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Precambrian Crustal Evolution of the Rehoboth Province, Southern Africa

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Abstract

This thesis uses U-Pb, Sm-Nd, Lu-Hf, Ar-Ar and Oxygen isotope data on well-documented rock samples, to investigate crustal evolution of the Precambrian Rehoboth Province of Southern Africa. This province is defined by its smooth magnetic character, reflecting deep magnetic basement in contrast to the adjoining mobile belts and the Kaapvaal Craton. Most of the area is covered by sedimentary sequences and the Kalahari sands.

A first indication of old crust in the Rehoboth Province was provided by granitoid and mafic cobbles from the ~300 Ma Dwyka glacial diamictite. The granitoid cobbles have Archaean ages between 3100 to 2500 Ma and a Palaeoproterozoic group between 2050 and 2020 Ma. The mafic cobbles yield ages of 1123–1111 Ma. The likely provenance of the Dwyka cobbles is the basement of the Rehoboth Province or the Kalahari Line east of Rietfontein. A source within the Kaapvaal Craton is excluded by the absence of typical Kaapvaal cover rocks in the diamictite cobbles. Previous theories of crustal growth or collision between the Rehoboth Province and the Kaapvaal Craton at either 1800 or 1200 Ma are not supported by these data.

The Rehoboth Basement Inlier (RBI) is a tectonic terrane at the northern margin of the Rehoboth Province, thrust up in the ~600 Ma Damara foreland. U-Pb, Lu-Hf and Oxygen isotope data for zircon from metasedimentary and magmatic rocks provide new insights on the crustal evolution of the Rehoboth Province. A small group of 3.41 to 2.45 Ga U-Pb zircon ages found in the metasediments of the RBI strengthens the concept of an Archaean foundation to the Rehoboth Province. A group of Palaeoproterozoic ages ranging from 2.2 to 1.92 Ga have not been identified in outcropping magmatic rocks. The Lu-Hf isotope character of these zircons requires mixing between Archaean crustal source rocks and juvenile mantle material. This again points to the presence of an Archaean nucleus within the Rehoboth Province. The 2.05 Ga event, seen in both Dwyka cobbles and detrital zircons, corresponds in age to the Bushveld event and thermal peaks in the Kaapvaal Craton and Limpopo Belt. It suggests that the Rehoboth Province was attached to the Kaapvaal Craton before 2.05 Ga, but after 2.45 Ga.

A large age peak at 1.87 Ga corresponds in age to the largely metabasaltic 1870 ±5Ma Elim Formation, now the oldest dated unit in the RBI. However, the Lu-Hf isotope data of the detrital zircons from metasediments shows a source with distinctly older crustal residence and it is likely that the magmatic event at 1.87 Ga was widespread over the Rehoboth Province.

The detrital zircon ages that correspond to the younger Palaeoproterozoic (1.83–1.72 Ga) magmatic ages of the RBI show similar Lu-Hf character and the source for these zircons was thus mainly provided by rocks related to the same subduction phase. The Palaeoproterozoic magmatic rocks of the RBI reveal a complex arc-related tectonic history which probably represents an Andean subduction setting.

The Kaaien Terrane in South Africa is part of the complex suture zone between the Kaapvaal Craton, Kheis Province, Rehoboth Province and the Namaqua-Natal Province related to a ~1200 Ma collision event. New metamorphic pressure-temperature (PT)-calculations combined with geochronology for unusual garbenschiefer rocks of the Groblershoop Formation reveal an unique burial and uplift history. A segment of the Kaaien Terrane reached depths around 40 km. This caused peak metamorphism at 1164 Ma (Lu-Hf on garnet), followed by rapid exhumation to hornblende and white mica Ar-Ar closure temperatures by ~1140 Ma, thought to be controlled by a change in the tectonic regime. This is the highest pressure found thus far in the Namaqua-Natal Province, most others being less than 5kb. Other parts of the Kaaien Terrane remained at the surface during this period.

The Rehoboth Province is thus revealed as an ancient crustal block with Archaean foundations, which may have been attached to the Kaapvaal Craton prior to 2.05 Ga. Major Palaeoproterozoic events within the Rehoboth Province involved mantle additions mixed with reworked Archaean crust. Finally, the Rehoboth Province played a major role during the evolution of the Mesoproterozoic Namaqua-Natal Province, which led to the formation of the Kalahari Craton.

Keywords: Rehoboth Province, Rehoboth Basement Inlier, Kaaien Terrane, Dwyka Diamictite, U-Pb, Sm-Nd, Lu-Hf, Ar-Ar Geochronology, Oxygen isotopes, Zircon, Baddeleyite

Popular Science Summary

The structural Rehoboth Province is a large triangular region with ca. 700 km long margins covering a large part of Namibia and the western side of South Africa. The Rehoboth Province is now part of a larger entity called the Kalahari Craton which comprises most of southern Africa. A craton is an ancient stable part of the crust often consisting of Precambrian rocks >550 million years (Ma) old. The assembly of the Kalahari Craton was completed when the Namaqua-Natal Province (south) was pushed together with the Kaapvaal Craton (east), Zimbabwe Craton (north-east) and the Rehoboth Province (west). This configuration is thought to be part of the formation of the Supercontinent Rodinia which formed about 1200 million years ago.

Most of the rocks of the Kalahari Craton have Archaean (3800-2500 Ma) or Palaeoproterozoic ages (2500-1600 Ma). However, the basement rocks (bedrock) of the Rehoboth Province are covered by a thick package of younger sediments like the sands of the Kalahari Desert, so there are not many bedrock outcrops. Therefore little is known of the age of this province or when it was joined with the Kaapvaal Craton.

Some minerals may be used for determining the age of a rock (geochronology). An example is the uranium-lead system in zircon $ZrSiO_4$. When zircon grows it incorporates a small amount of uranium into its crystal lattice. The radioactive mother ^{235}U and ^{238}U isotopes decay with known half-lives to daughter ^{206}Pb and ^{207}Pb respectively. The different ratios of both U and Pb can be measured by microbeam instruments and allow calculation of the time passed since the zircon crystallised. Several different geochronology methods are used in this work to determine the age of the rocks and what happened to them during metamorphism or erosion and deposition as sediments.

A first sign of very old crust in the Rehoboth Province was provided by cobbles from the ~300 Ma Dwyka glacial deposits. The cobbles have either Archaean ages between 3100 to 2500 Ma or a small range of Palaeoproterozoic ages between 2050 and 2020 Ma. There are good indications that the cobbles were plucked from the basement of the Rehoboth Province by the Dwyka Ice sheet. A source within the Kaapvaal Craton is excluded by the absence of the typical rocks like Banded Iron Formation from the Kaapvaal Craton in the glacial deposits.

The Rehoboth Basement Inlier (RBI) lies in Namibia at the northern margin of the Rehoboth Province. This is an area where the older basement rocks are exposed after being pushed up by tectonic movements during the mountain formation of the ca. 600 Ma Damara Orogeny. These rocks provide the only direct clue on what may lie under the Kalahari sands.

Detrital zircons in sedimentary rocks come from the magmatic rocks like granites that eroded to form sediment. The sediment was transported to a basin where it was deposited to form e.g. sandstone. Since zircon is a very robust mineral it survives the transport which may be up to several hundreds of kilometres. Detrital zircons give valuable clues about the source rocks, especially when these source rocks are not found anymore or, as in the case of the Rehoboth Province, are buried under younger rocks.

In our detrital zircon study on sedimentary rocks of the RBI we found that the Rehoboth Province is much older than previously thought. A small group of zircon gave Archaean ages between 3410 and 2450 Ma and Palaeoproterozoic ages between 2200 and 1920 Ma, which strengthens the concept of an Archaean foundation to the Rehoboth Province. There were also widespread magmatic events within the

Rehoboth Province at 2050 Ma and 1870 Ma. The 2050 Ma age has not been found in the magmatic rocks of the RBI but one sample from the Elim Formation gave an age of 1870 ± 5 Ma, which is now recognised as the oldest formation within the inlier.

The Palaeoproterozoic magmatic rocks of the RBI with ages between 1830-1720 Ma reveal a complex volcanic arc-related history which is comparable with the subduction of oceanic crust under continental crust, as we see in the Andes of South America today.

The Kaaien Terrane in South Africa lies at the southern end of the Rehoboth Province and is a complex suture zone between the Kaapvaal Craton, Kheis Province, Rehoboth Province and Namaqua-Natal Province. We studied the geological history of some unusual rocks called garbenschiefer which contain large hornblende and garnet crystals in a quartz-mica matrix. The Kaaien Terrane formed as the result of a ~1200 Ma collision between different crustal blocks. New pressure-temperature estimates combined with geochronology reveal an unique burial and uplift history in which parts of the Kaaien Terrane were pushed down to depths around 40 km, then brought back to the surface in a geologically short time, dated using the potassium-argon dating system.

The Rehoboth Province is thus revealed as an ancient crustal block with Archaean foundations, which suggest that it could be a target for diamond exploration. The Rehoboth Province may have been attached to the Kaapvaal Craton before the regional Bushveld magmatic event at 2050 Ma. Major Palaeoproterozoic events within the Rehoboth Province involved magmas coming from the mantle, mixed with older Archaean crust. Finally, the Rehoboth Province played a major role during the 1300–1100 Ma tectonic cycle in the Namaqua-Natal Province, which led to the formation of the Kalahari Craton.

Populärvetenskaplig Sammanfattning

Popular Science Summary in Swedish

Den strukturella provinsen Rehoboth är en stor triangulär region med ungefär 70 mil långa sidor som täcker en stor del av Namibia och västra Sydafrika. Rehobothprovinsen ingår nu i en större enhet som kallas Kalaharikratonen, och som täcker större delen av södra Afrika. En kraton är en uråldrig fast del av jordskorpan som ofta består av prekambrisk bergarter, över 550 miljoner år (Mår) gamla. Kalaharikratonen bildades när provinsen Namaqua-Natal (i söder) trycktes ihop med Kaapvaalkratonen (i öster), Zimbabwekratonen (i nordöst) och Rehobothprovinsen (i väster). Denna uppbyggnad tros ha ingått i bildandet av superkontinenten Rodinia som formades för ungefär 1200 miljoner år sedan (Mår).

Det mesta av berggrunden i Kalaharikratonen härstammar från arkeisk (3800–2500 Mår) och paleoproterozoisk (2500–1600 Mår) tid. Urberget i Rehobothprovinsen täcks dock av ett tjockt lager yngre sediment, till exempel sanden i Kalahariöknen, vilket innebär att det finns få platser där urberget kommer i dagen. Av denna anledning vet man inte mycket om åldern på denna provins, eller när den sammanfördes med Kaapvaalkratonen.

Vissa mineraler kan användas för att åldersbestämma bergarter (geokronologi). Det går till exempel att analysera zirkon ($ZrSiO_4$) med hjälp av uran-bly-metoden. När zirkon växer tas en liten mängd uran in i dess kristallstruktur. De radioaktiva moderisotoperna ^{235}U och ^{238}U (uran) sönderfaller med kända halveringstider till dotterisotoperna ^{206}Pb respektive ^{207}Pb (bly). De olika förekomsterna av både uran och bly kan mätas med mikrostrålningsinstrument, och på så sätt går det att beräkna hur lång tid som gått sedan zirkonen kristalliserades. I detta arbete används flera olika geokronologiska metoder för att bestämma åldern på bergarter och vad som hänt med dem under metamorfos eller erosion och sedimentavlagring.

Det första tecknet på att jordskorpan i Rehobothprovinsen är mycket gammal var flyttblock från glaciärvlagringar i den 300 Mår gamla Dwyka-formationen. Flyttblocken är antingen från arkeisk tid mellan 3100 och 2500 Mår eller en kortare tidsperiod i paleoproterozoisk tid mellan 2050 och 2020 Mår. Det finns mycket som talar för att flyttblocken fördes med från berggrunden i Rehobothprovinsen av Dwyka-istäcket. Det kan fastställas att de inte kommer från Kaapvaalkratonen eftersom typiska bergarter från området såsom bandad järnmalm inte förekommer i glaciärvlagringarna.

I Namibia, vid Rehobothprovinsens norra gräns, finns en inbäddning av äldre berggrund som kallas Rehoboth Basement Inlier (RBI). I detta område har den äldre berggrunden kommit upp i dagen efter att ha tryckts upp av tektoniska rörelser under bergsformningen för ungefär 600 Mår sedan som kallas Damara-orogesen. Dessa bergarter ger den enda direkta ledtråden om vad som kan tänkas finnas under Kalaharis sand.

Zirkon i sedimentära bergarter kommer från magmatiska bergarter som graniter vilka eroderats och bildat sediment. Sedimenten fördes med till en sänka där de avsattes och bildade exempelvis sandsten. Eftersom zirkon är ett mycket tålig mineral klarar den att transporteras hundratals kilometer. Sedimentära zirkoner ger värdefull information om ursprungliga bergarter, i synnerhet när dessa inte längre kan påträffas eller när de, som i Rehobothprovinsen, begravts under yngre bergarter. Genom våra studier av zirkoner i sedimentära bergarter i RBI har vi fastställt att Rehobothprovinsen är betydligt äldre än man tidigare trott. En liten mängd zirkon

har visat på arkeiska åldrar mellan 3410 och 2450 Mår och paleoproterozoiska åldrar mellan 2200 och 1920 Mår, vilket stöder tanken att Rehobothprovinsen bildades under arkeisk tid. Det inträffade också omfattande magmatiska händelser inom Rehobothprovinsen för 2050 och 1870 Mår sedan. Åldrar på 2050 Mår har inte påträffats i de magmatiska bergarterna från RBI, men ett prov från Elim-formationen gav en ålder på 1870 ±5 Mår, vilket nu anses vara den äldsta formationen inom den inbäddade berggrunden.

De paleoproterozoiska magmatiska bergarterna i RBI med åldrar mellan 1830 och 1720 Mår visar på ett komplext historiskt förlopp under påverkan av en vulkanbåge, som kan jämföras med den subduktion av en oceanplatta under en kontinentalplatta som skapat Anderna i Sydamerika.

Vid Rehobothprovinsens sydgräns i Sydafrika ligger den tektoniska terrängen Kaaien, som är en komplex suturzon mellan Kaapvaalkratonen och provinserna Kheis, Rehoboth och Namaqua-Natal. Vi studerade den geologiska historien för några ovanliga bergarter som kallas garbenschiefer, vilka består av stora kristaller i en matris av kvarts-mica. Kaaien-terrängen uppstod efter en kollision mellan olika jordskorpsblock för cirka 1200 Mår sedan. Nya uppskattningar av tryck- och temperaturförhållanden i kombination med geokronologi visar på ett unikt historiskt förlopp av landhöjning och -sänkning. Delar av Kaaien-terrängen har pressats ner till ungefär 40 kilometers djup, och sedan stigit upp till ytan igen på en geologiskt sett kort tid, vilket kunnat fastställas genom kalium-argon datering.

Rehobothprovinsen kan därmed påvisas vara ett uråldrigt jordskorpsblock med arkeisk berggrund, vilket talar för att den kan komma att bli intressant för diamantutvinning. Rehobothprovinsen kan ha suttit ihop med Kaapvaalkratonen före de magmatiska händelserna som ledde till Bushveldkomplexets bildning för omkring 2050 Mår sedan. Vid betydande händelser under paleoproterozoisk tid inom Rehobothprovinsen har magma från jordmanteln blandats med äldre arkeisk jordskorpa. Slutligen spelade Rehobothprovinsen en viktig roll för det tektoniska förloppet för 1300–1100 Mår sedan i provinsen Namaqua-Natal, som ledde till Kalaharikratonen bildades.

Rock Collection

By Christopher Brady

Dressed and grays and blues and yellows
Found it deep in the backyard
Underneath the cruel bent blades
Rock collecting can be so hard

A multicolored promise
I'll one day find them all
I'll lay them all around me
And slowly build a wall

Foamy quartz on milky green
You held my hand and whispered sometimes
I feel the weight of everything
Your hazel eyes shined in the sunshine

A multicolored promise
Creases map my hands
Pain ground into wisdom
That nobody understands

Relaying all my thoughts until they're warped and frayed
Swallowed up and quickly lost by the rock found on that day
A pure and simple silence a sharp and quelling dream
Pile them high and fill the gaps, a dam built to drown the screams

Chipped out from a fossil bed
The smell of oil snail spirals
I've always been haunted by what I've said
I try to be careful where my feet fall

A multicolored promise
Difficult to find
Lived and died and swallowed
And pressed out one more time

One day I'll go down, be covered by the dirt
Swallowed up and quickly ground
And added back into this earth
I'll sit I'll combine with the others over time
Pressed and polished till I shine
And wait to be another's find

Preface

- I. Cornell, D.H., Van Schijndel, V., Ingolfsson, O., Scherstén, A., Karlsson, L., Wojtyla, J., Karlsson, K., 2011. Evidence from Dwyka tillite cobbles of Archaean basement beneath the Kalahari sands of southern Africa. *Lithos* 125, 482–502. Reprinted with permission from Elsevier.

Van Schijndel contributed to sampling, ion probe zircon dating, oxygen isotope analysis, graphics and discussions. Cornell carried out the planning, sampling, dating, oxygen isotope analysis, whole-rock chemical analysis, tables, most figures, discussion, wrote and submitted the paper. Ingolfsson, Scherstén, L. Karlsson and Wojtyla contributed with sampling and discussion. K. Karlsson contributed with sampling and ion probe zircon dating.

- II. Van Schijndel, V., Cornell, D.H., Karlsson, L., Olsson, J.R., 2011. Baddeleyite geochronology and geochemistry of mafic cobbles from the Dwyka diamictite: New insights into the sub-Kalahari basement, South Africa. *Lithos* 126, 307–320. Reprinted with permission from Elsevier.

Van Schijndel separated and dated baddeleyite, interpreted the results, tables, figures, wrote and submitted the paper. Cornell did the planning, sampling and contributed to the discussion. Karlsson contributed with sampling, whole-rock chemical analysis and writing. Baddeleyite U-Pb geochronology, interpretations and discussion were made in collaboration with Olsson.

- III. Van Schijndel, V., Cornell, D.H., Hoffmann, K.-H., Frei, D., Three episodes of crustal development in the Rehoboth Province, Namibia. Van Hinsbergen, D. J. J., Buiters, S. J. H., Torsvik, T. H., Gaina, C. and Webb, S. J. (eds) *The Formation and Evolution of Africa: A Synopsis of 3.8 Ga of Earth History*. Geological Society, London, Special Publications, 357, 27–47.

Van Schijndel carried out planning, sampling, sample preparation, dating, tables, figures, wrote and submitted the paper. Cornell contributed with planning, sampling and discussion. Hoffmann contributed with discussion and writing. LA-ICPMS zircon dating in contribution with Frei.

- IV. Van Schijndel, V., Cornell, D.H., Frei, D., Simonsen, S.L., Whitehouse, M.J., Crustal evolution of the Rehoboth Province from Archaean to Mesoproterozoic times: Insights from the Rehoboth Basement Inlier. Submitted to *Precambrian Research*.

Van Schijndel carried out sampling, sample preparation, dating, oxygen isotope analysis, tables, figures, wrote and submitted the paper. Cornell contributed with planning, sampling and discussion. LA-ICPMS zircon dating was done in collaboration with Frei, Lu-Hf analyses were done in collaboration with Simonsen and ion probe zircon dating and oxygen isotope analyses were done in collaboration with Whitehouse.

- V. Van Schijndel, V., Cornell, D.H., Anczkiewicz, R., Page, L., Manuscript. Deep burial followed by rapid exhumation in the Kaaien Terrane, South Africa: Geochronology and P-T evolution of garnet-hornblende-mica-plagioclase-epidote schists from the Namaqua Front.

Van Schijndel carried out planning, sampling, sample preparation, mineral analysis, Theriak/Domino modelling, dating, tables, figures and wrote the manuscript. Garnet dating was performed by Van Schijndel under the supervision of Anczkiewicz who also contributed to the interpretations. Cornell contributed with planning, sampling and discussion. Page contributed with $^{40}\text{Ar}/^{39}\text{Ar}$ analyses.

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1. Introduction

The crustal evolution of a region starts with the creation of new crust from the mantle and continues with the reworking of existing crust or new mantle inputs, until a stable craton is formed. Today the continental crust occupies around 40% of the Earth's surface area and 70% by volume of the Earth's crust and is much older than the average oceanic crust. Recent research based on the Sm-Nd and Lu-Hf isotopic systems suggests that a large amount of the continental crust was already generated by the end of the Archaean and that the rate of new crust formation has decreased significantly since that time (Hawkesworth et al., 2010).

The cycle of dispersion and amalgamation of continents as a result of plate tectonics is referred to as the Wilson Cycle. The cycle begins when continental crust thins due to extension, as plates move apart. The crust continues to thin by rifting and heating by rising magma, this is followed by the opening of an ocean basin and the beginning of sea floor spreading. The ocean basin widens and sedimentation occurs at the passive margins. In connection with cooling subduction of oceanic crust starts accompanied by (island) arc magmatism and the ocean basin closes again, normally with different opposing sides. The arc(s) eventually collide with the continent and a mountain belt is formed which may be followed by a continent-continent collision, with mountain building, uplift and erosion ending the Wilson cycle. A new cycle may later start when a new phase of rifting is initiated. An entire Wilson cycle lies in the order of hundreds of millions of years.

During the subduction process, orogenic belts develop which may incorporate a variety of crustal blocks, called terranes, which are transferred onto the overriding plate. A terrane might have originated elsewhere before it is juxtaposed to the existing crustal block. The accretion of continental crust often occurs at the edge of a stable entity called a craton, a large region of continent that has the strength to withstand orogenic movements. An assemblage of terranes may form a structural province, which is defined as a large area with contiguous structural fabric and broadly coeval argon dates.

When a number of stable crustal blocks are assembled together to form a single landmass then it becomes a supercontinent. In the Earth's long history the continents have split up and collided several times to form supercontinents. During these Wilson cycles new continental crust grew mainly along subduction zones by emplacement of juvenile magmatic rocks which were then tectonically accreted to cratons. This process also normally involves accretion of existing crust by reworking of older crust by deformation, metamorphism and melting to form new granitoids.

Global peaks in zircon U-Pb ages indicate the formation of at least two Precambrian supercontinents: Rodinia, which formed ca. 1.3-1.0 Ga, and Nuna, which amalgamated ca. 1.9-1.8 Ga (Hawkesworth et al., 2009). Further back in time we can recognize the formation of Archaean cratons, parts of which have survived as the backbones of larger Proterozoic cratons. During the Phanerozoic the supercontinent Gondwana was formed at ~500 Ma and the last supercontinent Pangaea, formed about 300 million years ago.

Deciphering the crustal evolution of continental regions and reconstructing these supercontinents is not always straight forward. For example, precisely dated and reliable palaeomagnetic poles for Precambrian rocks are scarce and the reconstruction of the older supercontinents can be difficult, especially for the Zimbabwe and Kaapvaal Cratons and adjacent orogenic belts (Evans et al., 2002; de Kock et al., 2006; Hanson et al., 2011; Fig. 1).

Fig. 1 shows the Precambrian framework of southern Africa, which is subdivided into cratons and structural provinces. Their tectonostratigraphy, subdivision into terranes, and timing of events in their crustal evolution are generally well-documented. The least well-known area is the Rehoboth Province, for three main reasons:

1. The outcrops are limited because of thick Kalahari sand cover, shown stippled in Fig. 2.

2. Priority has been given to the ~1.1 Ga Namaqua-Natal and ~0.6 Ga Damara (Pan African) Provinces which are better exposed in South Africa and Namibia respectively and contain large ore deposits.

3. Modern petrological methods such as in situ U-Pb zircon dating, Lu-Hf dating, stable oxygen isotopes on zircon, argon step-heating and P-T determinations have not been available to previous workers.

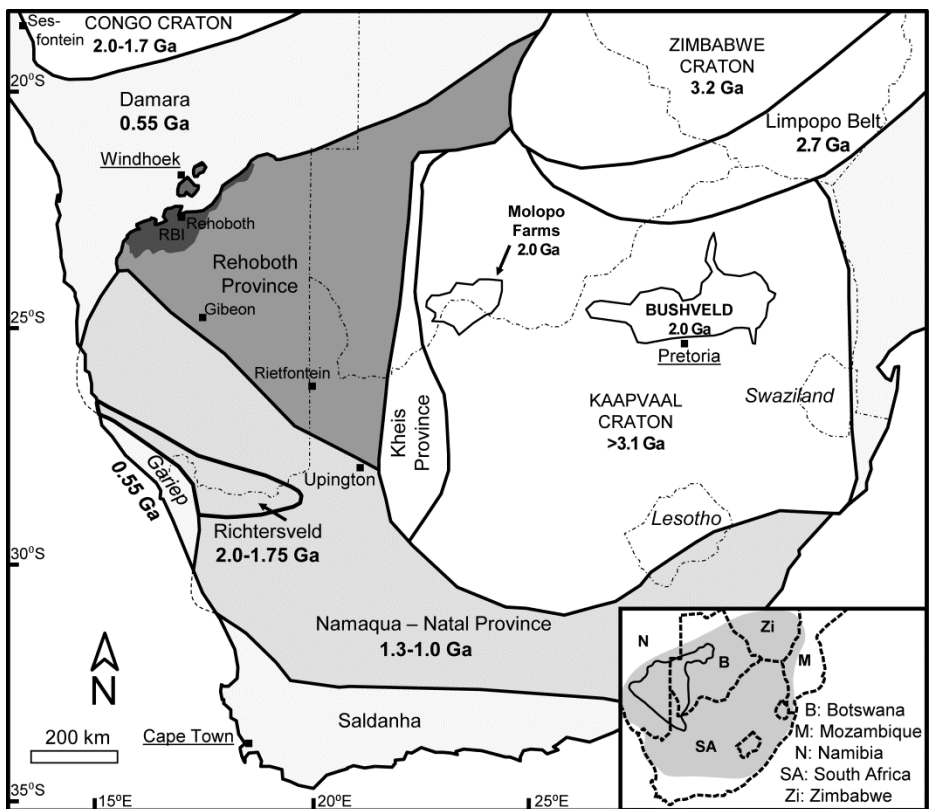


Figure 1 Simplified tectonic framework of Southern Africa and the distribution of the Palaeoproterozoic Rehoboth Basement Inlier (RBI) modified after Corner (2003); Cornell et al. (2006); Becker et al. (2006). The inset map shows the magnetically defined outline of the Rehoboth Province within the Kalahari Craton (grey area, after Jacobs et al., 2008). Approximate ages are given for the last major orogeny or crust-forming event (craton).

2. Aim of the thesis

This work aims to provide new insights into the origin and development of the Rehoboth Province utilising a substantial body of reliable radiometric dating and precise isotopic analyses. The improved knowledge of this centrally positioned province is of vital importance to achieve a better understanding of the crustal evolution of southern Africa and the context in which its bountiful ore deposits have formed. Several different aspects of crustal evolution have been addressed, including:

- what can be said about the crustal evolution of the Rehoboth Province from a regional perspective,
- investigation of the crustal development of the Rehoboth Province by the means of crustal and provenance studies within the Rehoboth Basement Inlier,
- investigation of the possibility of a coherent crustal evolution of the Rehoboth Province and the Kaapvaal Craton from Archaean or Palaeoproterozoic times,
- the nature and timing of crustal accretion during collisions forming the Kalahari Craton.

3. Crustal framework of southern Africa

The tectonic framework of Southern Africa shown in Fig. 1 consists of several major Archaean cratons and smaller cratonic fragments, stitched together and surrounded by younger orogenic belts. The present configuration was established during the Late Neoproterozoic to Cambrian Pan- African orogenic event (Begg et al., 2009). The Kalahari Craton, which constitutes the main part of Southern Africa, is an aggregate of the Kaapvaal and Zimbabwe Cratons that form the Archaean nucleus and is surrounded by Proterozoic provinces. The Kalahari Craton has been stable since Mesoproterozoic times (Jacobs et al., 2008) and previously formed part of the Rodinia supercontinent, then later the Gondwana supercontinent, which broke up at about 180 Ma ago into the present continents of Africa, India, Australasia, Antarctica and South America. The status of the Rehoboth Province within the Kalahari craton is not well understood and it is unclear if the Rehoboth Province was joined to the other cratons and provinces as the Mesoproterozoic supercontinent Rodinia formed (Moen, 1999; Moen and Armstrong, 2008) or if it was already accreted to the Kaapvaal Craton long before the Namaqua Wilson Cycle began (Cornell et al., 2013).

3.1. Geological setting of the Rehoboth Province

The Rehoboth Province was first defined by Hartnady (1985), as a subprovince of the Namaqua Province. Later authors interpreted it as a Palaeoproterozoic entity that was accreted to the Kaapvaal Craton sometime between 1.93 and 1.75 Ga (e.g. Cornell et al., 1998; Tinker et al. 2004; Jacobs et al., 2008), with a possible ancient core beneath the Proterozoic rocks (Begg et al., 2009). The structural outline of the Rehoboth Province is defined by an equilateral triangle that is characterized by long-wavelength anomalies reflecting deep magnetic basement on total magnetic intensity maps with depth to basement up to 10 km (Corner, 2008, figs 2.3, 2.4 and 2.10). The Namaqua Front in Namibia is the southern border of the Rehoboth Province and it

shows a large offset with depth to basement up to 6 km in the Rehoboth Province (Corner, 2008; Fig. 1). The eastern boundary is the Kalahari Line, interpreted by Meixner and Peart (1984) as a magnetic signature of the crustal suture between the Rehoboth Province and the Archaean Kaapvaal Craton. Corner (2008) calculated a change in depth to basement across the Kalahari Line from ~300 m in the east to 8–10 km in the west in Botswana. Rocks of the Karoo Supergroup and Nama Group lie at the surface and are underlain by ~1 Ga red beds in Namibia. Despite the lack of substantial geochronological data, a ca. 1.8 Ga orogeny which formed a continuous Magondi-Okwa-Kheis Belt on the western side of the Kaapvaal Craton was suggested (e.g. Hartnady, 1985). The thrust complex of the Kheis Province and Kaaien Terrane on the eastern margin of the Kaapvaal Craton comprises a complex foreland to the eastern Namaqua Sector of the Namaqua-Natal Province (Cornell et al., 2006). The Kheis Province and Kaaien Terrane have been subject to several studies to unravel the stratigraphic and structural complexities of these areas (c.f. Schlegel, 1991; Moen, 1999; Van Niekerk, 2006). In short, the timing of the deformation within the Kheis-Okwa-Magondi Belt is not well constrained and it also not clear if the belt is continuous. It might be that there is no evidence for a ~1.8 Ga within the Kheis deformation and that the penetrative fabric has been caused solely by the Mesoproterozoic Namaqua event (Moen and Armstrong, 2008).

Age data from within the Rehoboth Province comes from Re depletion model ages of the Gibeon Kimberlite xenoliths by Hoal et al. (1995) with ages at 2.2 to 2.0 Ga (Fig. 1). Luchs (2012, p. 63) reinterpreted the Re data of Pearson et al. (2004) and concludes that data point towards a primary source originated in the late Archaean at around 2.9 Ga. Lu-Hf isotope data from the xenoliths also show an enrichment event in the Rehoboth crust around 1.9-1.8 Ga (Luchs, 2012). Pettersson et al. (2007) found zircon xenocrysts aged 2.12–1.74 Ga in bimodal volcanic and intrusive rocks of the 1.17–1.09 Ga Koras Group near Upington (Fig. 1) along the south-eastern tip of the Rehoboth Province and detrital grains aged 1.9–1.82 Ga in Koras Group sandstone. Together, these data indicate a possible Palaeoproterozoic basement component in the southern Rehoboth Province.

3.2. Rehoboth Basement Inlier (Inlier)

The Rehoboth Basement Inlier lies along the northern margin of the Rehoboth Province (Fig. 1). The inlier is a Proterozoic terrane that has been thrust southwards as part of the Damara Foreland. This tectonic inlier is the only place where the basement crops out and gives a direct indication of the crustal composition. Available age data from this well-exposed area indicate two major magmatic and deformational episodes during the late Palaeoproterozoic and Mesoproterozoic (Ziegler and Stoessel, 1993; Becker et al., 2006; Miller, 2008). The Palaeoproterozoic Rehoboth Group is a volcano-sedimentary sequence intruded by related plutons (Becker et al., 2005). The oldest volcanic rocks were dated by conventional U-Pb zircon and have a crystallization age of 1782 ± 10 Ma (Nagel et al., 1996). However, Sm-Nd and U-Pb analyses of Palaeoproterozoic granitoids, amphibolites and basic dykes suggest that the earliest crust within the Rehoboth Basement Inlier was formed between 2.37 and 1.8 Ga (Ziegler & Stoessel 1993). This suggests that the major part of the crust near Rehoboth formed during the Palaeoproterozoic.

4. Methodology

Appropriate samples were taken during extensive fieldwork for petrology and geochronology purposes. The three main sample locations were:

- (1) Rietfontein, South Africa, where cobbles from the Permocarboneous Dwyka diamictite were investigated (Papers I and II; Fig. 2)
- (2) Rehoboth, Namibia, where magmatic and metasedimentary rock samples from the Rehoboth Basement Inlier were collected (Papers III and IV; Fig. 1)
- (3) Groblersshoop, South Africa. Metasediments of the Groblersshoop Formation, Kaaien Terrane, were sampled (Paper V; Fig. 7).

Prior to the analysis methods described below all samples were prepared by crushing, grinding of whole rock powders and sieving of the coarse crush for separation of heavy minerals. The methods summarised here are explained in more detail in the respective papers.

4.1. Zircon U-Pb Geochronology

The mineral Zircon (ZrSiO_4) is a common accessory mineral in a diversity of rocks. Zircon can form in magmatic and metamorphic rocks and is preserved as detrital grains in sedimentary rocks.

When zircon crystallises it incorporates a small amount of uranium into its crystal lattice. The ^{235}U isotope decays to ^{207}Pb with a half-life of ~ 0.7 Ga, whereas ^{238}U decays to ^{206}Pb with a half-life of ~ 4.5 Ga. The amounts of the different parent U and daughter Pb isotopes in zircon can be measured and allow calculation of the time passed since the zircon crystallised. Zircon is a refractory mineral and the U-Pb system in zircon is very robust and able to survive extreme conditions, such as metamorphism or sedimentary transport.

Electron microscope imaging (BSE: Backscattered electron; CL: Cathodoluminescence) combined with isotope ratio measurements by in situ microbeam techniques (ion probe: SIMS or laser-ablation inductively coupled plasma mass spectrometer: ICP-MS) document that single zircon crystals may consist of a core and a rim with different age domains. This shows that zircons can record multiple geological events within one grain where the core of the grain is largely unaffected by the later crystallisation event.

All U-Pb ages were calculated using the program ISOPLOT 3.0 (Ludwig, 2012). Analyses of U-Pb in zircon were performed in the following facilities: NordSIM ion-probe facility at Naturhistoriska Riksmuséet in Stockholm, Sweden; and Laser-ablation ICP-MS at GEUS in Copenhagen, Denmark.

4.2. Baddeleyite U-Pb Geochronology

The mineral baddeleyite (ZrO_2) occurs in silica undersaturated rocks, with insufficient silica to form zircon (ZrSiO_4). Dating of baddeleyite is also based on the uranium- (U) lead (Pb) isotope system and is a helpful tool for dating unmetamorphosed igneous mafic rocks. This method was used to determine the crystallization age of mafic cobbles retrieved from the Dwyka tillite. The baddeleyite grains were recovered from crushed and sieved cobbles using a Wilfley table following the water-based separation technique of Söderlund and Johansson (2002) at Lund University, Sweden. A strong pencil magnet was used for magnetic separation after which the baddeleyite grains were easily hand-picked.

U–Pb chemistry and mass spectrometry were performed at the Laboratory of Isotope Geology (LIG) in the Museum of Natural History in Stockholm. This technique was used for paper II.

4.3. $^{40}\text{Ar}/^{39}\text{Ar}$ Geochronology on Muscovite and Hornblende

The $^{40}\text{Ar}/^{39}\text{Ar}$ Geochronology method was used in Paper V to date cooling after metamorphism and was been carried out at the Argon geochronology laboratory at the University of Lund, Sweden.

The method can be applied to K-bearing minerals, such as muscovite and hornblende, and is based on the natural radioactive decay of ^{40}K . This parent isotope decays to two daughter isotopes, ^{40}Ca (89.52%) and ^{40}Ar (10.48%) with a half-life of ~ 1.25 Ga (Steiger and Jäger, 1977). The $^{40}\text{Ar}/^{39}\text{Ar}$ technique is based on the conversion of stable ^{39}K to ^{39}Ar by irradiation with neutrons in a nuclear reactor. The fixed natural $^{39}\text{K}/^{40}\text{K}$ ratio is known, so the efficiency of this transformation in the reactor can be measured (J-parameter) and the amount of ^{39}Ar measured can be used as a proxy for ^{40}K .

The $^{40}\text{Ar}/^{39}\text{Ar}$ is measured by a mass spectrometer during step-heating of the mineral by laser. From the ^{40}Ar and ^{39}Ar released during each step, an age can be calculated. The $^{40}\text{Ar}/^{39}\text{Ar}$ age is obtained from a plateau of similarly aged steps (Faure and Mensing, 2005).

The Ar daughter isotope is not retained in minerals at high temperatures and $^{40}\text{Ar}/^{39}\text{Ar}$ closure temperatures depend on the mineral type, grain size and cooling rate. Muscovite has a closure temperature of ~ 350 and hornblende ~ 540 °C (Deer et al., 2003). In this way a cooling path can be determined for a rock which contains both minerals.

4.4. Garnet Lu-Hf and Sm-Nd Geochronology

Because of the leading importance of garnet for P-T estimations in most metasedimentary rocks, age data from garnet have been frequently determined in order to link P-T calculations with geochronology. The age of garnets can be dated by two different isotope systems, Sm-Nd and Lu-Hf respectively.

^{147}Sm decays to ^{143}Nd with a long half-life ($\lambda = 6.54 \times 10^{-12}\text{yr}^{-1}$; Lugmair and Marti, 1978) and this results in small variations in the Nd isotopic composition and makes dating of young minerals difficult. Sm and Nd are both intermediate rare earth elements and garnets usually have a high Sm/Nd ratio compared to other minerals.

Garnet usually also has highly elevated levels of Lu/Hf with respect to other minerals. ^{176}Lu has a faster decay constant ($\lambda = 1.867 \times 10^{-11}\text{yr}^{-1}$; Scherer et al., 2001; Söderlund et al., 2004) which makes the Lu-Hf system more appropriate for dating younger rocks than the Sm-Nd system. Combined with the capability of analysing small sample fractions by multiple-collector ICP-MS (MC-ICP-MS), are the Lu-Hf and Sm-Nd garnet systems useful geochronology methods (Scherer et al., 2000).

Garnet geochronology may be affected by the presence of submicroscopic inclusions. Sm-Nd dating is hampered by rare earth element-rich phosphates and epidote, which lowers age precision and leads to inaccurate ages or make dating impossible (Anczkiewicz et al., 2003). Zircon has a higher Hf content than garnet. Inherited zircon inclusions in garnet may result in a lower $^{176}\text{Lu}/^{177}\text{Hf}$ ratio and this will subsequently lower the Lu-Hf age of the garnet. The closure temperature of the

Lu–Hf system in garnet appears to be greater or equal to that of the Sm–Nd system (Scherer et al., 2000).

The garnet Lu–Hf and Sm–Nd methods were used in Paper V to date a metamorphic event.

4.5. Lu–Hf isotopes on zircon

Zircon incorporates other important trace elements into its structure besides U and Th, for example rare earth elements (REE) and large amounts of Hf. Hafnium isotopes can be used to determine the contribution of old or new material during the pulses of magmatism indicated by the U–Pb ages. The basis of using the Hf isotopic ratios in zircon is the decay of ^{176}Lu to ^{176}Hf , whereas ^{177}Hf is a stable isotope. During mantle melting, Hf is partitioned more strongly than Lu into the melts which enter the crust. Over time the $^{176}\text{Hf}/^{177}\text{Hf}$ therefore evolves to higher values in the mantle than in crustal rocks. The Lu/Hf ratio of zircon is usually very low, < 0.0005 , which means that time-integrated changes to the $^{176}\text{Hf}/^{177}\text{Hf}$ ratio in zircon, as a result of in-situ decay of Lu, are virtually negligible (Kinny and Maas, 2003). Initial Hf isotope ratios can be written using the ϵ -notation, where the $^{176}\text{Hf}/^{177}\text{Hf}$ is expressed as parts per ten thousand deviation from the chondritic evolution line gives the initial epsilon Hf value (ϵHf_i). During the production of magmas, high values of $^{176}\text{Hf}/^{177}\text{Hf}$ (i.e. $\epsilon\text{Hf}_i \gg 0$) indicate juvenile mantle input, either directly from mantle-derived mafic melts, or by remelting of young mantle-derived mafic lower crust (Belousova et al., 2006). Low values of $^{176}\text{Hf}/^{177}\text{Hf}$ ($\epsilon\text{Hf}_i < 0$) provide evidence for crustal reworking in that much older crust is melted and possibly mixed with mantle-derived melts.

Combining the U–Pb age of the zircon and the ϵHf_i value a depleted mantle model age (T_{DM}^{C}) can be calculated. This age represents the timing when the crust from which the zircon was formed originated from the depleted mantle (Griffin et al., 2002). However, care should be taken since Lu–Hf T_{DM}^{C} ages are highly dependent on the parameters that are used for calculation and should therefore not be interpreted as real ages.

Lu–Hf isotope analyses on zircon were performed using a Nu Plasma HR multicollector ICPMS at the Department of Geosciences, University of Oslo. This technique was used for Paper IV.

4.6. Stable Oxygen Isotopes on Zircon

Oxygen isotope analyses of zircons can be made *in situ* and for Papers I and IV the NordSIM ion probe with a Cs primary beam and multicollector was used on the same type of epoxy mounts as for U–Pb dating.

Oxygen isotope data are presented with the notation $\delta^{18}\text{O}$. This is a measure of the ratio of stable isotopes $^{18}\text{O}:^{16}\text{O}$, expressed as the deviation (δ) in parts per thousand (‰) units from the Vienna Standard Mean Ocean Water (VSMOW or SMOW).

The $\delta^{18}\text{O}$ record of non-metamict zircon is generally preserved from the time of crystallization despite high grade metamorphism or hydrothermal alteration due to the robustness of the mineral. Therefore, the $\delta^{18}\text{O}$ of zircon can be used to relate the magmatic environment of the zircon to the U–Pb age (Valley, 2003).

Depleted mantle $\delta^{18}\text{O}$ zircon values are $5.3\text{‰} \pm 0.3\text{‰}$ (2σ , Valley, 1998) so material that is expected from mantle-derived magmas has a $\delta^{18}\text{O}$ between 5.0 and 5.6‰. Zircon which crystallised from magmas that incorporated crustal material previously affected by low-temperature alteration (with large fractionation resulting

in rock with positive $\delta^{18}\text{O}$) has values above 6.5‰ according to Valley et al. (2005). Oxygen isotope ratios of igneous rocks are thus strongly affected by incorporation of supracrustal materials into melts, which commonly have $\delta^{18}\text{O}$ values higher than primitive mantle magmas (Valley et al., 2005). Also, zircon $\delta^{18}\text{O}$ values above 7.5‰ are only found after 2.5 Ga, reflecting intra-crustal recycling of high $\delta^{18}\text{O}$ material. This reflects maturation of the crust by interaction with surface waters at low temperature (Valley et al., 2005). For example, the 91500 zircon standard has a $\delta^{18}\text{O}$ value of 9.86‰ (Wiedenbeck et al., 2004) which is considered to be the value for average crust.

Zircon with low $\delta^{18}\text{O}$ below-mantle values (<4.6‰) is more difficult to explain. It could originate from magmas formed by melting of rocks that were hydrothermally altered by low- $\delta^{18}\text{O}$ seawater or by meteoric water at high temperature, such as lower oceanic crust (Wei et al., 2002). High temperature alteration is favoured in this model since at high temperature (>300 °C) there would be little fractionation between the fluid and rock.

5. Summary of Papers

One way to study what lies under the Kalahari sands is to investigate basement cobbles from the uppermost Carboniferous to lowermost Permian Dwyka diamictite which crops out west of the Kalahari sands around Rietfontein, South Africa (Figs. 1 and 2). This method is used both in Paper I and II, where in Paper I we focused on the felsic cobbles and in Paper II the mafic cobbles are investigated.

Within the southern foreland of the Neoproterozoic Damara Belt lies the Rehoboth Basement Inlier (RBI) which contains the oldest outcrops that are considered to be part of the Rehoboth Province. Previous work indicates that the Rehoboth Basement Inlier is composed of a late Palaeoproterozoic domain (>1.8–1.72 Ga) and a Mesoproterozoic domain (Becker et al., 2006; Becker and Schalk, 2008). The division between the Palaeoproterozoic and Mesoproterozoic rocks is not always clear and most of the early zircon ages are mainly multigrain zircon thermionic mass spectrometry (TIMS) dates. These often represent mixed ages and are thus not meaningful. The use of new and refined methods of geochronology was necessary to get significant ages for both magmatic and metasedimentary rocks. We used the metasedimentary rocks of the Rehoboth Basement Inlier to characterize the crustal development history of the Rehoboth Province with in particular the presence of suspected Late Palaeoproterozoic and Archaean components. We focus on the rocks of the Rehoboth Basement Inlier in Papers III and IV.

Most of the suture zone between the Rehoboth Province and the Kaapvaal Craton lies under the Kalahari sands. Only the Palaeoproterozoic quartzites and schists of the Kaaien Terrane, which overlie the Rehoboth Province, and the Kheis Province, a thrust package which overlies the Kaapvaal basement, lie on the surface (Cornell et al., 2013). In paper V we combine Garnet Lu-Hf geochronology and Ar-Ar mineral cooling ages with P-T modelling to construct a metamorphic time path for the garbenschiefer schists of the Kaaien Terrane.

This thesis summarises the findings of the studies performed on the edges of the Rehoboth Province in order to gain more knowledge about this buried craton and its relation to the crustal framework of southern Africa (Table 1).

Table 1 Summary of age data presented in this thesis. The Roman numerals refer to the separate papers. U-Pb detrital ages are $^{206}\text{Pb}/^{207}\text{Pb}$ ages. (hbl) hornblende, (wm) white mica.

Name/Rock Type	Sample #	Zircon U-Pb age			T_{DM} ages mean (Ma)	$^{40}\text{Ar}-^{39}\text{Ar}$ $\pm 2\sigma$ (Ma)	Garnet	
		$\pm 2\sigma$ (Ma)	Magmatic	Detrital			Metamorphic	Lu-Hf
Kaapvaal Craton Paper I								
Koppiespan Granite	DC0912	3061 ± 9						
Motion Granite	DC0914	2867 ± 7						
Ditshiping Granite	DC0915	2882 ± 7						
Ditshiping younger Granite	DC0916	2854 ± 7						
Kgokgole Granite	DC0917	2857 ± 6						
Dwyka cobbles Papers I & II								
Diorite	DC0708	1111 $\pm 6^{\text{II}}$						
Gabbro	DC0711	1116 $\pm 7^{\text{II}}$						
Gabbro	DC0725	1123 $\pm 5^{\text{II}}$						
Gabbro	DC0726	1112 $\pm 5^{\text{II}}$						
Granite	DC0505	2047 $\pm 14^{\text{I}}$						
Granite	DC0506	2017 $\pm 15^{\text{I}}$						
Granite	DC0706	2797 $\pm 6^{\text{I}}$						
Biotite Gneiss xenocrysts	DC0710	2687 $\pm 16^{\text{I}}$						
main		2525 $\pm 10^{\text{I}}$						
rims					1395 $\pm 34^{\text{I}}$			
Rapakivi Granite	DC0712	2778 $\pm 10^{\text{I}}$						
Biotite Schist metasediment	DC0716			3079-3320 ^I				
Granite	DC0722	2061 $\pm 14^{\text{I}}$						
Foliated Granite	DC0723	2499 $\pm 24^{\text{I}}$						
Biotite Granite Gneiss	DC0724	2623 $\pm 16^{\text{I}}$						
Migmatite Gneiss	DC0727	2621 $\pm 13^{\text{I}}$						
Migmatite Granite Gneiss	DC0731	2013 $\pm 10^{\text{I}}$						
Granite	DC0740	2889 $\pm 11^{\text{I}}$						
Biotite Granite	DC0743	2877 $\pm 11^{\text{I}}$						
Granite	DC0745	2879 $\pm 11^{\text{I}}$						
Quartz Porphyry	DC0747	2661 $\pm 24^{\text{I}}$						
Rapakivi Granite	DC07101	2912 $\pm 13^{\text{I}}$						
Rehoboth Basement Inlier Papers III & IV								
Langberg Arenite	DC0925			1079-2031 ^{III}				
Marienhof Quarzite	DC0926			1742-2892 ^{III}				
Billstein Schist	DC0928			1689-2811 ^{IV}				
Elim Calc-Silicate Schist	DC0929	1870 $\pm 5^{\text{IV}}$		1129 $\pm 90^{\text{IV}}$	2169 ^{IV}			
Gaub Valley Andesitic Schist	DC0930	1770 $\pm 4^{\text{IV}}$			2348 ^{IV}			
Mt Barry Granodiorite	DC0931	1720 $\pm 6^{\text{IV}}$			2170 ^{IV}			
Weener Tonalite	DC0936	1741 $\pm 7^{\text{IV}}$			2188 ^{IV}			
Marienhof Felsic Gneiss	DC1001	1753 $\pm 6^{\text{IV}}$			2147 ^{IV}			
Billstein Conglomerate	DC1003			1566-3410 ^{IV}				
Kalkbrak Rhyolitic Gneiss	DC1130	1826 $\pm 5^{\text{IV}}$			2250 ^{IV}			
Koregas Diorite	DC1131	1816 $\pm 4^{\text{IV}}$			2262 ^{IV}			
Koregas Diorite	DC1132	1819 $\pm 7^{\text{IV}}$			2238 ^{IV}			
Billstein Quarzite	DC1133			1648-2121 ^{IV}				
Kamasis Migmatite Granite	DC1134	1811 $\pm 20^{\text{IV}}$						
Gamsberg Granite	DC1135	1221 $\pm 6^{\text{IV}}$			2057 ^{IV}			
Kaaien Terrane Paper V								
Garbenschiefer	DC0910		1861-2732	1211 ± 26		1147 ± 4 (wm)	1163 ± 3	
						1141 ± 3 (hbl)		
Garnet-mica schist	DC0949					1145 ± 3 (wm)		
Quartzite	DC0954					1132 ± 3 (wm)		
Quartzite	DC0955					1134 ± 3 (wm)		
Garbenschiefer	DC1148					1137 ± 3 (hbl)	1165 ± 4	
Garnet-mica schist	DC1151						1142 ± 4	973 ± 9

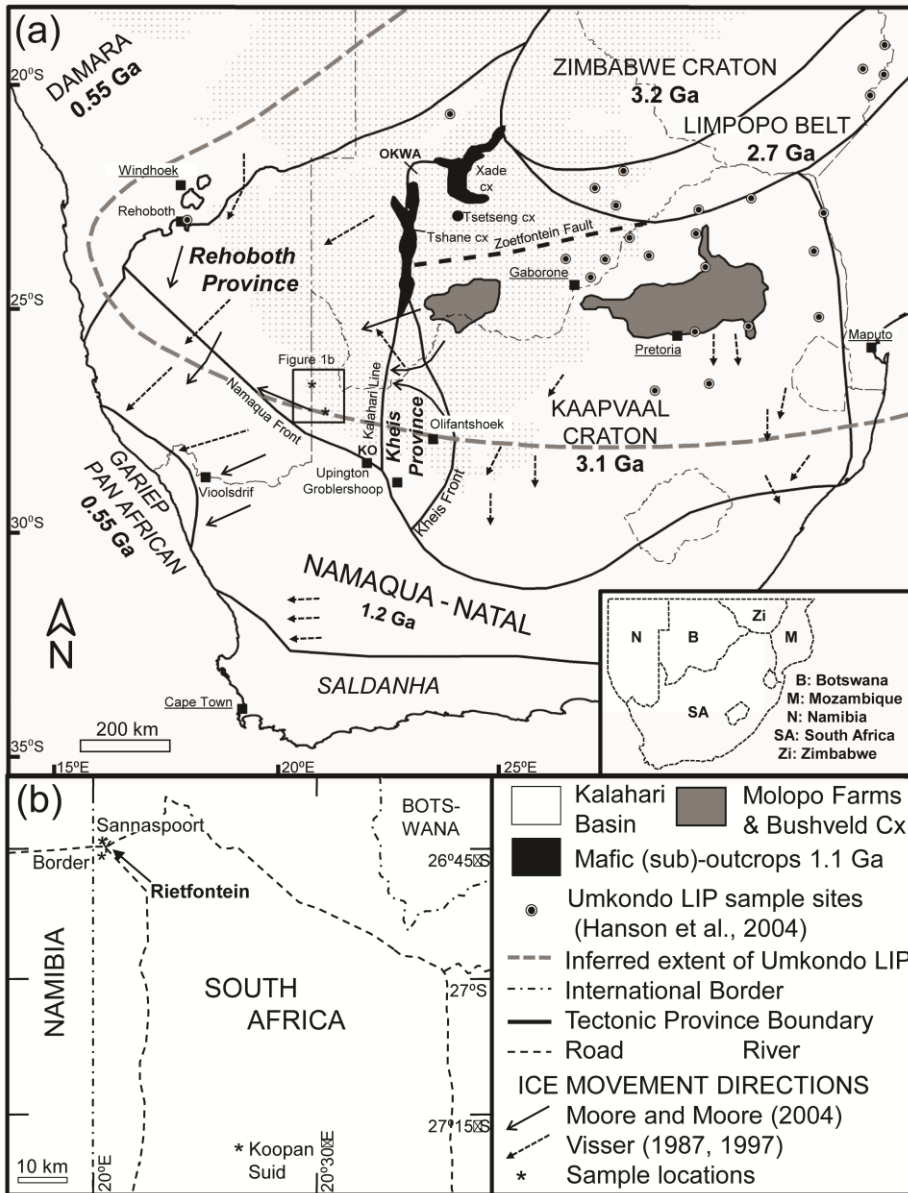


Figure 2 (a) Crustal framework of southern Africa showing structural provinces modified after Cornell et al. (1998) and Corner (2003), large mafic intrusions and Dwyka ice movement vectors after Visser (1987, 1997, solid arrows) and Moore and Moore (2004, dashed arrows). The area covered by the Kalahari sand is shaded, after Haddon and McCarthy (2005), KO: Koras Group. (b) Detail of sampling sites.

5.1. Paper I

Cornell, D.H., van Schijndel, V., Ingolfsson, O., Scherstén, A., Karlsson, L., Wojtyła, J., Karlsson, K., 2011. Evidence from Dwyka tillite cobbles of Archaean basement beneath the Kalahari sands of southern Africa. *Lithos* 125, 482–502.

In this paper we investigated glacial diamictites of the Permocarboneous Dwyka Group exposed at Rietfontein west of the Kalahari sands. These glacial deposits are believed to carry cobbles plucked from the bedrock by the ice sheet which covered the Gondwana supercontinent about 300 Ma ago. These cobbles are a source of information about what lies beneath the Kalahari sands (Fig. 2).

The Kheis and Rehoboth Provinces of southern Africa were thought to be underlain by either an ~1800 Ma orogenic belt, or a northern branch of the 1200 Ma Namaqua-Natal Province. Microbeam U-Pb zircon dating of the granitic cobbles shows that they contain no evidence of crustal growth or orogeny at either ~1800 or 1200 Ma. The basement under Kalahari sands seems to consist of two bedrock granite age groups, an Archaean group comprising trondhjemites and granites with ages 3100 to 2500 Ma and a Palaeoproterozoic granite group with ages between 2050 and 2020 Ma. Four of the Archaean Dwyka cobbles we dated are younger than the 2.7 Ga Kaapvaal cover sequence and are thus too young to be derived from the Kaapvaal Craton. Five trondhjemitic granites from the westernmost outcrops of the Kaapvaal Craton were also dated, the oldest being 3061 ± 9 Ma and four others between 2882 ± 7 Ma and 2854 ± 7 Ma, reflecting the cratonisation of the Kimberley Terrane. Three of the Archaean granite cobbles have unusual less-than-mantle zircon oxygen isotope values around $+3 \delta^{18}\text{O}$, which reflects alteration of the source material with high-temperature, originally meteoric water before melting.

All the mafic cobbles from the same Dwyka diamictites described in Paper II are much younger and are related to intrusions of the 1.1 Ga Umkondo Large Igneous Province, exposed to the southeast as the younger Koras lavas and gabbro's. The lack of Kaapvaal-derived mafic cobbles (3.0 to 1.9 Ga) supports a short transport distance for the granitic cobbles. Also, the pebble assemblages from the diamictites we sampled lack the diagnostic banded iron formation (BIF), stromatolitic limestone and other supracrustal pebbles which should characterise diamictites derived from the Kaapvaal Craton, thus we envisage shorter transport distances and derivation from the region now beneath the Kalahari sands.

All the granitic and mafic Dwyka cobbles described in papers I and II are most likely derived from basement directly east of Rietfontein, either the Rehoboth Province or the Kalahari Line with origins from the Kheis Province. The Kalahari Line, which might be an Archaean crustal suture, provides an explanation for the low $\delta^{18}\text{O}$ isotope data seen in some granites. We envisage the Rehoboth Province to consist of an Archaean core supplemented by Palaeoproterozoic granitoids, which was joined to the Kaapvaal Craton at an early stage of crustal development and played an important role during later tectonic events. The possibility that the Rehoboth Province has an Archaean basement has important implications for diamond and other mineral exploration and to the crustal evolution of southern Africa.

5.2. Paper II

Van Schijndel, V., Cornell, D.H., Karlsson, L., Olsson, J.R., 2011. Baddeleyite geochronology and geochemistry of mafic cobbles from the Dwyka diamictite: New insights into the sub-Kalahari basement, South Africa. Lithos 126, 307–320.

Geochronology and geochemistry on mafic cobbles from the ~300 Ma Dwyka diamictite on the western boundary of the Kalahari Basin provide new information into the sub-Kalahari basement (Fig. 2). Four mafic cobbles were dated by U–Pb baddeleyite geochronology and yield an age span of 1111–1123 Ma and are within error of each other. This indicates that the mafic Dwyka cobbles are coeval with 1106–1112 Ma Umkondo LIP dolerites and lavas and also with the upper units of the Koras Group near Upington.

Palaeo-ice flow directions suggest that the origin of the Dwyka diamictite deposits on the border between South Africa and Namibia is from beneath the Kalahari sands to the east or north-east. The lack of typical Kaapvaal mafic and cover rocks (e.g. Banded Iron Formation (BIF) cobbles) in these glacial diamictites indicates that their source region lies west or north of the Griqualand West Basin of the Kaapvaal Craton.

Geochemical data obtained on eight mafic cobbles show that they represent a genetically coherent suite with a probable within-plate basalt setting. The Dwyka cobbles share many geochemical similarities with the Umkondo LIP dolerites, but also exhibit important differences such as being affected by pre-Dwyka greenschist facies metamorphism or hydrothermal alteration, hinting at a fault dominated setting. They also show many similarities to the coeval Rouxville Formation, an upper unit of the Koras Group. However, a direct correlation to the Koras Group is unlikely considering the fact that no felsic cobbles, abundant in the Koras Group, were found in the Dwyka diamictite (Paper I). The most likely sources of the cobbles are the mafic intrusives and lavas along the Kalahari Line, the western border of the Kheis Province. Here there are southern equivalents of the ~1.11 Ga Tshane and Xade complexes or intrusive and extrusive mafic units related to the Umkondo LIP, now concealed beneath the Kalahari sands.

Other provenance possibilities are a source west of the Kalahari Line, within the Rehoboth Province, or less likely the Precambrian basement north of the Kaapvaal craton. This suggests a widespread distribution of intrusive and extrusive mafic units of the Umkondo LIP beneath the Kalahari sands.

5.3. Paper III

Van Schijndel, V., Cornell, D.H., Hoffmann, K.-H., Frei, D., Three episodes of crustal development in the Rehoboth Province, Namibia. Van Hinsbergen, D. J. J., Buiter, S. J. H., Torsvik, T. H., Gaina, C. & Webb, S. J. (eds.) The Formation and Evolution of Africa: A Synopsis of 3.8 Ga of Earth History. Geological Society, London, Special Publications, 357, 27–47.

The focus of this paper is to test whether zircon populations in detrital rocks from the Rehoboth Basement Inlier (RBI) can provide U–Pb age spectra which reflect the crustal events of the Rehoboth Province prior to the Pan-African orogeny. The Palaeoproterozoic to Mesoproterozoic RBI is a tectonic terrane that lies on the northern boundary of the Rehoboth Province. We investigated two samples from the RBI, a quartzite of the Late Palaeo-Early Mesoproterozoic Billstein Formation (Marienhof in Paper IV), formed in a continental basin, and a quartz-feldspar arenite

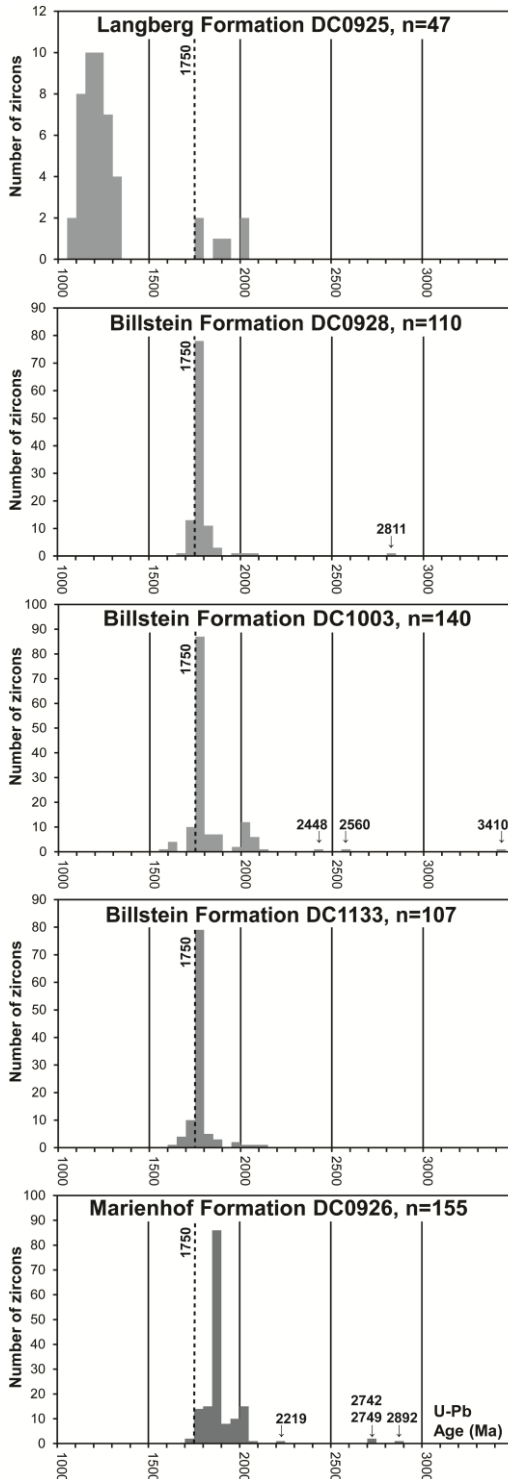


Figure 3 U-Pb age histograms for detrital zircon data, excluding data with >10% discordance. A dotted line is shown at 1750 Ma for comparison of the different peak ages between the Billstein and Marienhof Formations. **(a)** DC0925 Langberg Formation **(b)** DC0928 Billstein Formation **(c)** DC1003 Billstein Formation **(d)** DC1133 Billstein Formation **(e)** DC0926 Marienhof Formation

layer of the late Mesoproterozoic Langberg Formation conglomerates, immature sediments formed within a felsic volcanic system (both close to Rehoboth Town). The combined data indicate the presence of at least three episodes of crustal evolution in the Rehoboth Province at 2.98–2.7 Ga, 2.05–1.75 and 1.32–1.1 Ga (Fig. 3 and Table 1). The oldest phase is only documented in the quartzite by three Archaean zircons. The Palaeoproterozoic zircons between 2.2 and 1.9 Ga are older than any known exposures of the RBI. A large age peak at 1.87 Ga in the quartzite corresponds in age to the 1863 ±10 Ma Elim Formation, see Paper IV for discussion. The Langberg sample shows an age range related to the entire Namaqua–Natal Wilson cycle between c. 1.32 and 1.05 Ga. The absence of zircons of that age range in the quartzite indicates a pre-Namaqua age for the Billstein Formation. This indicates that the Archaean rocks were most likely exposed in the Rehoboth Province during the Late Palaeo-Early Mesoproterozoic and implying a much longer geological history for the Rehoboth Province than previously known.

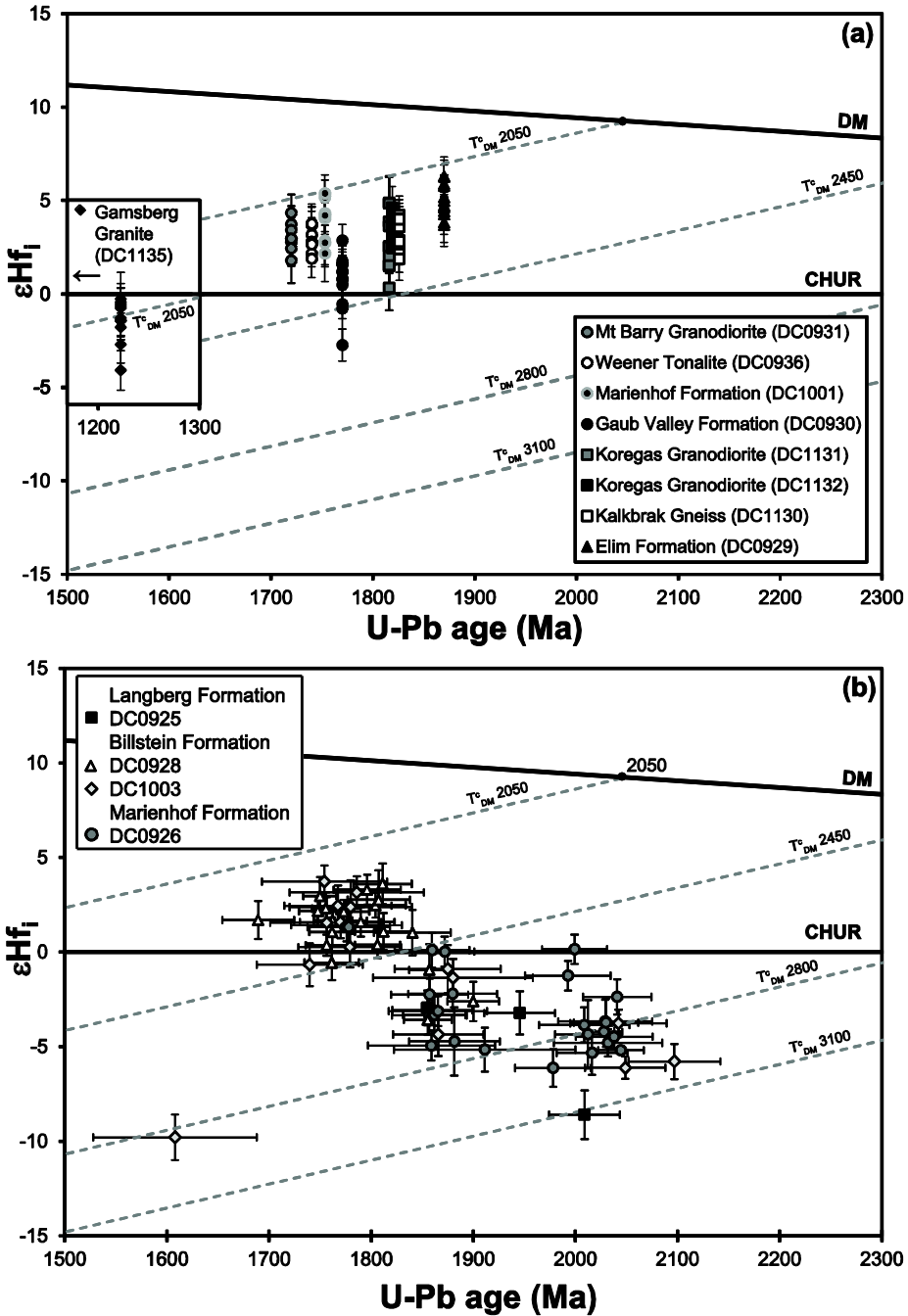


Figure 4 Results of combined U-Pb and Lu-Hf isotope data for **(a)** all zircon analyses for magmatic rocks in a U-Pb vs. ϵHf_i diagram, **(b)** all Palaeoproterozoic detrital zircon analyses from metasedimentary rocks in a U-Pb vs. ϵHf_i diagram. CHUR, chondritic uniform reservoir; DM, depleted mantle evolution line. Crustal evolution lines are shown for 2050 Ma, 2450 Ma, 2800 Ma and 3100 Ma with $^{176}Lu/^{177}Hf = 0.015$.

5.4. Paper IV

Van Schijndel, V., Cornell, D.H., Frei, D., *Crustal evolution of the Rehoboth Province from Archaean to Mesoproterozoic times: Insights from the Rehoboth Basement Inlier*. Van Schijndel, V., Cornell, D.H., Frei, D., Simonsen, S.L., Whitehouse, M.J. Submitted to *Precambrian Research*.

This paper is a combined study of magmatic and metasedimentary samples from the Rehoboth Basement Inlier. Data of the two metasedimentary samples from paper III are also included in this paper. Results of combined U–Pb and Hf and stable oxygen isotope analyses on zircon provide evidence for at least three major magmatic activities in the hinterland, at 1.87, 2.05 Ga but also Archaean times (Figs. 4 and 5). During these stages old crust was recycled giving strong indication to the presence of an Archaean nucleus within the Rehoboth Province. The existence of Archaean material is confirmed by 6 zircons of 3.41 to 2.45 Ga U–Pb zircon ages with subchondritic ϵHf_i values and crustal residence ages reaching back into the Hadean erathem. The combined U–Pb and the Lu–Hf data for both the Archaean and Palaeoproterozoic zircons, affirm the previous hints that the Rehoboth Province has an Archaean cratonic nucleus (Figs. 4 and 5).

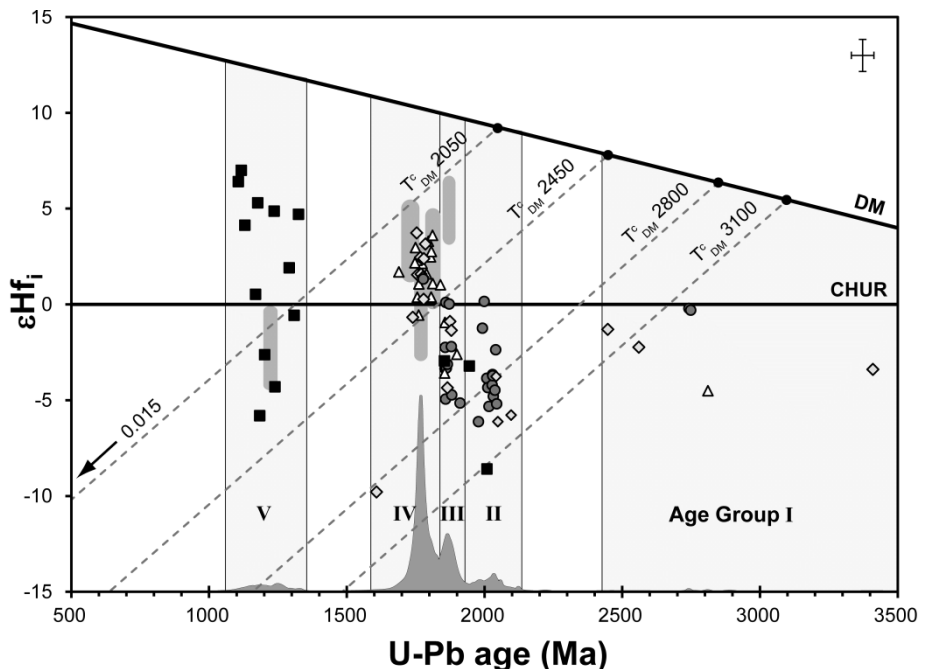


Figure 5 Results of combined U–Pb and Lu–Hf isotope data for all detrital zircon analyses in a U–Pb vs. ϵHf_i diagram. At the bottom the probability density plot for all the detrital zircon data is shown, note that it contains more U–Pb dates than the Lu–Hf analyses. Symbols as in Fig. 3b. Shaded ellipses show the data for the magmatic zircons from Fig. 5a. CHUR, chondritic uniform reservoir; DM, depleted mantle evolution line. Crustal evolution lines are shown for 2050 Ma, 2450 Ma, 2800 Ma and 3100 Ma with $^{176}\text{Lu}/^{177}\text{Hf} = 0.015$. The five U–Pb age groups are shown with Roman numerals, see text for discussion. An indicative error bar is shown top right.

The oldest rocks within the Rehoboth Basement Inlier (Table 1) are represented by the Elim Formation (1.87 Ga) and Kangas Metamorphic Complex (1.83-1.82 Ga) and are thought to have originated from the same low- $\delta^{18}\text{O}$ crustal source which originated at least before 1900 Ma in an off craton setting.

The combined Hf data for the Rehoboth Group and the Kangas Metamorphic Complex plus the Elim Formation lie in the same crustal trend. This shows that the inlier originated from the same dominant source which had entered the crust at 2.45-2.05 Ga (Fig. 4).

The Gaub Valley Formation is the oldest member of the magmatic rocks of the Rehoboth Group (1.77-1.72 Ga) and is affected by an older, heterogeneous source with a depleted mantle age up to 2.6 Ma. The presence of recycled sedimentary material within the Gaub Valley sample is indicated by the high oxygen isotope value and relatively low Hf values, suggesting the incorporation of supracrustal material. It is proposed that the andesitic magmatism of the Gaub Valley Formation was initiated by the dehydration of the slab during the first stages of subduction which affected the source material by incorporation high- $\delta^{18}\text{O}$ fluids and slab sediments.

Figure 6 shows the possible plate tectonic evolution of the Rehoboth Basement Inlier between 1.87 and 1.72 Ga.

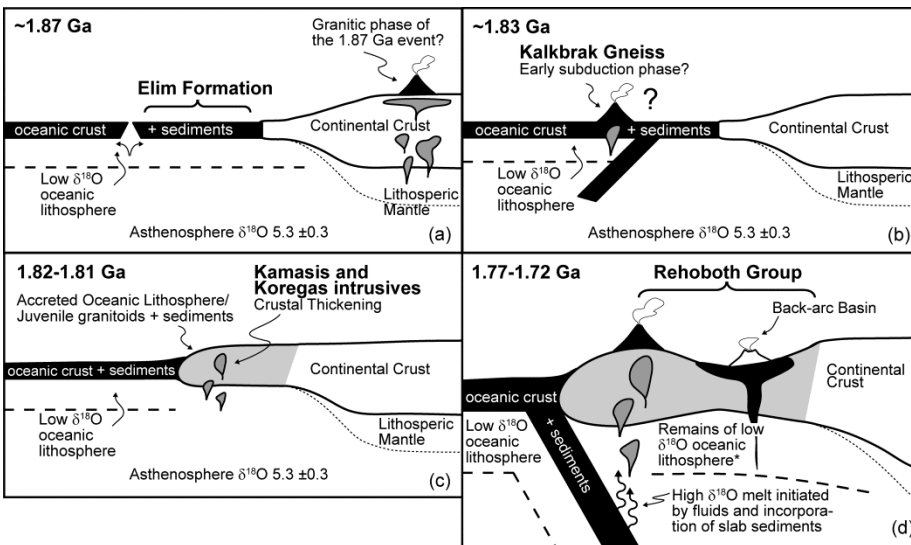


Figure 6 Sketch showing the proposed tectonic model for the Rehoboth Basement Inlier between 1.87 and 1.72 Ga. **(a)** at ~1.87 Ga the Elim Formation was formed as part of the continental margin during diversion of oceanic crust. Within the craton a thermal event took place, stirred by a crustal source with Archaean crustal residence ages. **(b)** At ~1.83-1.81 the metarhyolite of the Kalkbrak Gneiss was formed, perhaps in an early subduction event. **(c)** The Koragas and Kamasias Granitoids might have formed during crustal thickening and accretion of oceanic crust to the craton. **(d)** (Enlarge by a factor 2) At 1.77 Ga initiation of arc related volcanism by high- $\delta^{18}\text{O}$ fluids and sediments from the down going slab. During back-arc spreading the Marienhof Formation sampled the underplated low- $\delta^{18}\text{O}$ source. *Underplating of altered material at deep crust/upper-mantle level.

5.5. Paper V

Deep burial followed by rapid exhumation in the Kaaien Terrane, South Africa: Geochronology and P-T evolution of garnet-hornblende-mica-plagioclase-epidote schists from the Namaqua Front. Van Schijndel, V., Cornell, D.H., Anczkiewicz, R., Page, L., Manuscript.

In this paper we investigated the timing and nature of the Mesoproterozoic collision in the Kaaien Terrane. The Kaaien Terrane of the Namaqua-Natal Province of South Africa (Fig. 7) forms part of an NW-trending thrust sequence in the Namaqua front and is a complex suture zone between the Kaapvaal Craton, Kheis Province, Rehoboth Province and the Namaqua-Natal Province. The Groblershoop Formation in the Kaaien Terrane probably formed between 1880-1850 and consists of quartzites and mica rich schists. Some of these schists contain the unusual paragenesis of garnet + hornblende + mica + plagioclase + epidote + quartz. These schists are the main focus of this paper where we couple thermodynamic modelling with detrital zircon U-Pb dating, ^{40}Ar - ^{39}Ar dating on white mica and hornblende and Lu-Hf and Sm-Nd dating on garnet. Phase-equilibria calculations give peak temperatures of 675-725°C and pressures of 10.8-12.2 kbar, implying burial to approximately 40 km. Garnet Lu-Hf ages suggest that peak metamorphism occurred at ~1165 Ma with cooling

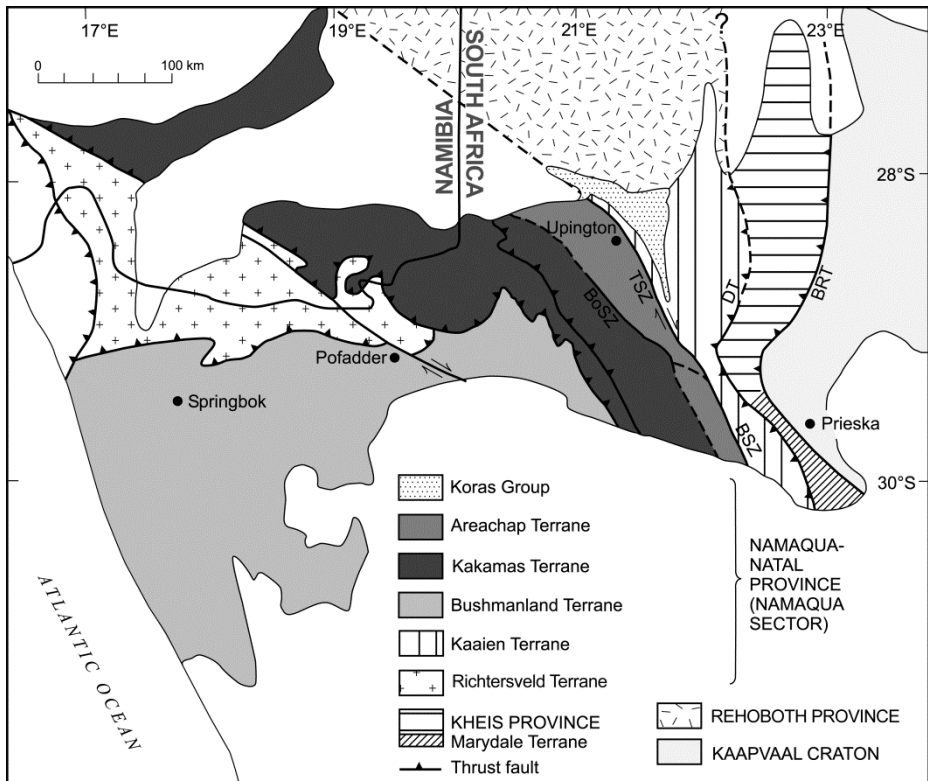


Figure 7 Map of the Namaqua Sector of the Namaqua-Natal Province, South Africa. BoSZ: Boven Rugzeer Shear Zone, BRT: Black Ridge Thrust, BSZ: Brakbosch Shear Zone, DT: Dabep Thrust, TSZ: Trooilapspan Shear Zone. Modified after Cornell et al. (2006).

between 1145-1135 Ma as indicated by the ^{40}Ar - ^{39}Ar ages. A new tectonic model is proposed for the Kaaien Terrane, involving deep burial and rapid exhumation for the metasediments of the Groblershoop, whereas other parts of the terrane acted independently. This suggests that there is no consistent transition from low to high grade within the Kaaien Terrane and it is a composite of several domains with different burial and exhumation histories.

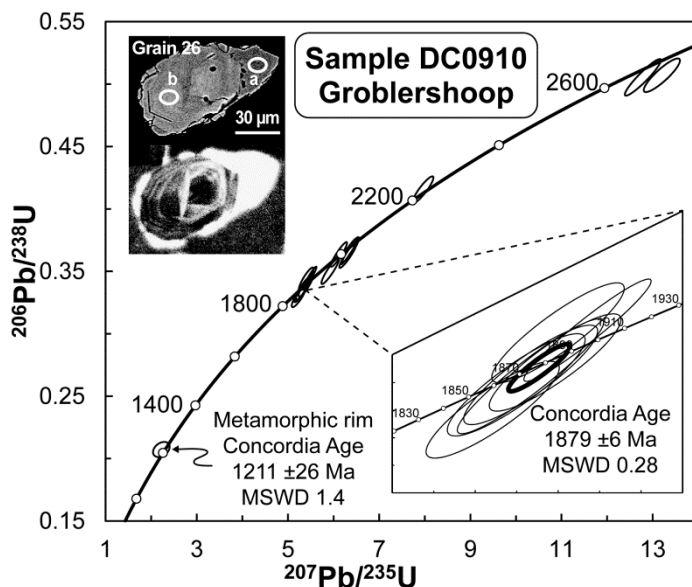


Figure 8 U-Pb Concordia diagram for sample DC0910 with concordia ages for the main age domain and the metamorphic rim. These domains are illustrated by a back scattered electron and cathodoluminescent image for grain 26.

6. Synthesis

6.1. Archaean to Palaeoproterozoic crust

The Palaeoproterozoic and Neoproterozoic (2.7–2.5 Ga) cobbles compared to the known 3.0 to 2.7 Ga age limits of western Kaapvaal basement and the anomalously low oxygen isotope ratios found in some of the cobbles, do not originate from the westernmost Kaapvaal granite outcrops (Fig. 2). U-Pb zircon ages of felsic cobbles in Carboniferous glacial diamictites from Rietfontein and Upington areas in the south-eastern part of the province indicate that there are Archaean (2.7–2.5 Ga) and ca. 2.05 Ga Palaeoproterozoic basement components in the Rehoboth Province (Paper I). This points at the existence of a late Palaeoproterozoic and also a Neoproterozoic crustal influence for the Rehoboth Province.

The magmatic event at ca. 2.05 Ga within the Rehoboth Province is not seen in the magmatic rocks of the Rehoboth Basement Inlier but is clearly present in its metasedimentary rocks. Together with the granite cobble data from Rietfontein, this suggests that the 2.05 Ga event was present in much of the Rehoboth Province and acted as a source for the Rehoboth Basement Inlier sediments (Fig. 3). This event corresponds exactly in time to the major thermal events in the Limpopo Belt and

Kaapvaal Craton, as well as the Bushveld Complex and related intrusions. This is a strong indication that the Rehoboth Province and the Kaapvaal Craton were attached during this thermal event.

The >1.87 Ga detrital zircons lie mainly in the same Hf isotope crustal evolution trend as the ca. 2.05 Ga zircons with T_{DM}^C ranging from 3.1 to 2.8 Ga (Fig. 5). This implies significant crustal residence time within the crust for the source material. The original material could be represented by remelted mafic lower crust, which was extracted from a depleted-mantle source during the Mesoarchaeon.

Individual (n=7) detrital U-Pb zircon ages from the Rehoboth Basement Inlier range from 3.41-2.20 Ga, and together with the Rietfontein cobble data confirm the existence of Archaean material in the Rehoboth Province (Figs. 4 and 5). The zircons have subchondritic ϵHf_i values and crustal residence ages reaching back into the Hadean erathem. The combined U-Pb and the Lu-Hf data for both the Archaean and Palaeoproterozoic zircons (Paper III and IV), as well as the Rietfontein cobble data (Paper I) are strong indications that the Rehoboth Province has an Archaean cratonic nucleus.

6.2. Palaeoproterozoic crust

The U-Pb data from Paper III and IV (Fig. 3) reveal that the source of the detrital zircons for Palaeoproterozoic and early Mesoproterozoic sedimentary successions of the Rehoboth Basement Inlier were affected by several important magmatic events with the most prominent ones at ca. 2.05 Ga, 1.87 Ga, 1.75 Ga.

The presence of zircons with an age of ~1.87 Ga within the Groblershoop Formation (Paper V, Fig. 8) is an indication that the Palaeoproterozoic metasediments of the Kaaien Terrane might have been deposited on the passive margin of the Rehoboth Province, since there is no clear source of felsic rocks on the Kaapvaal Craton.

The sediments of the Marienhof Formation within the RBI are believed to have been derived from the Rehoboth Province (Paper III) and the source for the Billstein Formation is clearly dominated by the input of material belonging to the Rehoboth Group and related intrusives (Paper IV).

The zircons from age populations older than 1.86 Ga, which are dominantly from the Marienhof Formation, all show subchondritic ϵHf_i values (Fig. 5). This indicates that the crustal events at ca. 1.87, 2.05 Ga and older involved reworking of a much older crustal source with Archaean crustal residence ages. Even though the 1.87 Ga age peak in the detrital samples is coeval with the Elim Formation, rocks with this age combined with the low ϵHf_i values have thus far not been recognised within the Rehoboth Basement Inlier (Fig. 5). This implies that there is a ~1.87 Ga (granitic) source within the Rehoboth Province.

This 1.87 Ga age peak has also been recognised within the sediments of the Groblershoop Formation of the Kaaien Terrane but is not present in the Olifantshoek sediments of the Kheis Province, suggesting that the Kaapvaal Craton and Rehoboth Province were together after 2050 Ma (the age of the Bushveld Complex and thermal event in both regions), and the Groblershoop Group was deposited in a basin corresponding broadly to their suture.

The Lu-Hf data of the RBI detrital zircons with ages between 1.81-1.69 have similar ϵHf_i values to the Rehoboth Group magmatic rocks. This indicates that the source material was dominated by the input of material belonging to the Rehoboth Group and related intrusives. The Elim Formation (1.87 Ga) and Kangas Metamorphic

Complex (1.83-1.82 Ga) lie in the same crustal evolution trend (Fig. 4) and are thought to have originated from the same low- $\delta^{18}\text{O}$ crustal source which originated before 1900 Ma but possibly as old as 2.4 Ga. This source material must have been altered by high-temperature interaction with meteoric or seawater and is therefore believed to be oceanic lithosphere (Fig. 6). This kind of crust could have formed in a rift related environment (Hiess et al., 2011).

Both the Lu-Hf and oxygen data point to a juvenile and perhaps oceanic lithospheric reservoir as the main source for crust of the Rehoboth Basement Inlier, separated from the depleted mantle between 2.4-2.05 Ga. This low- $\delta^{18}\text{O}$ signature is also present in the felsic Marienhof volcanic schist of the ~75 Ma younger Rehoboth Group. By contrast, the Gaub Valley Formation and the Weener Igneous Complex are clearly affected by incorporation of high- $\delta^{18}\text{O}$ material. It is therefore proposed that the high- $\delta^{18}\text{O}$ signal was caused by the initiation of subduction at 1.77 Ga and that high- $\delta^{18}\text{O}$ fluids and perhaps sedimentary material from the slab controlled the subduction driven dehydration melting of the mantle wedge (Fig. 6). The Marienhof Formation could then represent back arc sediments and bimodal volcanism (Fig. 6). In general the Hf data for Rehoboth Group, Kangas Metamorphic Complex and Elim Formation indicate that they originated from the same dominant source which had entered the lower crust at 2.45-2.05 Ga (Fig. 4).

The Mesoproterozoic Gamsberg Granite has subchondritic ϵHf_i values with depleted mantle ages between 2.22 and 1.99 Ga (Fig. 4). A large part of the data lies on the same crustal evolution trend as the Palaeoproterozoic Rehoboth Basement Inlier crust (Paper IV). However the mantle-like $\delta^{18}\text{O}$ (zircon) value for the Gamsberg Granite is not consistent with supracrustal contamination as the process behind the evolved Hf values. The source for this granite must be an underplated reservoir with mantle-like $\delta^{18}\text{O}$ that had resided within the lower crust of the Rehoboth Basement Inlier since the Palaeoproterozoic. We suggest that the material was derived from the same mafic lower-crust as the Elim and the Kangas Metamorphic Complex, separated from the depleted mantle between 2.22 and 1.91 Ga.

6.3. Mesoproterozoic crust

The Mesoproterozoic granitoids in the Rehoboth Basement Inlier have a long emplacement history and the few precise U-Pb ages in the literature range from 1210-1080 Ma (Table 1). Although the various Mesoproterozoic plutons differ in composition, texture, size and age, most of them are included in the Gamsberg Granitic Suite by Becker and Schalk (2008, Ch. 8, p. 83). Our emplacement age of 1221 ± 6 Ma for the Mesoproterozoic granite from Paper IV is seen as part of the first magmatic phase of the Gamsberg Granitic Suite which is coeval with the Nückopf Rhyolite (Table 1). The intrusives of the Gamsberg Granitic Suite are directly linked to the felsic volcanic rocks of the Nauzarus Group. This group is characterised by several cycles of felsic volcanism and basin formation lasting from ca. 1.23 to 1.10 Ga, thought to be the products of a magmatic arc (Becker et al., 2005; 2006). The volcanic rocks of the Nauzerus Group, Sinclair Supergroup were considered to represent a Mesoproterozoic Rehoboth volcanic arc which follows the curved north-western boundary of the Rehoboth Province by Watters (1976). However, the present semicircular outcrop pattern is actually determined by the tectonic fabric of the Namaqua-Natal Province and the Damara Belt, so the arcuate shape is unlikely to reflect the original geometry.

The Mesoproterozoic episode of crustal development seen in the Langberg Formation zircons (Paper III) corresponds to the complete Namaqua–Natal Wilson cycle with an age range of 1.32–1.05 Ga. Part of the provenance for this sample is probably from the local Gamsberg Granitic Suite and the felsic volcanic rocks of the Nauzarus Group within the Rehoboth Basement Inlier. The older 1.32–1.23 Ga component was probably derived from the Namaqua Province to the south-west, which was a mountain belt at that time, following 1.2 Ga collisions.

The Namaqua–Natal Wilson cycle is reviewed for South Africa by Cornell et al. (2006) and for Namibia by Miller (2008). It started with rifting and ocean basin development at ~1350 Ma. Subduction related island arc and back-arc basin volcanism was in progress between 1300 and 1200 Ma. By 1210 Ma, juvenile arc and older terranes to the west had begun colliding with the Kaapvaal Craton and Rehoboth Province (Pettersson et al., 2007). In Namibia the mafic magmatism of the rifting event is reflected in the ~1.37 Ga Kairab Formation in the Sinclair Region. These rocks were emplaced before or during an early Namaqua collision event along a suture now represented by the Namaqua Front (Miller 2008, Ch 7, p. 1). The closure of Namaqua ocean basins by subduction along the Rehoboth Province margin started between ~1250 and 1220 Ma in the Sinclair region (western margin) and within the Rehoboth Basement Inlier represented by the lower units of the Nauzarus Group (northern margin).

A cycle of post-collisional granite magmatism followed the subduction in the high-grade Namaqua metamorphic terranes from ca. 1180 until 1150, but in the southeastern Rehoboth Province around Upington the 1170 Ma lower Koras bimodal volcanic rocks were extruded and remained unaffected by deformation. However these rocks were later juxtaposed against the Wilgenhoutsdrift Group and Groblershoop Formation to form the Kaaie Terrane by late-tectonic uplift and transpressional movements after 1150 Ma. The Palaeoproterozoic Groblershoop Formation experienced burial to 40 km depth and maximum temperatures between 675–725 °C during peak metamorphism at 1164 Ma. This is the highest metamorphic pressure (>11kbar) yet found in the entire Namaqua–Natal Province; most other pressure determinations within the Namaqua Province are less than 5 kbar.

A tectonic and magmatic quiet period is seen in most Namaqua–Natal terranes after the post-collision granitic magmatism between ca. 1150 and 1100 Ma. This was followed by a new pulse of magmatism most likely related to the 1100 Ma Umkondo plume large igneous province (LIP) event which affected the entire Kalahari Craton (Hanson et al., 2004a). Our Langberg Formation sample was probably deposited during or after that event.

The Mesoproterozoic detrital zircons from the <1.03 Ga Langberg Formation show a large variation in Hf values, which suggests heterogeneous mixing of mantle-derived magma with crustal material as old as 2.4 Ga. This broad array of Hf values may be related to a different tectonic regime and could reflect continental collision (e.g. Collins et al., 2011).

The mafic cobbles from the ~300 Ma Dwyka diamictite give U–Pb ages of 1123–1111 Ma, coeval with dolerites of the Umkondo LIP (Paper II). They show many similarities to the Umkondo LIP dolerites and the coeval Rouxville Formation, an upper unit of the Koras Group. Outcrops of Umkondo LIP-related rocks are widespread over the entire Kalahari Craton (e.g. Hanson et al., 2004a) and extrusive rocks are found as far west as the Opdam tholeiitic basalts in Namibia as (Becker et al., 2006). Sub-surface occurrences of Umkondo LIP rocks are believed to be present below the Kalahari sands in the Rehoboth Province. Despite the Dwyka cobbles being

geochemically similar to the Umkondo LIP dolerites, they also exhibit important differences such as being affected by pre-Dwyka greenschist facies metamorphism or hydrothermal alteration, hinting at a fault-dominated setting. Therefore the most likely sources for the cobbles is the mafic intrusives and lavas along the Kalahari Line, southern equivalents of the ~1.11 Ga Tshane and Xade complexes (Key and Mapeo, 1999; Hanson et al., 2004b) or other intrusive and extrusive mafic units related to the Umkondo LIP, now concealed beneath the Kalahari sands.

7. Concluding remarks

The crustal evolution of the Rehoboth Province has been difficult to construct due to the extensive Kalahari sand cover. Therefore the timing of amalgamation between the Rehoboth Province and the Kaapvaal Craton has been the subject of much debate. A few views are that the collision was caused by an older Palaeoproterozoic ca. 1.8 Ga orogenic event (Cornell et al., 1998), or between 1.93 and 1.75 Ga (Tinker et al., 2004). Another idea is that it represents a northern branch of the ~1.2 Ga Namaqua-Natal Province (Moen, 1999; Moen and Armstrong, 2008). From the results in Paper I and II it is clear that there is no evidence for either scenario east of Rietfontein and it is proposed that the Rehoboth Province was already attached to the Kaapvaal Craton during an earlier event. Based on papers I, III and IV we envisage that the Rehoboth Province consists of an Archaean core supplemented by Palaeoproterozoic granitoids, which was joined to the Kaapvaal Craton at an early stage of crustal development and played an important role during later tectonic events. This occurred most likely after the deposition of the Ongeluk lavas at 2200 Ma and before the Bushveld event at 2050 Ma, followed by basin formation between the two crustal blocks. The Olifantshoek Group was possibly deposited in this basin at about 1.93 Ga and Groblershoop Formation may have formed between 1880-1850 with sediments derived from either the Kaapvaal Craton or the Rehoboth Province followed by a period of magmatic quietness until 1400 Ma (Wilgenhoutsdrift detrital zircons, Pettersson et al., 2007).

During the early Namaqua rifting at 1350 Ma, a passive margin formed approximately along the line which later became the Namaqua Front. Subduction started at 1300 indicated by the opening of the Wilgenhoutsdrift back-arc basin, closed by the <1200 collision in which the Groblershoop Formation was partly overthrust, metamorphosed, then rapidly exhumed due to transpressional movements, with different domains within the Kaaien Terrane acting independently.

The Rehoboth Province is thus revealed as an ancient crustal block with Archaean foundations, major Palaeoproterozoic events involving mantle additions mixed with reworked Archaean crust, and involving a number of different tectonic settings along its margins up to Mesoproterozoic times. Finally, it was incorporated as a stable part of the Kalahari Craton at the end of the Mesoproterozoic Namaqua Wilson Cycle. During Neoproterozoic times a small area along the northern margin of the Rehoboth Province was thrust up during the Damara Orogeny resulting in the Rehoboth Basement Inlier.

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