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Mesoproterozoic crustal evolution in Southern Africa

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ABSTRACT

The objects of this thesis were to use geochronology to investigate crustal evolution of part of Southern Africa that formed during a global event, resulting in the ~1 Ga supercontinent Rodinia. The timing of assembly by continent-continent collisions and the position of the individual continental blocks of this ancient landmass is still largely unknown. This research is a contribution to the investigation and understanding of Precambrian tectonism and the evolution of the continental crust. It also provides a basis for future ore and mineral exploration in the Namaqua Sector of the Namaqua-Natal Province.

The Namaqua-Natal Province is draped along the western and southern flanks of the > 3 Ga Kaapvaal Craton, South Africa. It formed at 1200-1100 Ma, in relation to the birth of Rodinia. The Natal Sector of the province in the south-east is contiguous with the Namaqua Sector in the west, separated by Phanerozoic cover. The Natal Sector is mainly composed of ~1.2 Ga juvenile crustal material. The Namaqua Sector is composed of six different terranes in which the metamorphic grade varies from greenschist facies to amphibolite and granulite facies. The major ore districts of the Namaqua Sector have been investigated, but the regional geochronology is poorly constrained and few regional studies have been done.

We provide new geochronology, including Sm-Nd model ages of crustal extraction from the mantle, microbeam U-Pb zircon dating of sedimentary, magmatic and metamorphic events and Ar-Ar dating of minerals indicating the cooling histories of rocks, to investigate and compare the chronological and geochemical evolution of the entire Namaqua Sector.

Sm-Nd model ages show that parts of the Namaqua crust were extracted from the mantle as early as the Archean Era (>2.5 Ga) in the Bushmanland Terrane, with major Paleoproterozoic (2.5-1.6 Ga) crustal growth in the Kaaien, Areachap, Kakamas (or eastern terranes), Bushmanland, Garies Terranes and Richtersveld Subprovince (or western terranes). Mesoproterozoic (1.6-1.1 Ga) juvenile additions to the crust took place in the Areachap, Kakamas and Garies Terranes. Several volcanic,magmatic and sedimentary events contributed to the building of crust, before, during and after the collisional orogeny at 1.21-1.16 Ga. Thickening of the crust led to voluminous grainitoid magmatism at this time, the extent of which strongly suggests a near complete reworking of the crust, accompanied by regional metamorphism in the eastern and parts of the western terranes. After a quiet period, a new pulse of magmatism took place at ~1.1 Ga in the eastern terranes, and a second pulse of high temperature metamorphism at 1.05-1.01 Ga in the western terranes. From this time and onwards to ~965 Ma the crust in the Areachap, Kakamas, Bushmanland and Richtersveld cooled rapidly, likely related to crustal uplift. Hence, the Namaqua Sector has a long history of crustal extraction, in contrast with the essentially juvenile Natal sector.

This work represents a regional documentation of the geochronology of the Namaqua Sector and is a significant contribution to the understanding of its complex geological evolution.

Keywords: Namaqua-Natal Province, Mesoproterozoic, Geochronology, U-Pb zircon dating, Sm-Nd model ages, Ar-Ar dating, Southern Africa.

PREFACE

This thesis includes the following papers:

I **Ion-probe dating of 1.2 Ga collision and crustal architecture in the Namaqua-Natal Province of southern Africa.** *Å. Pettersson, D. Cornell, H.F Moen, S. Reddy, D.Evans* Precambrian Research 158, p 79-92, 2007.

II **Ion probe dating of the Achab gneiss, a young basement to the Central Bushmanland Ore District?** *D. Cornell, Å. Pettersson.* Journal of African Earth Sciences 47, p 112-116, 2007.

III **Ion probe zircon dating of metasediments from the Areachap and Kakamas Terrane, Namaqua-Natal Province and the stratigraphic integrity of the Areachap Group.** *D. Cornell, Å. Pettersson.* South African Journal of Geology 110, p 169-178, 2007.

IV **Regional granitoids geochronology in relation to the Namaquan Orogeny.** *Å. Pettersson, D. Cornell.* Submitted to Lithos, February 2008.

V **Sm-Nd data for granitoids across the Namaqua sector of the Namaqua-Natal Province, South Africa.** *Å. Pettersson, D. Cornell, M. Yuhara, Y. Hirahara.* Accepted Nov. 2007, Geol. Soc. of London, Special Publications in 2008.

VI **A new chronostratigraphic paradigm for the age and tectonic history of the Mesoproterozoic Bushmanland Ore District.** *D. Cornell, Å. Pettersson, A. Scherstén.* Manuscript, for Economic Geology.

VII **Insights to the cooling history from Ar-dating in the (1.2-1.1 Ga) Namaqua Sector.** *Å.Pettersson, D. Cornell, L. Page.* Submitted to Journal of African Earth Sciences, March 2008.

I have done field work planning, field work and sampling for all papers. Authors are indicated in order of their contributions.
My contributions: Sample preparations (zircon and geochemistry) and analysis (SEM, ICP-MS), and ion-probe work, petrography, ion-probe work, interpretations, writing, figures and tables, submission, overall ~80% for papers I, IV, VII and 70% for paper V. In paper II my overall contribution is estimated at 30%, paper III at 20% and paper VI at 40%. In paper V, samples were analysed by Yuhara and Hirahara, our co-authors.

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1. Introduction

The Earth's crust has developed mainly in episodes of crustal growth, often linked to repeated, cyclic events of supercontinents forming and breaking up. Evidence of ancient supercontinents is sometimes difficult to establish, as repeated heating, deformation and melting of the crust erase most of the previously recorded history.

Episodes of orogenic events characterize the amalgamation of ancient supercontinents. An orogeny is defined as the creation of mountain belts by tectonic activity (Bates and Jackson, 1995) and the affected areas are referred to as orogenic belts or provinces. These are characterised by magmatism, regional metamorphism and deformation such as folding, faulting and thrusting. Orogenic belts are markers for zones of continent-continent or continent-island arc collisions that occurred in the past. The orogens are composed of areas often classified as terranes. These crustal fragments have been separated from their original crustal blocks and transported along major faults in the collision phase. A terrane can sometimes later be recognised as an area with different geological history to its neighbours, a 'strange terrane'. The new orogenic belts are composed of terranes including oceanic island arcs, fragments of older continental crust, oceanic floors and sediments. These new composite areas are added to the older stable crustal blocks, often referred to as cratons. Such continental blocks came together to form the supercontinent ***Rodinia***, a billion years ago (1 Ga), (Dalziel, 1991; Hoffman, 1991). The positions of the participating continental blocks are sometimes well constrained by radiometric dating and reliable measurements of paleomagnetic poles, whereas others are poorly investigated.

Orogenic belts, marking the birth of Rodinia, are found scattered across the globe in several parts of South America, Australia, North America, Antarctica, India, China, Baltica (southwest Sweden) and southern Africa.

The Namaqua-Natal Province is one of these areas, situated in southern Africa, draped around the western and southern flanks of the >3.0 Ga Kaapvaal Craton. It is made up of two sectors, the Natal sector to the southeast, and the Namaqua sector to the west. Neoproterozoic to Mezozoic sediment sequences cover the part in between. The continuity of this province under younger cover rocks has been affirmed by dating of drill cores recovered from the crystalline basement beneath the cover rocks (Eglington and Armstrong, 2003).

2. Aim of the thesis

The aim of this project was to use new, refined methods of geochronology, to accurately time the different crustal events in the Namaqua Sector of the Namaqua-Natal Province. This would yield a more detailed history of the crustal evolution, including:

- what pretectonic information could be found in the different terranes,
- whether or not the terrane boundaries still hold,
- when the continent-continent collision(s) took place,
- how the magmatism in the area relates to the collision(s)
- when tectonism, related to the ~1 Ga collision event, ceased in all terranes
- what can be said about differences in the evolution of the terranes from a regional perspective
- investigation of the possibility of a coherent tectonic evolution of the Namaqua-Natal Province and a postulated continent 'collider', the Llano Belt, Texas, south western inlier of the Grenvillian Province, USA.

3. Geological background of the Namaqua-Natal Province

The Natal Sector

The Natal Sector (Fig. 1) is composed of three terranes, the Tugela, Mzumbe and Margate Terranes, small crustal blocks separated by tectonic boundaries. The terranes in the Natal Sectors were defined by Thomas (1989) and are made up of essentially juvenile arc sequences, related marine sediments and arc-root granitic to gabbroic intrusions (Cornell et al., 2006, references therein). These slivers of oceanic crust were thrust and stacked onto the southeast margin of the Kaapvaal Craton.

The Namaqua Sector

The Namaqua Sector (Fig. 1), on the other hand, is composed of six different terranes and subprovinces, the majority of which are not juvenile,

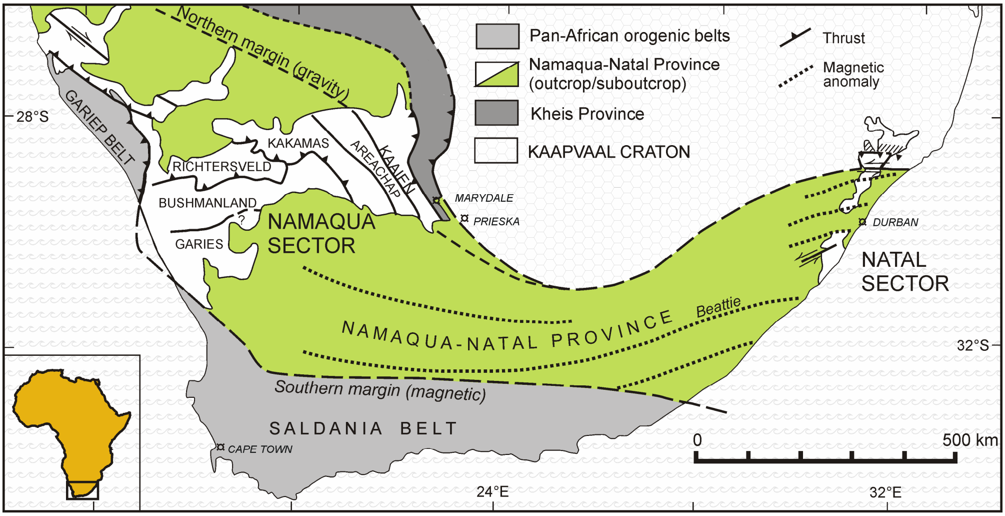

Figure 1. Map of Southern Africa. Modified after Cornell et al. (2006).

and they are also quite large. If the terranes are not juvenile, they should have a previous history within a continent.

The Namaqua Sector is composed of NNW-SSE, NW to SE and finally E-W oriented terranes, as shown in Fig. 1. Their orientation corresponds to the regional fabric in each terrane. The direction of orogenic accretion was towards the Kaapvaal Craton, so that the Kheis Province and the Kaaien Terrane are regarded as the foreland. The Kheis Province is dominated by Paleoproterozoic north-trending ridges of quartzite (Moen, 1999), its basement unknown and its pre-Namaquan history debated. The Kaapvaal Craton itself was not much affected by the orogeny, but banded-iron formations along the southwestern margins are folded. The change in direction from NW in the eastern terranes (Kaaien, Areachap and Kakamas Terranes) to E-W in Bushmanland most likely records a shift in collision direction when Bushmanland and the Richtersveld joined the collision.

Structural evolution of the Namaqua Sector

The structural evolution is similar in the eastern terranes, with four fold phases (Stowe, 1983; 1986), related to four deformation events (D1-D4). The first D1 is related to S1 fabric, partly overprinted by the main deformational phase D2, which caused isoclinal local to regional scale NNW – SSE trending folds. This deformation is related to the main phase of the Namaquan tectonism. It was followed by large-scale, upright and open folds, generally NE trending, of the D3-event along with wrench-faulting near major shear zones. D4 is mainly related to NW trending movements along subvertical shearzones and faults, related to compression from the SW and affected by the geometry of the wedge-shaped Kaapvaal Craton around Prieska (Fig. 2) (Van Bever Donker, 1991; Jacobs et al., 1993). In the west, the Richtersveld Subprovince, the Bushmanland Terrane and the recently established Garies Terrane, display three or four major deformation phases, depending on the classification of different authors and whether they use sub-groupings. The first is found in the Richtersveld Terrane (D1), and also preserved in xenoliths in the 1.86 Ga Goodhouse Suite granites (Kröner et al., 1983). Many structural descriptions rely on early work done by Joubert (1971). An early folding event, also termed D1, is seen as isolated fold closures in Bushmanland. The second (D2) is dominated by regional recumbent ENE-trending folds, along with D3 ENE-striking open folding. The D3 event is also related to 'steep structures' according to Moore (1989), narrow north-trending linear zones, occasionally with noritic intrusions in the Okiep Copper District. The differences in timing of the two D3 events led Clifford et al. (2004) to subdivide D3 into D3a and D3b, whereas Raith and Harley (1998) instead divide D2 into two subphases, each corresponding to a metamorphic event (D2a ~1200 Ma, D2b ~1060 Ma). Clifford's D3a event corresponds in time to Raith and Harleys D2b event. Several other definitions and names have been used to describe the structural evolution in the Namaqua Sector.

Geochronology in the Namaqua Sector

Previous published work in geochronology is to a large extent from investigations done in the late 1970's or early 1980's, often related to the mining districts in the area: Copperton (Prieska Mines), Areachap, Aggeneys-Gamsberg (Bushmanland Ore District), and Okiep Copper District near Springbok (Fig. 2). Some recent important work on U-Pb dating in zircon concerning mainly the western Namaqua Sector has been published (Raith and Harley, 1998; Robb et al., 1999; Raith et al., 2003; Clifford et al., 2004), work partly summarized in Cornell et al. (2006) and Eglington (2006). We follow the stratigraphic and structural classification of Thomas et al. (1994) for the terranes of the Namaqua Sector (Fig. 1, 2).

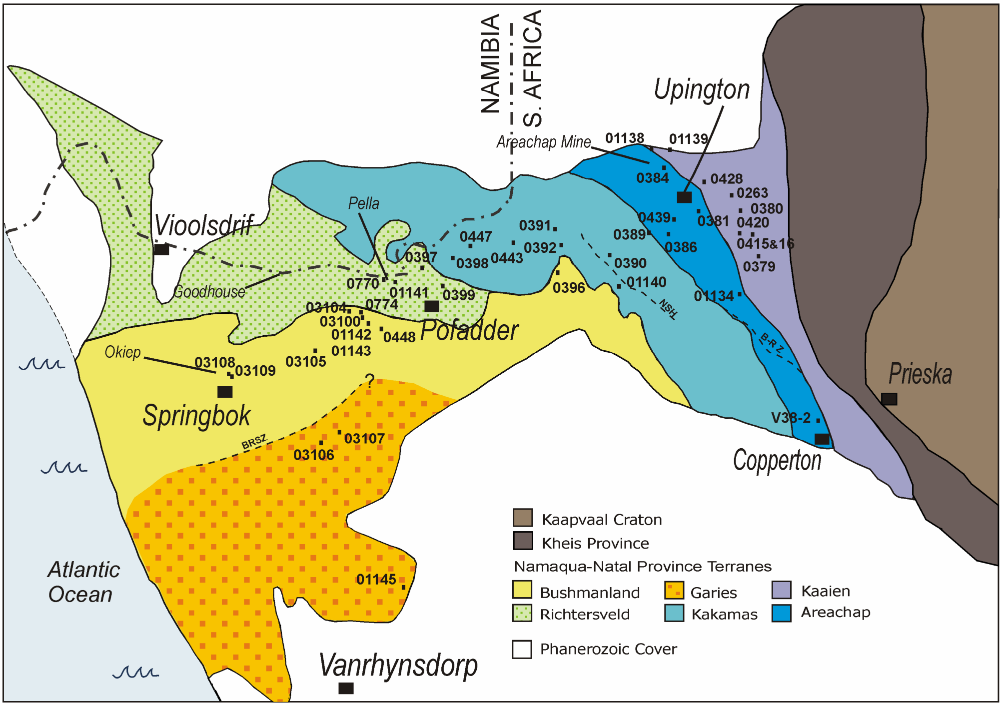

Figure 2. Map of the Namaqua Sector, Namaqua-Natal Province. After Cornell et al. (2006) with additions. Samples are shown as dots, indicated by sample numbers omitting the prefixes 'DC'. Drillcore-samples from the Areachap Mine are omitted. Terrane boundaries normally correspond to shear zones. Dashed lines represent some other major shear zones in the area. BRSZ: Buffels River Shear Zone, NSH: Neusspruit Shear Zone, B-R Z: Boven-Rugzeer Shear Zone.

A further division of the Garies Terrane from the Bushmanland Terrane has been made partly in papers in this thesis (Paper V) as suggested by Yuhara et al. (2001) and later discussed by Andreoli et al. (2006).

The Richtersveld Subprovince

The western Richtersveld Subprovince (Fig. 2) is largely unaffected by deformation and contains well preserved supracrustal assemblages formed in a 2.0 Ga island arc setting (Reid, 1979; 1997, Reid et al., 1987), intruded by granites of the Vioolsdrif Suite at 1730 ± 20 Ma (Reid, 1982). The eastern part is not yet well investigated, but deformation and amphibolite grade metamorphism in this area distinguishes its deformational history from that of the western part. The supracrustal assemblages (Orange River Group) consist of volcanic rocks ranging in composition from basalt to rhyolite, volcanoclastic rocks, conglomerates, schists and quartzites. The northern terrane boundary between the supracrustal Orange River Group and metasediments of the Kakamas Terrane in the eastern Richtersveld Terrane has been described as interlayered by Blignault et al. (1983), but may consist of remnants of Kakamas rocks thrust onto the Richtersveld Subprovince during the Namaquan collision (Blignault et al., 1983; Van Aswegen et al., 1987; Collistion and Schoch, 2006).

The Bushmanland Terrane

The Bushmanland Terrane (Fig. 2) is a high grade (amphibolite to granulite facies) metamorphic terrane, dominated by granitic gneisses, structurally overlain by metasedimentary sequences. Metasediments are dominated by thick sequences of schists and quartzites in the Central Bushmanland Ore District with stratabound sulphide sedimentary exhalative deposits, sillimanite rocks, minor amphibolites and rare iron formations. Some of the granitic gneisses have been regarded as basement to the sediments. In the south western part, metasediments occur primarily as quartzo-feldspathic gneisses. Undeformed granites, norites and mafic rocks occur, particularly in the western part, and have been used to better constrain models for timing of magmatism and metamorphism in the Bushmanland Terrane (Raith and Harley, 1998; Robb et al., 1999; Raith et al., 2003; Clifford et al., 2004). Magmatism was found to be connected to two pulses, the first at 1210 – 1190 Ma thought to be affected by the main phases of deformation, suggested by Raith and Harley (1998) to be related to an early metamorphic event and the second, probably related to high temperature metamorphism at 1060-1030 Ma, and less affected by deformation. The low pressure-high temperature character found in the Bushmanland Terrane is reflected by mineral paragenesis at various localities, particularly in the west where granulite facies prevail (Mouri et al., 2003; Raith et al., 2003).

The eastern terranes

In the eastern part of the sector around Upington, the Kakamas, Areachap and Kaaien Terranes, very little geochronological work has been carried out. Barton et al (1983) did Rb-Sr and U-Pb work but ages were often too imprecise to distinguish different events, rather confirming the area as part of the Namaqua - Natal Province.

The Kakamas Terrane

The Kakamas Terrane (Fig. 2) is dominated by many intrusions with various degrees of deformation, along with sequences of metasedimentary rocks. The metasediments are composed of marbles, calc-silicates, sandstones, schists and metapelites (Moen, 2007) which are folded and intruded by undeformed granites. The metamorphic grade in the Kakamas Terrane varies from lower granulite facies to mid amphibolite facies, generally lower grade to the east.

The Areachap Terrane

In the Areachap Terrane (Fig. 2), metavolcanic rocks and immature sediments, occasionally migmatized, dominate the geology and granites and gabbros belonging to a volcanic arc sequence occur. The Areachap Terrane is a thin, amphibolite grade terrane and includes several ore-deposits of Cu, Sn and W (Copperton and Upington areas).

The Kaaien Terrane

Further to the east lies the Kaaien Terrane (Fig. 2), dominated by thick folded sequences of quartzites. This is the easternmost terrane in the province, affected by Namaquan overprinting and is metamorphosed in lower greenschist grade. Bimodal volcanic basins were developed at least three times, to generate the Wilgenhoutsdrif Group, described by Moen (1980) and two pulses of volcanism in the Koras Group (Sanderson-Damstra, 1982; Moen, 1987). The sequences were regarded as pre-tectonic (Wilgenhoutsdrif Group) and post-tectonic (Koras Group) in relation to the Namaquan Orogeny. The basins have generally been regarded as trans-tensional basins developed around major strike-slip faults. Gutzmer et al. (2000) published an age at 1171 Ma for the Koras Group, a well-known and tectonically important volcano-sedimentary sequence in the Kaaien Terrane, concluding that this age defined the end of tectonism in the entire Namaqua Sector.

4. Presentation of the parts of the thesis

***Paper 1** – Ion-probe dating of 1.2 Ga collision and crustal architecture in the Namaqua-Natal Province of southern Africa.*
Petterson et al, 2007. Precambrian Research 158, 79-92.
We investigate the timing of mesoproterozoic collision and magmatic events in the Kaaien, Areachap and Kakamas Terranes. We demonstrate that the volcanosedimentary Koras Group of the Kaaien Terrane, considered to represent a tectonostratigraphic marker for the Namaquan tectonism in the Namaqua Sector, was generated in two separate pulses and cannot be used as time constraint for the deformation in the Namaqua Sector.

***Paper II** – Ion probe dating of the Achab gneiss, a young basement to the Central Bushmanland Ore District? Cornell and Pettersson, 2007. Journal of African Earth Sciences 47, 112-116.*
We discuss the age of the Achab Gneiss, the postulated basement rock in central Bushmanland Terrane, and conclude that it is ~800 Ma younger than believed and may therefore not represent a basement to the supracrustals in the Bushmanland Group.

***Paper III** – Ion probe zircon dating of metasediments from the Areachap and Kakamas Terrane, Namaqua-Natal Province and the stratigraphic integrity of the Areachap Group. Cornell and Pettersson, 2007. South African Journal of Geology, 110, 169-178.*
Discusses the evolution of the Areachap Terrane as a volcanic arc complex along with new dates from metasediments in the Kakamas Terrane.

***Paper IV**- Regional granitoids geochronology in relation to the Namaquan Orogeny. Pettersson and Cornell., Submitted to Lithos 2008.*
Discusses the magmatic and metamorphic evolution of granitoids in the Namaqua Sector as a whole, based on a regional traverse with ion probe dates. We mainly focus on the main magmatic event during the Namaquan Orogeny at ~1200 Ma that almost completely reworked the crust and the differences of post-namaquan evolution in the eastern and western terranes.

Paper V *– Sm-Nd data for granitoids across the Namaqua sector of the Namaqua-Natal Province, South Africa. Pettersson et al., Accepted. Geological Society, London, Special Publications.*
Investigates the crustal extraction (Sm-Nd T_{DM}) ages from a traverse of mainly granitoid rocks and their significance for individual terrane integrity in the Namaqua Sector. We find that crust was generated in the Archaen, Paleoproterozoic and partly during the Mesoproterozoic.

Paper VI *– A new chronostratigraphic paradigm for the age and tectonic history of the Mesoproterozoic Bushmanland Ore District. Cornell et al. Manuscript.*
We investigate and redefine the chronostratigraphy of Central Bushmanland Ore District and its consequences for tectonic evolution in Bushmanland.

Paper VII *– Insights to the cooling history from Ar-dating in the (1.2-1.1 Ga) Namaqua Sector. Petterson et al., Submitted to Journal of African Earth Sciences.*
We relate Ar-Ar mineral cooling ages to the end of tectonism and metamorphism following the collision and Namaquan Orogeny in the Namaqua Sector.

5. A short presentation of methods

In addition to the methods presented below, field work consisted of describing and sampling fresh rock and investigating geological relationships. Our plan was to sample granitoid or volcanic rocks and to investigate their relationships to the specific terranes and terrane boundaries in a profile across the Namaqua Sector. In some cases metasediments were also investigated to better constrain tectonic models. The number of samples from each terrane and their spatial distribution (Fig. 2) was largely dependant on access to land and availability of outcrops. Petrography on thin sections was also carried out.

Major and Minor elements

The geochemistry of rocks, particularly trace element fingerprints, can be used to compare rocks of similar or different origin and to investigate the processes and conditions under which rocks were either formed in the first place, or experienced later during metamorphism.

Rock samples collected in the field were crushed and ground into rock powder. The powder was later ignited and fused into glass in an inert gas chamber. The glass shards were mounted in epoxy and analysed for major elements in a Hitachi Scanning Electron Microscope with an energy dispersive X-ray spectrometer (SEM-EDS). Several rocks standards were treated the same way.

Minor elements were analysed in rock powder or fused glass, dissolved and run as solutions in an Agilent 7500 Inductively Coupled Plasma Mass Spectrometer, (ICP-MS). Internal drift standards (JB-1) and rocks standards of granitic to andesitic composition were dissolved and analysed along with the other rock samples.

All major and minor element chemistry was performed at the Department of Earth Sciences, University of Gothenburg.

Radiometric dating of minerals or rock samples

U-Pb zircon dating

The mineral zircon $ZrSiO_4$, forms as small crystals in magmas at high temperatures of ~800-1000º C, although this temperature depends on the composition of the magma (higher in mafic rocks). When it crystallises it usually incorporates small amounts of U into the crystal lattice. After the crystal is formed, the ^{235}U isotope starts to decay to ^{207}Pb with a half life of ~0.7 Ga and ^{238}U decays to ^{206}Pb with a half life of ~4.5 Ga. The amounts of U and different Pb-isotopes in zircon can be measured and are proportional to the time passed since the zircon crystallized. The mineral zircon is also quite resistant to many crustal conditions that may later affect it, such as metamorphism, and may therefore record several events in different domains of the crystal without losing earlier information. The major part (Paper I, II, III, IV and parts of paper VI) of the U-Pb analysis work was done at the NordSim ion-probe facility at Naturhistoriska Riksmuséet in Stockholm, Sweden, methods used as described by Whitehouse et al. (1997, 1999). A laser-ablation ICP-MS at GEUS in Copenhagen, Denmark was used for samples in Paper VI. Ages were calculated using the program ISOPLOT 3.0 (Ludwig, 1998; 2003).

Sm-Nd whole rock model age dating

Sm-Nd dating is applied to whole rock samples as opposed to dating individual minerals as in U-Pb zircon dating (above) or Ar-Ar (below). The Sm-Nd model age does not give an exact age of formation of a rock Instead, analyses are related to models describing the evolution of Nd isotopes in the mantle, which is more rapid than in most crustal rocks. The Sm-Nd isotopic system is particularly applicable to old rocks, as the radioactive isotope ^{147}Sm decays very slowly to ^{143}Nd, with a half-life of 106 Ga. Both elements being Rare Earth Elements (REE) they act coherently and behave similarly in magmatic systems. They are also not easily affected by metamorphism. Hence this system can be used to track events that happened before the latest magmatic and metamorphic events that a rock experienced. Depleted mantle model ages, cited as T_{DM} are commonly calculated for Precambrian rocks. A model age is a measure of the time that a rock sample has been separated from the mantle, the time of crustal extraction. The basic idea is that the Sm/Nd ratio changes during mantle melting and extraction, due to small but significant differences in melt compatibility. Nd is then slightly depleted relative to Sm, giving rise to a slower evolution of the ^{144}Nd/^{143}Nd ratio. Whole rock samples were analysed for Sm and Nd isotopes by our colleagues Masaki Yuhara and Yuka Hirahara at Niigata University, Japan (Paper V).

Ar-Ar dating

This technique allows minerals with K in their crystal lattice, such as hornblende, muscovite and biotite to be dated. The minor K isotope ^{40}K has a half life of 1.26 Ga and decays to 89% ^{40}Ca and 11% ^{40}Ar. After these minerals have cooled below ~500º, ~350º and ~290ºC respectively, they retain all ^{40}Ar formed by radioactive decay, trapped in the mineral lattice. In the ^{39}Ar-^{40}Ar method, the stable ^{39}K isotope is converted to ^{39}Ar by neutron activation in a nuclear reactor. The ^{39}K is transformed to ^{39}Ar by adding a neutron and omitting a proton. ^{39}Ar has a very short half life of some hundred years, and the mineral therefore contains none before irradiation. A number of interfering nuclides are also produced and need to be corrected for, therefore standard samples are irradiated at the same time to monitor the production rates and neutron flux which differs from one reactor to another. The portion of ^{39}K which has been converted to ^{39}Ar provides a measure of the original K content of the mineral. It can be liberated from the crystal by heating, and measured together with the radiogenic ^{40}Ar. If a crystal has not been disturbed, the step-heating procedure will generate an age plateau consisting of a few steps during which most of the Ar is released. This plateau gives the age, which is proportional to measured ^{39}Ar/^{40}Ar of the crystal, calibrated with the standards. Mineral separates were sent for irradiation to NRG Petten HFR RODEO nuclear facility in the Netherlands and after a 'cooling-off ' period, analysed by Laurence Page at Lund University, Sweden.

6. Results and discussion

We sampled rocks in an east-west traverse across the Namaqua Sector, crossing four known terrane boundaries. Most of these rocks are granitoid rocks, often gneissic, but some rocks of volcanic and sedimentary origin were also sampled, particularly in the Kaaien and Areachap Terranes (Fig. 2). Sm-Nd, ion-probe U-Pb zircon data and Ar-Ar dating as well as geochemistry of rocks of granitic composition along the profile in Fig. 2, results compiled in Table 1, provides new evidence about the timing of crustal extraction from the mantle, magmatic and metamorphic evolution during the Namaquan Orogeny, cooling and uplift history. These events are linked to geochemical signatures which provide information about the geological environment in which the rocks formed.

Our ion probe zircon dating shows that, contrary to earlier interpretations mainly based on structural observations, the majority of the magmatic rocks were emplaced during the 1290 to 1090 Ma Namaqua tectogenesis. Very little U-Pb evidence of older precursors remains in most of the terranes. Sm-Nd model ages on the other hand, show that although some Mesoproterozoic crustal extraction from the mantle did occur, the mantle extraction responsible for crustal growth was mostly Paleoproterozoic, with additional evidence for the former presence of Archean crust.

Division of Terranes

The distribution of model ages generally corresponds with the established terranes, subdivided by Thomas et al. (1994) using lithostratigraphic and structural criteria, however modifications are needed. The northern part of the Bushmanland Terrane shows early Paleoproterozoic to Archean model ages and is clearly different from the southern part, which has

Mesoproterozoic model ages (Paper V). This supports recently published results (Yuhara et al., 2001; Andreoli et al., 2006) and justifies the separation of the younger terrane from the Bushmanland Terrane (Fig. 2). The southern part is called the Garies Terrane, following Yuhara et al. (2001) and later Eglington (2006). The Buffels Shear Zone is most likely the northern boundary, as shown by previous studies, although its eastern continuation is not known. To the south, Phanerozoic sequences cover the Namaquan basement, although the extension of the Garies Terrane is probably limited to roughly 32ºS, 21ºE , approximately 300 km northeast of Cape Town (Fig. 1), as shown from Sm-Nd borehole data (Eglington and Armstrong, 2003).

This change of crustal residence ages cannot be seen in U-Pb zircon ages; instead they clearly indicate a common magmatic and metamorphic evolution of the Bushmanland and Garies Terranes during the Namaquan Orogeny (Raith and Harley, 1998; Robb et al., 1999; Raith et al., 2003; Clifford et al., 2004, Paper II, IV and VI). The northern part should continue as the Bushmanland Terrane without further subdivision at this stage. The continuation of the Richtersveld Subprovince east of Pofadder is now confirmed. The first magmatic additions to the crust by oceanic arc volcanism started at 1996 to 1875 Ma. Its short crustal recycling times of 100 - 200 Ma, shown by Reid (1997) and Paper V, suggest different origins for the 2.0 - 2.3 Ga Richtersveld Subprovince and the 2.1 - 2.8 Ga Bushmanland Terrane, though their common history is often assumed. The terrane boundary between the Bushmanland and Kakamas Terranes is marked by an abrupt change from Paleoproterozoic to Mesoproterozoic model ages (Paper V), confirming the Hartbees River Thrust as a distinct terrane boundary. Sm-Nd model ages (T_{DM}) for the Kakamas and Areachap Terranes do not distinguish them well. They suggest a Mesoproterozoic to late Paleoproterozoic origin for both terranes (Paper V), neither of which has a purely juvenile character. The terranes should be retained at this stage in view of their different supracrustal assemblages, suggesting separate origins. Xenocrystic zircons in magmatic populations, together with detrital zircon data from highly metamorphosed sedimentary sequences from the Kakamas Terrane indicate the presence of ~1550 Ma material (Paper III), an age not yet represented elsewhere in South Africa. The time between 1700 and 1300 Ma has generally been regarded as one of no volcanic or magmatic activity.

Initiation of Namaquan tectonism

The second period of magmatism in the Namaqua Sector was the initiation of rifting in the Kaaien Terrane (Fig. 2) at 1290 Ma to form the Wilgenhoutsdrif Group (Moen, unpublished data in Cornell et al., 2006). The volcano-sedimentary Wilgenhoutsdrif Group contains Archaean and Paleoproterozoic detrital zircons (Paper I), showing that it probably formed in a continental rift or a passive margin setting, close to the Kaapvaal Craton. Rifting and volcanism at 1290 Ma was probably related to the initiation of oceanic plate subduction in the west, followed by arc magmatism in the Areachap volcanic arc (Fig. 2). Subduction of this arc progressed from Copperton in the south, where the magmatism was coeval with faulting and trans-tension in the Kaaien Terrane and Kheis Subprovince at 1290 Ma (Cornell et al., 1990, Paper III), to the north around Upington, where magmatism was active between 1270 – 1241 Ma (Paper I, IV). The integrity of the thin arc-related Areachap Terrane and its correlation across the Boven Rugseer Shear zone and hence its continuation from Upington to Copperton is discussed in Paper III. The similarities of volcanic-arc related volcanism, ages of formation ranging between 1285 Ma (Copperton Formation) and 1241 Ma (Jannelsepan Formation), Cu-Zn ores and rock types in these formations suggest a correlation across the Boven Rugseer Shear Zone. However, T_{DM} ages clearly indicate a heterogeneous source for the rocks in the Areachap Terrane in general, with an old crustal component particularly in the north (Paper V). Hence, a purely juvenile origin for the Areachap Terrane as previously considered (Geringer et al., 1994) is no longer valid. The arc-related rocks appear to vary in character from south to north, from oceanic to more continental, along the strike of the terrane. This might be reflect an assemblage of several smaller arcs, partly continental in the north and less influenced of older crust in the south. Alternatively, a large arc simply extended from an oceanic environment in the south coastwards and inland along the westernmost Kaaien Terrane in the Upington area. This might explain the later magmatism in the north. The direction of subduction is obscured by later deformation and orogeny, although it is easy to envisage a roughly eastward subduction perpendicular to the edge of the craton.

Crust-forming events dated by T_{DM} ages of Mesoproterozoic granitoids and felsic rocks in the Kaaien Terrane (Paper V) show that it is dominated by late Palaeoproterozoic crust. The 2252 Ma model age of the Kalkwerf

Gneiss could reflect the influence of the Kaapvaal Craton, which probably underlies the Kaaien Terrane. These data, combined with presence of 1814 -2117 Ma xenocrystic zircons (Paper I), indicate that a crust-forming event occurred at the edge of the Kaapvaal Craton some time during the Palaeoproterozoic, possibly during the enigmatic ~1.8 Ga Kheis Orogeny.

The Namaquan Orogeny, main orogenic period

Subduction of the Areachap volcanic arc was closely followed by the fourth and main period of magmatism between 1220 and 1150 Ma in the entire Namaqua Sector (Raith and Harley, 1998; Robb et al., 1999; Raith et al., 2003; Clifford et al., 2004, Bailie et al., 2007*b*, Paper I-IV and VI). Back-arc basins and fore-arc basins in relation to the Areachap volcanism were closed and the accretion of the arc or arcs onto the Kaaien Terrane was completed. The collisions that followed brought Kaaien, Areachap, Kakamas together more or less synchronously. At 1165 ± 10 Ma the Areachap Terrane which was deeply buried and heated, formed migmatites in the volcanic sequences, yielding thin rims on already existing zircons. This age represents the time of regional metamorphism in the Areachap and Kakamas Terranes (Paper I).

At roughly the same time (1173 ± 12 Ma) in the adjoining Kaaien Terrane the first sequence of Koras Group bimodal magmatism (Gutzmer et al., 2000 and Paper I) formed in a fault basin. This invalidates the concept that this Group is a tectonostratigraphic marker for the end of tectonism in the whole Namaqua Province. It is valid only in the Kaaien Terrane, if at all (Paper I). Magmatism in the Kakamas, Bushmanland and Garies Terranes (Robb et al., 1999; Clifford et al., 2004; Raith et al., 2003; Paper II, IV and VI) was coeval with Koras magmatism in the foreland of the orogen at 1173 Ma and the migmatization of the Areachap Terrane. Granitic magmas were dominated by reworked crustal material (Paper IV), particularly in the Kakamas Terrane, due to thickening of the crust and to a minor extent by mantle-derived melts added to the growing Kalahari Craton. Geochemical data show that especially the Kakamas Terrane granitoids that formed during the Namaquan Orogeny have relatively high HREE levels, compared to contemporary intrusions in Bushmanland. HREE levels would be expected to increase during repeated melting processes, whereas material with a less complex orogenic history should have lower levels. During this period (1220-1150 Ma) sedimentary rocks were probably

Name	Rock type	Sample	T_{DM} ages	Zircon U-Pb Age ± 2σ (Ma)			Ar-Ar
			(paper V)	**magmatic**	**detrital**	**metamorphic**	**cooling ages**
Kaaien Terrane							
Bloubos Granite	Granite	DC01138	-	1093±10[I]	-	-	-
Rooiputs Granophyre	Granophyre	DC03139	-	1093±11[I]	-	-	-
Leeuwdraai Fm, Koras Group	Rhyolite	DC0263	1729	1093±7[I]	-	-	-
Leerkrans Fm, Wilgenhoutsdrif Group	Sandstone	DC0415	-	-	*2016-2760* [I]	-	-
Leerkrans Fm, Wilgenhoutsdrif Group	Conglomerate	DC0416	-	-	*1337-2864* [I]	-	-
Kalkwerf Gneiss	Granite	DC0379	2252	-		-	-
Kalkpunt Fm, Koras Group	Sandstone	DC0411	-	-	1116±16[I]	-	1129±6[VII] (m)
Leeuwdraai Fm?, Koras Group	Rhyodacite	DC0420	-	1104±8[I]	-	-	-
Swartkopsleegte Fm, Koras Group	Rhyodacite	DC0380	1570	1173±12[I]	-	-	-
Straussburg Granite	Granite	DC0381	1752	1092+13/-12[IV]	-	-	-
Swanartz Gneiss	Granite	DC0428	1978	1371±9[I]	-	-	-
Areachap Terrane							
Josling Granite	Granite	DC0384	1499	1275±7[IV]	-	-	-
Jannelsepan Fm, Areachap Group	Metadacite, migmatitic	DC0439	2356	1241±12[I]	-	1165±10[I]	-
Jannelsepan Fm, Areachap Group	Amphibolite	DC0441	-	-	-	-	1025±5[VII] (h)
Boksputs Formation	Metaquartzite	DC01134	-	-	1275±7[III]	1204±50[III]	-
Copperton Formation	Metapelite	V38-2	-	1285±45[III]	-	1098±9[III]	-
Kakamas Terrane							
Kenhardt Formation	Biotite Gneiss	DC01140	-	-	1197±5[III]	-	-
Friersdale Charnokite	Granodiorite	DC0386	1591	1111±8[IV]	-	-	-
Dyasons Klip Granite	Granite	DC0387	-	1220±10[IV]	-	1156±14[IV]	-
Biesje Poort Group	Schist	DC0388	-	-	-		968±4[VII] (m)
Vaalputs Granite	Granite	DC0389	1616	1146±14[IV]	-	1062±27[IV]	-
Friersdale Charnokite	Granodiorite	DC0390	1618	-	-	-	-
Riemvasmaak Gneiss	Granite	DC0391	1549	1156±8[IV]	-	-	-
Riemvasmaak Gneiss	Granite	DC0392	1360	1151±14[IV]	-	-	995±8[VII] (h)
Witwater Gneiss	Granite?	DC0443	-	-	-	-	967±4[VII] (m)
Polisiehoek Granite	Granite	DC0447	2244	1203±11[IV]	-	-	-
Beenbreek Gneiss	Granite	DC0398	1445	1113±7[IV]	-	-	-
Richtersveld Subprovince							
Coboop Gneiss	Granite	DC0397	2274	1874±5[IV]	-	-	962±4[VII] (m)
Guadom Fm	Metadacite	DC01141	-	1909±36[IV]	-	984±18[IV]	-
Guadom Fm	Metadacite	DC0770	-	1855±10[IV]	-	1041±9[IV]	-
Guadom Fm	Metadacite	DC0770	-	1855±10[IV]	-	998±14[IV]	-
Bushmanland Terrane							
Banks Vlei Gneiss	Granite	DC0396	2121	1188±8[IV]	-	1041±15[IV]	-
Aroams Gneiss	Granite	DC0399	2322	1204±11[IV]	-	1015±14[IV]	-
Achab Gneiss	Granite	DC03100	2740	1163±13 Ma[II]	-	1038±14[II]	-
Achab Gneiss	Granite	DC0448	-	1166±13 Ma[II]	-	1030±18[II]	-
Hogoor Gneiss	Granite	DC03104	-	1149±15 Ma[VI]	-	-	-
Hotson Fm, Bushmanland Group	Quartzite	DC01143	-	-	1285±15[VI]	1045±9[VI]	-
Koeris Formation	Conglomerate	DC01142	-	-	1154±16[VI]	1016±21[VI]	-
Koeris Formation	Amphibolite	DC0774	-	1131±35[VI]	-	-	-
Klein Namaqualand Suite	Granite	DC03105	1628	-	-	-	1000±7[VII] (h)
Burtons Puts Granite	Granite	DC03106	1540	-	-	-	-
Klein Namaqualand Suite	Granite	DC03107	1525	-	-	-	-
Concordia Granite	Granite	DC03108	2161	-	-	-	-
Modderfontein Gneiss	Granite	DC03109	1923	-	-	-	-
Landplaas Gneiss	Granite	DC01145	1422	-	-	-	-

Table 1. Summary of age data presented in this thesis, with references to separate papers using roman numerals.(h) hornblende, (m) muscovite (b) biotite.

deposited in the Bushmanland, Kakamas, Areachap terranes, already shown to have taken place in the Garies Terrane (Raith et al., 2003).

The Richtersveld Subprovince, the Bushmanland and Garies Terranes (Fig. 2) are suggested to have joined the eastern terranes a little later. We found that zircons from the ore-bearing Hotson Formation of the Bushmanland Group, Bushmanland Ore District, suggest a maximum depositional age of 1285 ± 14 Ma for quartzites and schists (Paper VI). The ore and related sediments proved to be significantly younger (Paper VI) than previously believed. The ore-bearing horizon is not older than ~1650 Ma as postulated by Reid et al. (1997), and its 'old basement', the Achab Gneiss, is in fact younger than the major part of the sediments. The depositional setting of the Bushmanland Group is generally considered as a stable environment with little tectonism. The Koeris Formation overlies the Bushmanland Group unconformably and has an age of 1131 ± 35 Ma, determined on metabasalts and supported by detrital zircon ages (1154 ± 18 Ma) from the interbedded conglomerate matrix (Paper VI). The major unconformity, presence of conglomerate, and shift in detrital zircon histogram to much less Paleoproterozoic (Bailie et al., 2007*a*) and more 1200-1250 Ma material (Paper VI) indicates a change in environment related to tectonism. The shift in provenence ages shows that the Koeris Formation partly derived its detrital material from rocks which were previously regarded as its basement. Both the Bushmanland Group and Koeris Formation are seen at Gamsberg to be isoclinally folded and overturned by ENE trending isoclinal F2 folding, the pervasive fold-phase in Bushmanland related to the D2 event. The revised age of the Hotson Formation has implications for the timing of ore-formation, suggesting a Mesoproterozoic age instead of Paleoproterozoic. The age of the folded and overturned conglomerate and amphibolite on top of the stratigraphy in the Aggeneys area gives a maximum age for D2 deformation in the Bushmanland Terrane at ~1140 Ma, previously generally considered to be ~1200 Ma. There is still some uncertainty in the absolute ages, and how to correlate them with D2 and D3 in Bushmanland, partly due to the few rocks found in the age spectrum between 1190-1060 Ma to record the deformation. However, a strongly deformed gneiss in southern Garies Terrane was dated by Raith et al. (2003) at 1111 ± 21 Ma, which supports a later D2 event in the western terranes. Although an early metamorphic event also was found in meta-sedimentary rocks in roughly the same area at 1187 ± 15 Ma, it is more likely to be the result of intrusion-related metamorphism, and not directly related to the D2 event following collision. Hence, the major Namaquan folding event was slightly later in the Bushmanland Terrane (Paper VI), than in the eastern terranes (Paper I, IV), although folding (D3) probably occurred as late as ~1150 Ma in the Kakamas Terrane. These data indicate that a direct time correlation of the D2 and D3 events across the Hartebees River Thrust, and consequently the whole of the Namaqua Sector, is not very robust.

Post-Namaquan event I

A time of little activity or quiet period followed. Then another, fifth pulse of magmatism took place at 1110–1090 Ma, giving rise to a second sequence of sedimentation and volcanism in the Koras Group, as well as intrusive rocks (Paper I, IV). This second pulse is not related to any significant regional deformation in the eastern terranes and may have been thermally induced. It is in part coeval with the large Umkundo Igneous Province of the Kaapvaal and Zimbabwe Cratons (Hanson et al., 2004). These magmatic rocks preserve an important paleomagnetic 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, cited as a Kalahari Craton paleopole (Jacobs et al. 2008). The 1100 Ma magmas probably intruded a tensional crustal regime (Moen, 2007), affecting only the eastern Kakamas, Areachap and Kaaien Terranes (Paper I, IV). These mainly granitic rocks (Paper IV) are not just remelted granites from the main Namaquan Orogeny at 1220-1150 Ma, as their HREE levels are generally lower than expected if derived from 1220-1150 Ma parents. They rather reflect calc-alkaline magmatism related to mafic intrusions intruding and mixing with the deeper crust.

Post-Namaquan event II

A later period of regional metamorphism occurred at ~1030 Ma. It can be found throughout the Garies and Bushmanland Terranes (Robb et al., 1999, Raith et al., 2003; Clifford et al., 2004, Bailie et al., 2007b, Paper II, IV) and traced into the eastern Richtersveld Subprovince. This event is mostly seen as a high temperature, low pressure event with associated occasional granitoids and noritic dikes. As a portion of the Bushmanland Terrane and Garies Terrane has been found to be high in uranium, the post-tectonic heating at 1030 Ma might be related to internal radioactive heating

(Andreoli et al., 2006). However, the extent of this more radioactive crust is not known, and among the rocks we sampled (Paper IV), only two samples from the Garies Terrane show elevated U and Th levels. Other reasons put forward for this late heating event have been a hot mantle due to mantle delamination (Gibson et al., 1996) or extensional collapse bringing the deep crust of western Bushmanland up quickly (Dewey et al., 2006). A mantle delamination process would need to explain the relative consistency of metamorphic U-Pb zircon ages throughout Bushmanland, as well as the lack of metamorphism in the eastern terranes at that time. A major extension event giving rise to magmatism by pressure-release would need to explain the relative scarcity of magmatic rocks in the affected area affected by this heating event.

Possible later collision of the western terranes?

The general idea, although not so often explicitly stated, is that the Namaqua Sector was all assembled at the same time in collisions at around 1200 Ma. From our results, this idea may still be feasible. However it needs adjusted into a sequence of collision events to account for the decrease in age of deformation towards the west. As demonstrated in paper VI, our constraints on the timing of deformation in Bushmanland is still rather poor. Despite the general idea, it seems possible that the eastern part (Kaaien, Areachap and Kakamas Terranes) and the western (Bushmanland, Richtersveld and Garies Terranes) parts of the Namaqua Sector were not joined prior to ~1050 Ma. This hypothesis needs further investigation, but cannot be totally discarded. It could explain why the abovementioned 1100 Ma magmatism is found only in the eastern part and the discrepancy in metamorphic ages between the eastern and western parts, remarkably sharp at the Hartebees River Thrust (Paper 1, IV, VI). The collision at ~1200 Ma, if there was one affecting the whole Namaqua Sector at the same time, did not record a well-defined age in the Bushmanland, Garies Terranes and the Richtersveld Subprovince. It may have occurred any time after the deposition (~1150 Ma) of the Koeris Formation, later folded (Paper VI) and before the 1030 Ma metamorphic and magmatic event, lacking deformation. However, the main magmatism between 1200 and 1165 Ma did occur at the same time in both eastern and western terranes. The main modes of deformation in the two areas are similar, although the main deformation phase differs somewhat in both age and direction from east - west in Bushmanland, Garies and eastern Richtersveld Subprovince, to northwestwards in the Kakamas Terrane and rotating further to north-northwest in the Kaaien Terrane. An interesting aspect in this context is that an unknown continent may be required to collide with the Kakamas Terrane from the SW, to account for the deformation and metamorphism in the Kakamas and Areachap Terranes. This would then have to be quite rapidly removed, possibly by dextral strike-slip faulting parallel to the prevailing terrane boundaries and shear zones, and replaced by the Richtersveld Subprovince and Bushmanland and Garies Terranes by 1050-1000 Ma. This idea is however contradicted by the low-pressure, high-temperature nature of the 1050-1010 Ma metamorphic event in these terranes.

Cooling event in the Namaqua Sector

By 1000 Ma the entire Namaqua Sector was clearly acting as a single crustal block. The crust exposed today in Namaqualand started to cool down and the whole region reached temperatures below ~350° by 960 Ma. This conclusion is the result of Ar-Ar dating of hornblendes, muscovites and biotite discussed in Paper VII, and shows a rather uniform last crustal response and cooling history, except for the Kaaien Terrane. The Kaaien Terrane cooled directly in response to the peak metamorphism at 1165 Ma and cooled below ~350° C in mica schists by 1129 Ma. The results from the Richtersveld Subprovince, and the Areachap, Kakamas, Bushmanland Terranes indicate a rapid cooling of ~5° per Ma, probably initiated by uplift that occurred between 1020 - 960 Ma, and then appear to have experienced more moderate levels of cooling of 1 - 2° per Ma. The rapid uplift indicated by Paper VII coincides with, or just follows the high-T, low-P event at ~1030 Ma in the Bushmanland Terrane. This may also possibly be related to the late phases of D3 (Raith and Harley, 1998; Clifford et al., 2004), giving rise to steep structures and providing conduits for anorthosite-norite magmatism in the Okiep Copper District of western Bushmanland Terrane.

7. Concluding remarks

The Namaqua Sector of the Namaqua- Natal Province has a long history of crustal development by extraction from the mantle and reworking in orogenic events, stretching back to the Archean Era (>2500 Ma), with major Paleoproterozoic (2500 - 1600 Ma) and Mesoproterozoic (1600 - 1100 Ma) crust-forming events. This differs from the Natal Sector, which has a largely juvenile character related to a Mesoproterozoic Wilson cycle.

The Namaqua-Natal Province of southern Africa became part of the Kalahari Craton at 1200 - 1100 Ma, likely in relation to the ~1.0 Ga supercontinent Rodinia, although the timing of assembly and its position in relation to other components is still debated. The timing of deformation and folding events throughout the Namaqua Sector is still not completely understood, and correlations are difficult to assess. However, the broad similarities of these events may eventually justify a uniform nomenclature. Better time constraints are needed in for example the Bushmanland Terrane. The time gap between the two main magmatic pulses in the Bushmanland Terrane provides difficulties with the resolution of the different folding events. The identity of the colliding continent to the present south and west and the nearest neighbours of the Kalahari Craton in Rodinia are still unresolved (Jacobs et al., 2008; Li et al., 2008). Paleomagnetic investigations by Powell et al. (2001) seem to rule out the earlier proposed Llano Belt in Texas, USA (Dalziel et al., 2000; Hanson et al., 2004), for which we have dated the main phase of metamorphism at 1115 - 1125 Ma (Pettersson et al., 2008). This agrees well with recently published work on the tectonic evolution of the Llano Belt (Mosher et al, 2008) where the main Grenvillian orogeny was initiated shortly after collision between the different mainly young to juvenile areas and the southern edge of the North American continent at ~1150 Ma. This event does not correspond to any known deformation and metamorphic event in the Namaqua Sector. Our Sm-Nd data from the Namaqua Sector and the accumulating body of Sm-Nd data worldwide will provide new constraints on matches of continental fragments for reconstructions of the Rodinia supercontinent. We have also constrained the age of a sandstone formation in the Kaaien Terrane used for paleopole and palaeolatitude of the Kalahari craton at the time of Rodinia's existence.

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