ± 26	904 ± 16
~~17c~~	403	24	0.059	{0.04}	2.2061 ±	1.8035	0.20055 ±	1.6592	0.92	-1.2	**1192** ± 14	1178 ± 18
~~30a~~	439	5	0.011	{0.00}	2.1121 ±	1.7579	0.19675 ±	1.6487	0.94	1.4	**1143** ± 12	1158 ± 17
~~65a~~	113	111	0.980	{0.07}	5.5908 ±	1.8318	0.36478 ±	1.6491	0.90	11.9	**1818** ± 14	2005 ± 28
~~69a~~	98	109	1.108	{0.04}	4.5445 ±	1.9836	0.30918 ±	1.7370	0.88	-0.4	**1742** ± 17	1737 ± 26
~~72a~~	392	24	0.062	{0.03}	2.1869 ±	1.8291	0.19979 ±	1.6490	0.90	-0.7	**1182** ± 16	1174 ± 18
DC01139 - Blauwbosch Granite												
19a	933	429	0.460	0.18	1.9744 ±	1.9891	0.18887 ±	1.9510	0.98	2.5	1090 ± 8	1115 ± 20
25a	110	132	1.208	{0.13}	1.9749 ±	2.1784	0.18869 ±	1.8951	0.87	2.2	1093 ± 21	1114 ± 19
6a	469	407	0.867	0.92	1.8948 ±	2.0624	0.18254 ±	1.8995	0.92	0.5	1076 ± 16	1081 ± 19
8a	240	191	0.795	0.35	1.9594 ±	2.1375	0.18580 ±	1.8952	0.89	-0.9	1108 ± 20	1099 ± 19
~~25b~~	78	90	1.150	{0.15}	1.9403 ±	2.4045	0.18299 ±	1.9958	0.83	-3.4	1119 ± 27	1083 ± 20
~~6b~~	621	353	0.568	0.39	1.7928 ±	2.0266	0.17383 ±	1.9401	0.96	-3.1	1063 ± 12	1033 ± 19
~~26a~~	54	64	1.180	{0.00}	1.9511 ±	2.3742	0.18233 ±	1.9113	0.81	-5.5	1137 ± 28	1080 ± 19
~~26b~~	340	261	0.767	3.21	1.6860 ±	2.7771	0.16678 ±	1.9488	0.70	-3.0	1023 ± 40	994 ± 18
~~47a~~	4124	2778	0.674	3.44	0.3789 ±	3.6886	0.04844 ±	1.8978	0.51	-37.5	482 ± 68	305 ± 6
~~47a2~~	3879	2670	0.688	7.77	0.4148 ±	5.5568	0.05115 ±	1.9197	0.35	-43.7	560 ± 110	322 ± 6
~~50a~~	441	414	0.938	0.38	1.7446 ±		0.16830 ±	1.9107	0.94	-7.1	1073 ± 14	1003 ± 18
~~53a~~	171	82	0.477	0.63	1.8521 ±	2.2849	0.17626 ±	1.8971	0.83	-5.3	1101 ± 25	1047 ± 18
~~53b~~	364	266	0.730	0.08	1.8255 ±	2.0143	0.17435 ±	1.8958	0.94	-5.7	1093 ± 14	1036 ± 18
~~63a~~	544	621	1.143	1.56	1.7620 ±	2.1983	0.16594 ±	1.8966	0.86	-12.7	1121 ± 22	990 ± 17
DC0263 - Leeuwdraai Rhyolite, Koras Group												
18a	47	66	1.392	0.98	1.9097 ±	3.7424	0.18427 ±	2.2666	0.61	1.8	1073 ± 59	1090 ± 23
20b	80	79	0.983	{0.15}	1.9851 ±	3.9651	0.18828 ±	2.2532	0.57	0.5	1107 ± 64	1112 ± 23
21a	122	98	0.803	{0.16}	1.9638 ±	2.6587	0.18434 ±	2.2532	0.85	-3.6	1128 ± 28	1091 ± 23
21b	50	46	0.931	{0.13}	1.9747 ±	3.3270	0.18454 ±	2.2677	0.68	-4.3	1137 ± 48	1092 ± 23
25b	53	51	0.951	{0.11}	1.9693 ±	2.8585	0.18584 ±	2.2663	0.79	-1.8	1117 ± 34	1099 ± 23
27a	130	107	0.819	{0.10}	1.8713 ±	2.6013	0.17942 ±	2.2495	0.86	-2.2	1086 ± 26	1064 ± 22
2a	133	113	0.846	{0.09}	1.9471 ±	2.5831	0.18651 ±	2.2610	0.88	1.5	1088 ± 25	1102 ± 23
37a	126	145	1.148	0.18	1.9313 ±	2.5830	0.18585 ±	2.2566	0.87	2.1	1078 ± 25	1099 ± 23
39a	94	92	0.986	{0.11}	1.9632 ±	2.6225	0.18521 ±	2.2479	0.86	-2.2	1118 ± 27	1095 ± 23
3a	187	168	0.900	{0.05}	1.9460 ±	2.4565	0.18539 ±	2.2587	0.92	-0.2	1098 ± 19	1096 ± 23
44a	69	102	1.482	0.30	1.8412 ±	3.2562	0.17887 ±	2.3183	0.71	0.2	1059 ± 45	1061 ± 23
4a	138	157	1.139	0.39	1.8744 ±	2.6516	0.18143 ±	2.2442	0.85	0.8	1067 ± 28	1075 ± 22
7a	216	222	1.029	{0.06}	1.9567 ±	2.4826	0.18637 ±	2.2801	0.92	0.3	1099 ± 20	1102 ± 23
9a	138	137	0.991	{0.13}	1.9224 ±	2.5415	0.18308 ±	2.2583	0.89	-1.5	1099 ± 23	1084 ± 23
~~11a~~	201	159	0.793	0.18	1.8741 ±	2.5455	0.17804 ±	2.3090	0.91	-4.7	1104 ± 21	1056 ± 23
~~11b~~	45	44	0.970	{0.32}	1.9322 ±	3.0643	0.17685 ±	2.2923	0.75	-11.8	1178 ± 40	1050 ± 22
~~20a~~	168	150	0.895	{0.10}	1.7820 ±	2.7874	0.16876 ±	2.4810	0.89	-10.2	1110 ± 25	1005 ± 23
~~25a~~	119	131	1.104	3.10	1.4685 ±	4.4927	0.18913 ±	2.2483	0.50	153.0	465 ± 84	1117 ± 23
~~29a~~	156	151	0.967	0.32	1.7824 ±	2.7931	0.17590 ±	2.3843	0.85	1.8	1028 ± 29	1045 ± 23
~~38a~~	75	92	1.218	0.54	1.8255 ±	3.0642	0.18127 ±	2.2956	0.75	6.3	1015 ± 41	1074 ± 23
DC0380 - Swartkopsleegte Rhyolite, Koras Group												
7a	524	47	0.090	0.40	2.2578 ±	2.4076	0.20545 ±	2.2491	0.93	1.4	1190 ± 17	1205 ± 25
8a	458	34	0.075	{0.01}	2.2218 ±	2.3256	0.20297 ±	2.2467	0.97	0.9	1182 ± 12	1191 ± 24
9a	267	31	0.116	{0.03}	2.2493 ±	2.5620	0.20559 ±	2.2494	0.88	2.3	1181 ± 24	1205 ± 25
9b	285	39	0.135	{0.00}	2.2557 ±	2.7565	0.20599 ±	2.3248	0.84	2.3	1183 ± 29	1207 ± 26
9c	208	44	0.213	{0.06}	2.1797 ±	2.4854	0.19941 ±	2.3071	0.93	-0.6	1179 ± 18	1172 ± 25
10a	392	141	0.359	{0.05}	2.2049 ±	2.3342	0.20237 ±	2.2448	0.96	1.4	1173 ± 13	1188 ± 24
14a	690	257	0.372	0.21	2.2233 ±	1.5917	0.20314 ±	1.5070	0.95	1.0	1182 ± 10	1192 ± 16
25b	67	38	0.571	0.75	2.0780 ±	2.4082	0.19190 ±	1.5063	0.63	-2.7	1160 ± 37	1132 ± 16
27b	966	437	0.452	1.47	2.0442 ±	1.6678	0.18998 ±	1.5090	0.90	-2.5	1148 ± 14	1121 ± 16
~~4a~~	508	193	0.380	0.06	2.2690 ±	2.3266	0.21013 ±	2.2481	0.97	7.1	1155 ± 12	1230 ± 25
~~11a~~	295	90	0.307	0.67	1.9820 ±	2.5222	0.18523 ±	2.2436	0.89	-4.0	1137 ± 23	1095 ± 23
~~13a~~	800	395	0.494	0.05	2.3038 ±	2.3769	0.21017 ±	2.2457	0.94	4.2	1185 ± 15	1230 ± 25
~~20a~~	896	298	0.332	0.05	2.2839 ±	2.3544	0.20977 ±	2.2579	0.96	5.3	1171 ± 13	1228 ± 25
~~24a~~	3196	1195	0.374	8.52	0.5098 ±	2.9022	0.06253 ±	2.2766	0.78	-32.6	572 ± 39	391 ± 9
~~13a~~	622	191	0.307	0.05	2.4896 ±	2.3916	0.22713 ±	2.2612	0.95	12.6	1185 ± 15	1319 ± 27
~~24a~~	1652	701	0.424	0.08	2.3103 ±	2.3039	0.21154 ±	2.2632	0.98	5.6	1177 ± 9	1237 ± 26
~~21a~~	278	110	0.394	{0.06}	2.1592 ±	2.5975	0.19492 ±	2.4901	0.96	-5.2	1205 ± 14	1148 ± 26
~~25a~~	154	168	1.090	0.13	2.1836 ±	1.8465	0.20298 ±	1.5064	0.82	4.2	1147 ± 21	1191 ± 16
~~26a~~	2392	472	0.198	2.93	1.2132 ±	1.7154	0.12296 ±	1.5115	0.88	-24.6	974 ± 16	748 ± 11

~~24b~~	1460	571	0.391	2.42	1.6811 ± 1.7400	0.16183 ± 1.5114	0.87	-11.1	1078 ± 17	967 ± 14
~~28a~~	1259	475	0.378	1.24	1.6758 ± 1.6449	0.15947 ± 1.5135	0.92	-14.3	1101 ± 13	954 ± 13
~~12a~~	388	65	0.166	0.22	2.2662 ± 1.6754	0.21226 ± 1.5063	0.90	10.5	1132 ± 15	1241 ± 17
DC0411 - Sandstone, Kalkpunt Formation, Koras Group										
7a	254	143	0.562	{0.03}	2.0043 ± 1.2708	0.18963 ± 1.1495	0.90	0.7	1112 ± 11	1119 ± 12
22a	173	136	0.788	0.08	5.4796 ± 1.2219	0.34242 ± 1.1450	0.94	0.1	1896 ± 8	1898 ± 19
24a	283	24	0.084	{0.03}	2.2809 ± 1.2476	0.20680 ± 1.1456	0.92	1.4	1197 ± 10	1212 ± 13
32a	292	42	0.144	{0.05}	2.2259 ± 1.2394	0.20325 ± 1.1456	0.92	0.9	1183 ± 9	1193 ± 12
46a	108	97	0.900	{0.11}	2.0259 ± 1.4116	0.19098 ± 1.1482	0.81	0.7	1120 ± 16	1127 ± 12
50a	217	181	0.832	{0.07}	2.5983 ± 1.2562	0.22461 ± 1.1449	0.91	1.4	1290 ± 10	1306 ± 14
~~9a~~	365	363	0.995	1.94	4.0226 ± 1.4581	0.26157 ± 1.2731	0.87	-20.0	1825 ± 13	1498 ± 17
~~23a~~	1141	101	0.088	2.04	1.8858 ± 1.7855	0.17355 ± 1.3315	0.75	-12.6	1167 ± 23	1032 ± 13
~~26a~~	456	30	0.067	3.07	1.6870 ± 1.6179	0.15665 ± 1.1888	0.73	-19.8	1150 ± 22	938 ± 10
~~53a~~	103	118	1.143	5.46	3.6994 ± 18.4155	0.52933 ± 2.2668	0.12	1379.1	227 ± 375	2739 ± 51
DC0415 - Quartzite, Leerkrans Formation, Wilgenhoutsdrif Group										
3a	238	138	0.578	1.31	6.4683 ± 2.4412	0.37790 ± 2.3299	0.95	2.9	2017 ± 13	2066 ± 41
13a	165	88	0.532	0.09	13.9303 ± 1.1605	0.52597 ± 1.1202	0.97	-1.6	2760 ± 5	2724 ± 25
15a	220	232	1.058	{0.04}	6.9786 ± 1.1562	0.38680 ± 1.1033	0.95	-0.1	2109 ± 6	2108 ± 20
18a	194	114	0.586	0.07	6.8605 ± 1.1684	0.38252 ± 1.1001	0.94	-0.6	2099 ± 7	2088 ± 20
17a	120	49	0.408	{0.04}	13.0256 ± 1.1632	0.51202 ± 1.1070	0.95	-1.3	2694 ± 6	2665 ± 24
26a	160	137	0.854	0.08	6.5050 ± 1.2288	0.37145 ± 1.1552	0.94	-1.2	2057 ± 7	2036 ± 20
26b	170	137	0.807	0.23	6.3926 ± 1.2106	0.36635 ± 1.1238	0.93	-2.2	2051 ± 8	2012 ± 19
28a	53	29	0.549	{0.15}	7.0073 ± 1.5105	0.38833 ± 1.2136	0.80	0.3	2110 ± 16	2115 ± 22
32a	134	66	0.497	0.08	13.4038 ± 1.2363	0.51611 ± 1.1853	0.96	-2.0	2728 ± 6	2683 ± 26
~~1a~~	141	67	0.474	0.43	6.1140 ± 2.5333	0.35066 ± 2.4442	0.96	-6.3	2049 ± 12	1938 ± 41
~~5a~~	694	402	0.580	3.99	3.4911 ± 1.2456	0.10134 ± 1.1347	0.91	-84.1	3184 ± 8	622 ± 7
~~6a~~	405	227	0.560	0.35	5.1259 ± 1.3717	0.30034 ± 1.3352	0.97	-18.0	2011 ± 6	1693 ± 20
~~10a~~	311	244	0.785	1.64	5.0297 ± 1.6631	0.33647 ± 1.2275	0.74	6.3	1773 ± 20	1870 ± 20
~~15b~~	139	116	0.839	3.74	6.1752 ± 2.0018	0.34117 ± 1.1004	0.55	-12.1	2115 ± 29	1892 ± 18
~~32b~~	256	88	0.346	0.26	12.6146 ± 1.1983	0.48937 ± 1.1692	0.98	-6.6	2716 ± 4	2568 ± 25
~~41a~~	100	97	0.977	2.76	2.4865 ± 1.7355	0.14531 ± 1.2865	0.74	-60.4	2016 ± 21	875 ± 11
DC0416 - Conglomerate, Leerkrans Formation, Wilgenhoutsdrif Group										
4a	301	211	0.701	0.24	6.3663 ± 2.2477	0.36976 ± 2.1835	0.97	0.1	2027 ± 9	2028 ± 38
9a	169	135	0.803	0.34	5.0708 ± 2.3427	0.32981 ± 2.1833	0.93	0.8	1824 ± 15	1837 ± 35
13a	302	104	0.346	0.27	15.5326 ± 2.2156	0.55021 ± 2.1850	0.99	-1.7	2864 ± 6	2826 ± 50
20a	173	126	0.725	0.30	7.6810 ± 2.3032	0.40687 ± 2.2027	0.96	0.6	2189 ± 12	2201 ± 41
28a	109	311	2.847	0.61	5.0630 ± 2.4920	0.33294 ± 2.1988	0.88	3.1	1804 ± 21	1853 ± 36
29a	266	110	0.414	0.32	6.8816 ± 2.2548	0.38294 ± 2.1850	0.97	-0.7	2102 ± 10	2090 ± 39
30a	146	184	1.259	0.18	5.1196 ± 2.3368	0.32873 ± 2.1832	0.93	-0.9	1847 ± 15	1832 ± 35
31a	291	141	0.483	0.12	5.5571 ± 2.2525	0.34128 ± 2.1826	0.97	-2.1	1928 ± 10	1893 ± 36
32a	132	134	1.015	0.57	6.7814 ± 2.4117	0.38741 ± 2.1815	0.90	3.1	2056 ± 18	2111 ± 39
33a	364	360	0.988	0.21	7.2063 ± 2.2422	0.39958 ± 2.1821	0.97	3.3	2109 ± 9	2167 ± 40
51a	368	201	0.546	0.10	12.0762 ± 2.2083	0.49951 ± 2.1815	0.99	0.1	2609 ± 6	2612 ± 47
64a	154	94	0.610	0.52	5.2620 ± 2.3979	0.33350 ± 2.1816	0.91	-1.0	1871 ± 18	1855 ± 35
65b	261	122	0.467	0.50	2.9064 ± 2.3840	0.24285 ± 2.1829	0.92	3.7	1356 ± 18	1401 ± 28
~~65a~~	417	132	0.316	0.20	2.8947 ± 2.2784	0.24422 ± 2.1824	0.96	5.9	1337 ± 13	1409 ± 28
DC0420 - Rhyolite at Ezelfontein, Koras Group										
96a	55	57	1.037	{0.10}	1.9394 ± 1.7082	0.18319 ± 1.1633	0.68	-3.0	1116 ± 25	1084 ± 12
97a	55	105	1.898	{0.21}	1.9830 ± 1.7250	0.19078 ± 1.1509	0.67	4.7	1079 ± 26	1126 ± 12
102b	53	55	1.046	{0.15}	1.9654 ± 1.7523	0.18838 ± 1.1452	0.65	2.6	1086 ± 26	1113 ± 12
102c	71	81	1.137	{0.09}	2.0252 ± 1.5762	0.18960 ± 1.1450	0.73	-1.4	1133 ± 21	1119 ± 12
104b	81	59	0.735	0.79	1.9678 ± 1.9040	0.18600 ± 1.1745	0.62	-1.4	1114 ± 30	1100 ± 12
9a	81	121	1.497	{0.10}	1.9341 ± 2.1136	0.18664 ± 1.8318	0.87	3.1	1073 ± 21	1103 ± 19
11a	96	138	1.440	{0.07}	1.9844 ± 2.0394	0.18739 ± 1.8248	0.89	-0.9	1116 ± 18	1107 ± 19
45a	64	71	1.111	0.31	1.9221 ± 2.2224	0.18629 ± 1.8328	0.82	3.8	1064 ± 25	1101 ± 19
58a	49	50	1.019	{0.20}	1.9290 ± 2.3995	0.18924 ± 1.8335	0.76	8.1	1040 ± 31	1117 ± 19
~~94a~~	130	80	0.617	{0.04}	2.7849 ± 1.3255	0.23452 ± 1.1488	0.87	1.4	**1341** ± 13	1358 ± 14
~~96b~~	94	114	1.215	{0.19}	1.8057 ± 1.8680	0.17341 ± 1.1606	0.62	-5.2	1082 ± 29	1031 ± 11
~~99b~~	48	44	0.934	{0.26}	1.8110 ± 2.0195	0.17154 ± 1.1449	0.57	-8.7	1110 ± 33	1021 ± 11
~~21a~~	480	317	0.660	0.03	7.1009 ± 1.1767	0.39195 ± 1.1533	0.98	0.8	**2117** ± 4	2132 ± 21
~~23a~~	260	92	0.352	{0.04}	2.2164 ± 1.3009	0.20016 ± 1.1778	0.91	-2.6	**1205** ± 11	1176 ± 13
~~33a~~	119	171	1.433	0.34	2.0229 ± 1.6637	0.19790 ± 1.1449	0.69	12.4	1045 ± 24	1164 ± 12
~~49a~~	50	59	1.165	0.63	2.0143 ± 2.0888	0.19557 ± 1.1562	0.55	9.4	1060 ± 35	1151 ± 12
~~50a~~	1237	77	0.062	0.09	5.7726 ± 1.1661	0.35239 ± 1.1555	0.99	0.5	**1938** ± 3	1946 ± 19
~~50b~~	395	152	0.386	{0.01}	6.0576 ± 1.2169	0.35774 ± 1.1449	0.94	-1.5	**1997** ± 7	1971 ± 19
~~66a~~	316	129	0.410	{0.02}	2.2230 ± 1.2693	0.20303 ± 1.1665	0.92	0.9	**1182** ± 10	1192 ± 13
~~66b~~	86	66	0.762	3.92	1.5868 ± 3.7238	0.15101 ± 1.1479	0.31	-18.9	1101 ± 69	907 ± 10
~~6a~~	69	87	1.267	1.62	1.6732 ± 3.3383	0.18174 ± 1.8666	0.56	32.2	831 ± 57	1076 ± 19
~~99a~~	276	435	1.575	2.05	4.3393 ± 2.1082	0.28385 ± 1.5459	0.73	-12.6	**1814** ± 26	1611 ± 22
~~102a~~	78	107	1.370	{0.20}	1.8370 ± 1.7232	0.17384 ± 1.1666	0.68	-7.7	1112 ± 25	1033 ± 11
~~36a~~	48	43	0.896	0.79	1.9073 ± 2.7362	0.18885 ± 1.9317	0.71	10.1	1021 ± 39	1115 ± 20
~~102d~~	85	111	1.307	{0.12}	2.0005 ± 2.1273	0.19428 ± 1.8349	0.86	8.7	1060 ± 22	1144 ± 19
~~104a~~	433	19	0.045	{0.02}	2.2118 ± 1.2628	0.20198 ± 1.1500	0.91	0.3	**1183** ± 10	1186 ± 12
DC0428 - Swanartz Gte gneiss										
41a	109	84	0.773	{0.05}	2.9038 ± 1.7316	0.23945 ± 1.4098	0.81	0.2	1381 ± 19	1384 ± 18
32a	180	115	0.641	{0.03}	2.8609 ± 1.5864	0.23976 ± 1.3809	0.87	2.9	1350 ± 15	1385 ± 17
6a	257	159	0.619	0.67	2.7909 ± 1.7234	0.23291 ± 1.3882	0.81	-0.7	1358 ± 20	1350 ± 17
85a	113	109	0.963	{0.06}	2.9193 ± 1.7360	0.24149 ± 1.4083	0.81	1.5	1375 ± 19	1394 ± 18

76a	183	130	0.712	{0.02}	2.8684 ± 1.6274	0.23605 ± 1.3864	0.85	-1.5	1385 ± 16	1366 ± 17
101a	57	44	0.764	{0.15}	2.7822 ± 2.0783	0.23152 ± 1.4379	0.69	-1.7	1364 ± 29	1342 ± 17
118a	133	116	0.873	{0.07}	2.8612 ± 1.8943	0.23954 ± 1.3819	0.73	2.6	1352 ± 25	1384 ± 17
85b	146	67	0.456	{0.05}	2.9073 ± 1.7740	0.23859 ± 1.3953	0.79	-0.9	1391 ± 21	1379 ± 17
~~101b~~	315	220	0.700	0.05	2.9685 ± 1.4996	0.24795 ± 1.3726	0.92	5.8	1357 ± 12	1428 ± 18
~~100a~~	888	626	0.704	0.30	2.1901 ± 1.7972	0.18941 ± 1.7278	0.96	-14.4	1289 ± 10	1118 ± 18
~~118b~~	156	66	0.426	0.44	2.8148 ± 1.8069	0.24553 ± 1.3840	0.77	12.5	1273 ± 22	1415 ± 18
~~106a~~	282	130	0.460	{0.04}	2.9693 ± 1.7062	0.24613 ± 1.3773	0.81	3.8	1371 ± 19	1418 ± 18
~~73a~~	66	8	0.116	0.57	2.2911 ± 2.3488	0.19935 ± 1.5591	0.66	-9.1	1278 ± 34	1172 ± 17
~~41b~~	317	140	0.441	1.73	2.6340 ± 2.4107	0.25788 ± 1.4225	0.59	46.7	1044 ± 39	1479 ± 19
~~40a~~	649	270	0.417	1.82	2.3769 ± 1.7950	0.23178 ± 1.3705	0.76	30.8	1052 ± 23	1344 ± 17
~~106b~~	47	22	0.463	0.89	2.2294 ± 2.9844	0.20030 ± 1.5932	0.53	-3.4	1215 ± 49	1177 ± 17
DC0439 - Migmatite, Jannelsepan Formation, Areachap Group										
4a	1072	797	0.744	2.00	2.4543 ± 2.3651	0.21729 ± 2.2280	0.94	2.1	1244 ± 15	1268 ± 26
40a	691	547	0.791	5.18	2.4434 ± 9.0795	0.21860 ± 2.3505	0.26	4.6	1223 ± 163	1274 ± 27
40b	758	649	0.856	4.18	2.3889 ± 2.5414	0.20904 ± 2.2272	0.88	-3.7	1266 ± 24	1224 ± 25
76a	1139	1003	0.881	1.90	2.3549 ± 2.3330	0.20798 ± 2.2271	0.95	-2.7	1248 ± 14	1218 ± 25
56a	1634	1466	0.897	0.78	2.4192 ± 2.2784	0.21605 ± 2.2261	0.98	3.1	1227 ± 10	1261 ± 26
4b*	1553	146	0.094	0.32	2.0348 ± 2.2702	0.18783 ± 2.2260	0.98	-4.8	1161 ± 9	1110 ± 23
12a*	1791	120	0.067	0.29	2.1947 ± 2.2641	0.20319 ± 2.2261	0.98	3.5	1156 ± 8	1192 ± 24
71a*	1706	19	0.011	0.12	2.2054 ± 2.2543	0.20299 ± 2.2260	0.99	2.3	1167 ± 7	1191 ± 24
75a*	1856	23	0.012	0.56	2.0838 ± 2.2960	0.19103 ± 2.2265	0.97	-4.5	1175 ± 11	1127 ± 23
115a*	1587	24	0.015	0.03	2.2062 ± 1.3357	0.20326 ± 1.3004	0.97	2.6	1165 ± 6	1193 ± 14
~~139a~~	1832	247	0.135	0.13	1.9409 ± 1.3388	0.17841 ± 1.2988	0.97	-10.3	1170 ± 6	1058 ± 13
~~2a~~	1904	35	0.018	0.25	1.5708 ± 2.3070	0.15049 ± 2.2315	0.97	-18.1	1087 ± 12	904 ± 19
~~2b~~	2902	86	0.030	4.74	0.6651 ± 2.6702	0.07273 ± 2.2260	0.83	-46.2	817 ± 31	453 ± 10
~~11a~~	1187	523	0.440	4.26	2.0737 ± 2.5156	0.18490 ± 2.2261	0.88	-12.0	1230 ± 23	1094 ± 22
~~39a~~	1962	33	0.017	0.20	1.5872 ± 2.2664	0.14950 ± 2.2260	0.98	-21.3	1121 ± 8	898 ± 19
~~106a~~	1930	28	0.015	0.05	1.4942 ± 1.3435	0.14061 ± 1.3001	0.97	-26.1	1123 ± 7	848 ± 10
~~105a~~	1755	18	0.010	0.16	2.0512 ± 1.3439	0.18785 ± 1.3016	0.97	-6.2	1177 ± 7	1110 ± 13
~~110a~~	2795	55	0.020	0.27	0.6587 ± 1.3938	0.07004 ± 1.3095	0.94	-51.8	875 ± 10	436 ± 6
~~53a~~	1502	32	0.021	0.87	1.6621 ± 2.3143	0.16255 ± 2.2261	0.96	-7.7	1046 ± 13	971 ± 20
~~53b~~	2986	54	0.018	0.20	0.6779 ± 2.2866	0.07126 ± 2.2267	0.97	-52.4	899 ± 11	444 ± 10
~~71b~~	1793	29	0.016	0.16	1.8825 ± 2.2853	0.17533 ± 2.2279	0.97	-9.7	1144 ± 10	1041 ± 21
~~75b~~	2522	2604	1.032	0.72	2.0624 ± 2.2598	0.18651 ± 2.2263	0.99	-9.0	1202 ± 8	1102 ± 23
~~81a~~	1572	29	0.019	0.17	2.2433 ± 2.2601	0.20783 ± 2.2260	0.98	6.0	1154 ± 8	1217 ± 25
AP15-825 - Biotite Gneiss, Jannelsepan Formation, Areachap Group										
2c	290	45	0.154	0.08	2.26659 ± 1.6072	0.2060 ± 1.3345	0.83	1.4	1192 ± 18	1208 ± 15
1b	200	32	0.160	0.08	2.16089 ± 1.7632	0.1963 ± 1.3341	0.76	-3.4	1193 ± 23	1155 ± 14
1c	183	51	0.276	0.08	2.29214 ± 2.0407	0.2076 ± 1.3349	0.65	1.5	1199 ± 30	1216 ± 15
1a*	434	3	0.007	{0.03}	2.12399 ± 1.4905	0.1952 ± 1.3321	0.89	-1.9	1170 ± 13	1150 ± 14
2a*	337	2	0.007	0.06	2.14116 ± 1.5220	0.2000 ± 1.3325	0.88	3.5	1138 ± 15	1175 ± 14
2b*	312	4	0.012	0.08	2.12787 ± 1.6041	0.1993 ± 1.3325	0.83	3.8	1132 ± 18	1172 ± 14
S03-10 - Rhyolite, Leeuwdraai Formation, Koras Group										
10.1	111	101	0.93	0.15	1.9578 ± 3.7529	0.1787 ± 2.1308	0.57	-10.4	1060 ± 21	1184 ± 61
10.2	63	60	0.97	0.63	1.9549 ± 3.9330	0.1877 ± 2.2090	0.56	2.4	1109 ± 23	1083 ± 65
10.3	63	51	0.83	0.81	1.8698 ± 3.9625	0.1759 ± 2.2011	0.56	-7.1	1044 ± 21	1124 ± 66
10.4	25	29	1.23	2.35	1.8274 ± 8.3010	0.1859 ± 2.6252	0.32	13.7	1099 ± 27	966 ± 161
10.5	302	370	1.27	0.17	2.0044 ± 2.3670	0.1869 ± 2.0118	0.85	-3.2	1104 ± 20	1141 ± 25
10.6	26	40	1.60	2.93	1.8118 ± 13.9696	0.1874 ± 2.7310	0.20	18.8	1107 ± 28	932 ± 281
10.7	29	27	0.96	2.24	1.8361 ± 12.0168	0.1846 ± 2.6426	0.22	10.4	1092 ± 27	990 ± 238
10.8	162	140	0.89	0.42	1.9565 ± 2.7856	0.1863 ± 2.0650	0.74	0.2	1101 ± 21	1099 ± 37
10.9	83	73	0.90	0.45	1.9428 ± 3.1082	0.1858 ± 2.1440	0.69	0.7	1099 ± 22	1091 ± 45
10.1	51	46	0.93	1.01	1.9852 ± 5.3844	0.1831 ± 2.3208	0.43	-6.8	1084 ± 23	1163 ± 96
10.11	93	87	0.96	0.53	2.0575 ± 3.7566	0.1872 ± 2.1511	0.57	-7	1106 ± 22	1190 ± 61
10.12	60	50	0.86	0.94	1.9384 ± 4.3568	0.1848 ± 2.2453	0.52	-0.3	1093 ± 23	1097 ± 75
10.13	65	61	0.97	0.70	2.0046 ± 4.3281	0.1886 ± 2.2151	0.51	-0.9	1114 ± 23	1124 ± 74
10.14	18	16	0.95	1.95	1.8919 ± 11.9583	0.1883 ± 2.9271	0.24	10.1	1112 ± 30	1010 ± 235
10.15	110	111	1.05	0.84	1.8328 ± 3.7869	0.1843 ± 2.1199	0.56	10.2	1090 ± 21	989 ± 64
10.16	78	118	1.58	3.33	1.3908 ± 8.3375	0.1831 ± 2.2259	0.27	160.7	1084 ± 22	416 ± 180
10.17	69	94	1.42	0.75	1.9896 ± 4.5524	0.1870 ± 2.2082	0.49	-1.8	1105 ± 22	1125 ± 79
10.18	13	17	1.31	4.62	1.8046 ± 19.5018	0.1863 ± 3.3567	0.17	17.7	1101 ± 34	935 ± 394
10.19	93	86	0.96	0.50	2.0031 ± 3.5426	0.1870 ± 2.1488	0.61	-3	1105 ± 22	1139 ± 56
10.2	107	95	0.91	0.42	1.9420 ± 3.3216	0.1874 ± 2.1254	0.64	3.2	1107 ± 22	1073 ± 51

Unmarked data has been used for a group, magmatic or detrital poulation
Data indicated by* has been used for a group, metamorphic rim/overgrowth population.
Crossed out spots/data has not been used in isoplot concordia calculations
For detrital samples (DC0411, DC0415, DC0416) crossed out spots are either non-concordant and
or they are duplicate spots from the same grain, and not represented in concordia or probability density plots, .
For sample DC01138 and DC0420 likely xenocrystic zircons are highlighted in their Pb-Pb age with bold text.
{} indicates values close to or below detection limit
Discordance in % was calculated from the ratio between the 206Pb/238/U age over the 207Pb/206Pb age, not including errors,
where discordant data is given as negative values and reversed discordant sopts as positive.