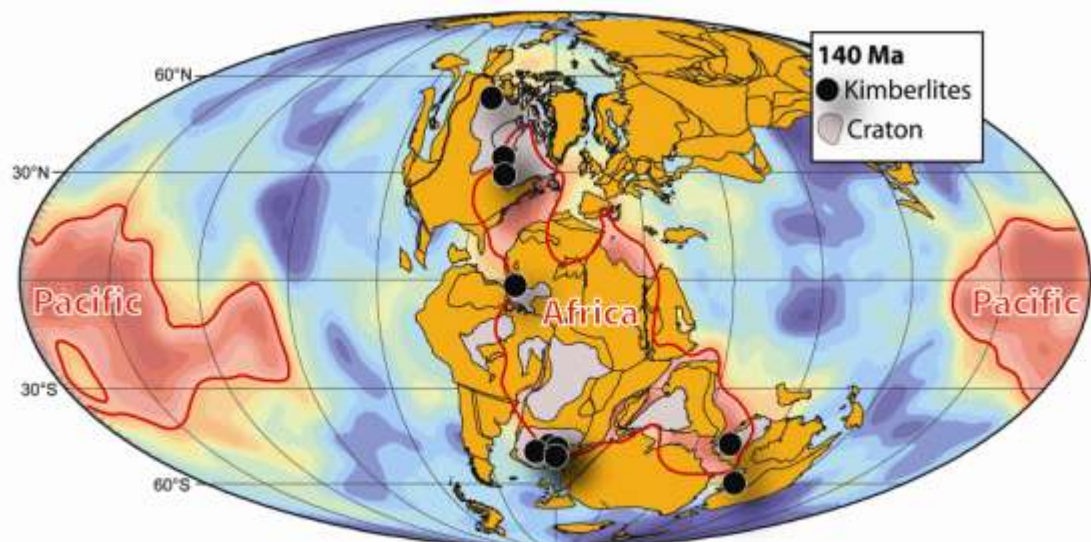




Out of Africa: 140 years with Kevin Burke and Lew Ashwal

15-18 November 2009, University of the Witwatersrand, Johannesburg, South Africa



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15 to 18 November 2009 at the University of the
Witwatersrand, Johannesburg, South Africa

The organising committee:

Trond Torsvik (PGP Oslo/NGU Trondheim)
Sue Webb (Wits Johannesburg)
Susanne Buitter (NGU Trondheim)
Stephanie Werner (PGP Oslo)
Carmen Gaina (NGU Trondheim)

Abstract book: Susanne Buitter and Sue Webb

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PROGRAMME MONDAY 16 NOVEMBER

09:00 – 09:10 Welcome by **Roger Gibson** (University of the Witwatersrand)
09:10 – 09:20 Welcome by the organisers

(Chair: Carmen Gaina)

09:20 – 09:50 **Thomas Jordan (keynote):** Implications of the Strong Isopycnic Hypothesis for Cratonic Evolution

09:50 – 10:05 **Jörg Ebbing:** The lithospheric structure of Northern Africa from seismological constrained gravity inversion

10:05 – 10:20 **Susan Webb:** Magnetic studies of the Bushveld Complex

10:20 – 10:35 **Manoj K. Pandit:** A synopsis of recent contributions on the Neoproterozoic tectonic evolution of NW India

10:35 – 11:00 Coffee break

(Chair: Sue Webb)

11:00 – 11:15 **Colin Reeves:** The Bouvet Hotspot, South Patagonia and the initiation of Gondwana Dispersal

11:15 - 11:30 **Torgeir Andersen:** Early-Alpine subduction between Africa and Europe: Earthquakes and Metamorphism on an extremely cold geotherm

11:30 – 11:45 **Grant Bybee:** Alaskan-Uralian Intrusions in Africa and their Tectonic Significance

11:45 – 12:00 **Louise Coney:** The Bosumtwi impact structure, Ghana: Deep drilling unravels the formation and history of a well-preserved young impact crater

12:00 – 12:15 **Iain McDonald:** Distribution of meteoritic material in the Morokweng crater, South Africa: an unique African impact

12:15 – 13:30 Lunch

(Chair: Colin Reeves)

13:30 – 14:00 **Maarten de Wit (keynote):** New stratigraphic & volcanic architecture of the Onverwacht Suite, Barberton Greenstone Belt, South Africa: Fresh ferment for Mid-Archean tectonic models

14:00 – 14:15 **Richard Viljoen:** Discovery of Komatiite – the 40th Anniversary

14:15 – 14:30 **Carl Anhaeusser:** Archean layered ultramafic complexes and volcano-sedimentary cyclicity in komatiite flow sequences at Schapenburg, Barberton Mountain Land, South Africa

14:30 – 14:45 **Jay Barton:** The Source and History of the Sand River Gneisses, Limpopo Belt, South Africa

14:45 – 15:10 1 minute poster presentations

15:10 – 16:15 Coffee break and Poster session

(Chair: Louise Coney)

- 16:15 – 16:30 **Roger Gibson:** New Constraints on Mesoarchean Crustal Development in the Vredefort Dome, South Africa: Quantitative Phase Equilibria Modeling in THERMOCALC
- 16:30 – 16:45 **Grant Cawthorn:** Emplacement Geometry of the Pilanesberg Complex, South Africa
- 16:45 – 17:00 **Laurence Robb:** Polyorogenic tectonic setting for gold mineralization in Nigeria
- 17:00 - 17:15 **Tony Naldrett:** Platinum-group Elements in the chromitites of the Bushveld Complex: New evidence on how the PGE got there
- 17:15 – 17:30 **Stephen Haggerty:** Deep carbon repositories: Evolution and dynamics

PROGRAMME TUESDAY 17 NOVEMBER

(Chair: Trond Torsvik)

- 09:30 – 10:00 **Kevin Burke (keynote):** Is Plate Tectonics being forgotten?
- 10:00 – 10:15 **Hans Thybo:** Magmatism and continental rifting
- 10:15 - 10:30 **Allan Wilson:** The 3.0 Ga Pongola Supergroup – the world's oldest continental rift or the world's oldest continental margin?
- 10:30 – 10:45 **Matt Rowberry:** Widespread denudation and uplift within a passive continental setting: geological and geomorphological insights into the late Mesozoic and Cenozoic evolution of southern Africa
- 10:45 – 11:15 Coffee break

(Chair: Susanne Buiter)

- 11:15 – 11:30 **Leigh Royden:** Late Cenozoic evolution of the Hellenic system
- 11:30 – 11:45 **Douwe van Hinsbergen:** Geological expressions of subduction, collision, delamination and slab break-off in western Turkey: a record of a continuous process
- 11:45 – 12:00 **Irina Artemieva:** How representative are mantle xenoliths?
- 12:00 – 12:15 **Nico de Koker:** Physics of Silicate Melts at Deep Mantle Conditions
- 12:15 – 12:30 **Jan Kramers:** Is the D'' layer a very early sunken mafic crust? Problems solved and new ones created.
- 12:30 – 12:45 **Trond H. Torsvik:** Diamonds sampled by plumes from the core-mantle boundary
- 12:45 – 14:00 Lunch

(Chair: Sharad Master)

- 14:00 – 14:30 **Celâl Şengör (keynote):** The Palaeo-Tethys and the Permian extinction: problems of tectonics and palaeontology
- 14:30 – 14:45 **Carmen Gaina:** The African plate: an overview of plate tectonic forces since the Jurassic
- 14:45 – 15:00 **Bernard Ingram:** The Palaeoproterozoic Transvaalide Orogeny
- 15:00 – 15:15 **Susanne Buiter:** The uplift of the Atlas Mountains
- 15:15 – 16:15 Coffee break and Poster session

(Chair: Stephanie Werner)

- 16:15 – 16:30 **Bjørn Jamtveit:** From Africa with vents
- 16:30 – 16:45 **Chris Harris:** Origin of low $\delta^{18}\text{O}$ magmas in South African large igneous provinces
- 16:45 – 17:00 **Luke Longridge:** Constraining the timing of deformation, metamorphism, and crustal recycling in the Central Zone of the Damara Orogen, Namibia
- 17:00 – 17:15 **Trishya Owen-Smith:** Petrogenesis and mode of emplacement of the Doros Complex, Namibia, with implications for early Cretaceous continental reconstruction
- 17:15 – 17:30 **Terence McCarthy:** The pre-Karoo geology of the southern portion of the Kaapvaal Craton
- 17:30 – 17:45 Closing remarks

POSTER PRESENTATIONS

Carla Braitenberg: Gravity-gradient fields in mapping unknown structures of the African plate

Susanne Buiter: Could subsidence in the Congo Basin be caused by the interplay of lithosphere deformation and mantle flow?

Natalie Deseta: Structural constraints on the generation of ultramafic pseudotachylites from Cima di Gratera, Corsica

Jörg Ebbing: The lithospheric structure of Northern Africa from seismological constrained gravity inversion

Morgan Ganerød: Paleoposition of the Seychelles continent in relation to the Deccan Traps and the Plume Generation Zone in KT boundary time

Ashley Gumsley: Towards establishing a ‘bar code’ for the southeastern terrane of the Kaapvaal Craton in northern KwaZulu-Natal, South Africa

Bart Hendriks: African 30 Ma and younger volcanism and its relationship to the Plume Generation Zone

Antje Kellner: Deformation of the forearc wedge along the obliquely convergent Chilean margin

Nico de Koker: First principles computations of lattice thermal conductivity at high P and T: Implications for CMB heatflux

Nico de Koker: Self-consistent thermodynamic description of silicate liquids

Cinthia Labails: Insights on the deep structure of the conjugate East African and Madagascan margins

Sharad Master: Neoproterozoic DARC's in the Damara-Lufilian-Zambezi and Ubendian belts and the Western Rift Rise- relics of Rodinia fragmentation at 750 ± 50 Ma.

Iain McDonald: Geochemistry of 2.63-2.49 Ga impact spherule layers in Western Australia and South Africa.

Sergei Medvedev: Estimations of stresses within the African Plate

Leone Melluso: U-Pb ages, Pb-Os isotopes and PGE composition of Mailaka picritic basalt to rhyodacite volcanic sequence, West-Central Madagascar LIP

Colin Reeves: The Bouvet Hotspot, South Patagonia and the initiation of Gondwana Dispersal

Anika Solanki: A geochronological, geochemical and petrographic study of granitoids from the Mt. Abu pluton and surrounds, SW Rajasthan, India.

Valby van Schijndel: New microbeam zircon dating insights on migmatites of the former Mooirivier metamorphic complex and the Neuhof formation, Sinclair group, Namibia

Marek Wendorff: Rodinia breakup and Gondwana assembly in the Lufilian Arc, Central Africa: new tectonic stages revealed by syntectonic conglomerates

Stephanie Werner: The Lunar rayed-crater population – Characteristics of the spatial distribution and ray retention

Kevin Burke and Lew Ashwal: The Big Picture

Trond Torsvik, Susan Webb, Susanne Buitter, Stephanie Werner, Carmen Gaina (the Organizing Committee at the Geological Survey of Norway, University of Oslo and the University of the Witwatersrand).



Kevin Charles Antony Burke was born on November 13th 1929 at about 4:00 pm on a Saturday afternoon in London (England), and just few weeks after the collapse of the New York Stock exchange. He was a Goldsmid Scholar at University College London, where he earned a B.Sc. in 1951 and a Ph.D. two years later. His first position in 1953 was Lecturer at the University of Gold Coast, followed by a 5-year stint as a geologist and later senior geologist with the British Geological Survey. For two decades (1961-1981), Kevin held university teaching and research positions in Ghana, Korea, Jamaica, Nigeria, the United States and Canada. He met and worked with Tuzo Wilson at the University of Toronto in the early 1970s, an obvious turning point in Kevin's career. Perhaps his most important position was as professor and chairman of the Geology Department at SUNY Albany 1973-1982. The department that he put together and the science that emerged in that period had a profound influence on reshaping modern geology.

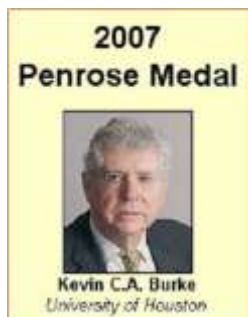


In 1983 Kevin moved to the University of Houston, and for 5 years he served as Director of the Lunar and Planetary Institute (LPI), where, among other things, he coordinated the Early Crustal Genesis Project, a NASA-sponsored partnership between the planetary and geological science communities. It is difficult to fully appreciate the impact that he had in revitalizing LPI and emphasizing the importance of understanding the early history of our own Planet. Between 2000 and 2004 he shared his time between the University of Houston and the Carnegie Institution of Washington where he concentrated on the geology and tectonics of Africa, Asia and the Caribbean. Since 2002 he has been an Honorary Professor at the School of Geosciences at the University of the Witwatersrand where he has been teaching Plate Tectonics and African geology during their winter months. Since 2004, still maintaining his position at Houston at the age of 80 and lecturing every spring, Kevin now enjoys half his time at the Earth, Atmospheric and Planetary Sciences Department at MIT.

Kevin has made fundamental and lasting contributions to our understanding of the origin and evolution of the lithosphere, on Earth and other planets. His influence has been grand and global in its reach, and as a synthesizer of global geology and global geological processes, Kevin has few peers. It is almost impossible to quantify the breadth of his innovation and knowledge, from the oldest remnants in the Archean to those ongoing today.

It was Kevin Burke who coined the term “Wilson Cycle” for the succession of continental rifting, subsidence and ocean opening, initiation of subduction and ocean closure, and eventual continent-continent collision. He quickly recognized that the continents would hold the record of plate interaction in deep time and in the early 1970's in conjunction with John Dewey he wrote a series of papers that fundamentally changed the way we think about the formation of continental lithosphere in general and Precambrian lithosphere in particular. Kevin was a pioneer in suggesting that Precambrian orogens like the Grenville are the eroded products of Himalayan-style collisions. He was the first to propose that the Archean

auriferous Witwatersrand sedimentary sequence is a foreland basin. He also proposed in the early 1970's that greenstone belts, present in nearly all Archean regions, are allochthonous volcano-sedimentary packages originally formed as marginal basins, ocean islands, and arcs and were later thrust onto older continents. Kevin continues to critically evaluate the question of whether plate tectonics operated in the Archean.



Listing all of Kevin's contributions to geology is almost impossible; they cover a great variety of topics, including: models of the birth of rift valleys; ocean basins; vast areas of collision-related basement reactivation; influence of oceanic plateaus on the evolution of oceans and continental margins; the nature of the Archean and Proterozoic tectonics and related environments; tectonic controls on basaltic volcanism; the nature of mantle plumes and their relations to hotspots; how tectonic processes interact with the hydrosphere and atmosphere and how they act on other rocky planets such as Mars and Venus. The Penrose Medal, awarded by the Geological Society of America for outstanding original contributions in the science of geology, was presented to Kevin in 2007.

Kevin Burke never stops to amaze the Earth Science community with his innovative and provocative ideas. Over the last six years he has re-energized his long-lasting interest in mantle plumes: In 2004 Kevin discovered that large igneous provinces for the past 200 million years must have originated as plumes from the edges of the seismically slower shear-waves and stable parts of the deepest mantle near the core-mantle boundary. This surprising observation implies that deep mantle heterogeneities have not changed much for hundreds of millions of years. Recognizing long-term stability of lower-mantle structures and the corresponding parts of the gravity field also fundamentally influences our thinking of how the Earth's moment of inertia and rotation may have changed over geological times.

We would be remiss if we didn't mention Kevin's presence at scientific meetings. Many of us since student days have watched Kevin sit in the front row of a session and proceed to stimulate the often-reticent audience into animated discussion. In addition, Kevin never allows a missing speaker to derail a good session and he has occupied many unscheduled vacancies by delivering his own ideas and questions and encouraging discussion. Kevin is generous with his time and is as ready to discuss science with a graduate student as he is with a member of the National Academy.



Lewis David Ashwal was born November 16th 1949 in New York City (USA), the day after Nathuram Godse and Narayan Apte were executed for assassinating Mohandas Gandhi. Lew was a 1961 graduate of DeWitt Clinton High School in Bronx and earned a B.S. in 1971 from the State University of New York at New Paltz. Later, he received a M.Sc. (1974) from the University of Massachusetts and four years later a Ph.D. from Princeton University (1979). The topic of Lew's Ph.D. thesis was *Petrogenesis of massif-type anorthosites* and he would later become the world leader in the understanding of the origin of anorthosites, a subject of heated theoretical debate for many decades. His first position from 1978-1980 was postdoctoral research associate at NASA, Johnson Space Center, followed by 9-years as staff scientist at the Lunar and Planetary Institute in Houston. In this period he was also a visiting lecturer at Yale

University (1983-1984) while enjoying a leave of absence from the Lunar and Planetary Institute.

Lew has made fundamental contributions to petrology, mineralogy and geochemistry of anorthosite and related rocks, layered mafic intrusions, origin and evolution of planetary crusts, Precambrian geologic history, origin of magmatic ore deposits, role of fluids in igneous and metamorphic processes, meteorites and their parent bodies, abundance and distribution of crustal radioactivity, thermal and petrologic aspects of granulite metamorphism; geology of Madagascar and other Indian Ocean continental fragments, Rodinia supercontinent and Gondwana assembly and break-up.



Meteorites and their parent bodies occupied Lew's mind in the late seventies and early eighties. By the process of elimination, like an excellent Sherlock Holmes story, Chuck Wood and Lew, in a 1981 groundbreaking paper, suggested that meteorites of the so called SNC group (Shergottites-Nakhlites-Chassignites) were derived from a differentiated planetary body, and most likely Mars. The difficulty of blasting material off a planetary surface and into an Earth-crossing orbit made planets like Venus and Mercury as unlikely sources, and chemical comparisons with Lunar samples (collected by the Apollo missions) also eliminated the moon as a potential source; Mars remained the only viable possibility. Lew and colleagues published a follow-up manuscript in 1982 where they demonstrated that petrologic, geochemical and isotopic evidence were inconsistent with an asteroidal origin, and concluded that Mars remained the most likely parent body for SNC meteorites; they were later proven correct.



During the Lunar and Planetary Institute period (1980-1989), Lew clearly interacted with his boss (Kevin), but they only wrote one paper together, relatively unrelated to the moon and planets but instead on African lithospheric structure, volcanism and topography (1989). Lew was also busy with his musical career and between 1985 and 1990 he had his own band, originally named *The Bodybag*, but that was too rough, and so it later simply became *The Bags*.

In 1990, at age 41, and at the same time as Margaret Thatcher, the only female Prime Minister of the United Kingdom resigned, Lew was fully fledged and was geared up for his first permanent job as Professor of Geology at the Rand Afrikaans University (RAU), Johannesburg, South Africa. He served RAU with distinction for more than 10 years, but in 2001 he moved across the road to the School of Geosciences at the University of the Witwatersrand, where he is an enduring Professor and Director of the African Lithosphere Research Unit. Lew has received the Jubilee Medal (Geological Society of South Africa), he is an elected member of the Academy of Science of South Africa, elected Fellow of the Geological Society of South Africa, and has been awarded the Academic colours by the Student Council (Rand Afrikaans University).

Lew has written several books and hundreds of scientific papers, reports and essays, and listing all of his contributions to geology is undoable. Almost 20 years in Africa has been rewarding for Lew, both scientifically and privately, and his breathtaking book on anorthosites in 1993 must clearly be regarded as one of his scientific highlights. We would be negligent if we did not mention Lew's genuine passion for Africa, not only for her geology

but also for her inhabitants, as a student educator Lew is legendary and many South African students have not only experienced fieldwork with Lew in South Africa, but also many exotic places in the Indo-Atlantic realm. Lew is extremely generous with his time (and money) and many of us have experienced uncultivated parties in Melville.



Lew and Kevin have remained friends and colleagues since the Lunar and Planetary Institute days in the 1980's, they still work, converse and passionately argue with each other. Both have enjoyed great scientific success in diverse scientific fields. They have collaborated on projects probing into the world's oldest rocks, the deep continental crust and global characterization of the ancient continents and lithosphere. Joint papers cover diverse subjects such as characterization of

terrestrial anorthosites, lithospheric delamination on Earth & Venus, African lithosphere structure & volcanism, identification of old sutures guided by deformed alkaline rocks & arbonatites, Proterozoic mountain building, and most recently, plumes from the deepest mantle. Many more papers are likely to appear in the coming years and we wish them a happy 140th birthday.

Early-Alpine subduction between Africa and Europe: Earthquakes and Metamorphism on an extremely cold geotherm

Torgeir B. Andersen (1), Erling Krogh Ravna (2), Håkon Austrheim (1), Laurent Jolivet (3), Sergei Medvedev (1) and Timm John (1)

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2) Department of Geology, University of Tromsø, Norway

3) Université Pierre and Marie Curie, Paris 6, France

The crystalline basement of the Adriatic plate (Austro-Alpine nappes) as well as the Pre-Alpine South-European margin are both peri-Gondwanan terranes and standard plate-reconstructions show that they were parts of the northern Gondwanaland until the Early Devonian when they rifted off and came ‘*out of Africa*’.

Here we present new results and discoveries from the much visited and well-exposed blueschist- to eclogite facies subduction complex of the Cape Corse region of Corsica. The high-pressure rocks formed when Early-Alpine convergence between the Adriatic plate and the European margin commenced within the narrow Alpine Tethyan basin. This small ocean basin, in which ‘Ligurian’ ophiolites and deep-marine sediments originated, formed by large magnitude continental extension exhuming continental mantle lithosphere and was also associated with local oceanic spreading in the Jurassic. The Ligurian ophiolites were already ~100 million years old, cold and heavy by the onset of the Alpine convergence. This slow convergence resulted in subduction of the Tethyan oceanic crust as well as deep burial of parts of the European continental margin-rocks, now seen as blueschist- to eclogite facies ophiolites and jadeite bearing granitoids in the Sera del Pigno Unit, respectively.

A new *lawsonite-eclogite* locality in the much visited excursion locality at Défilé de Lancone of Cape Corse is described here for the first time. The lw-eclogite is locally very well preserved. The lw-eclogite facies minerals statically overgrow the primary igneous minerals. The eclogite is only preserved in the cores of well-preserved pillows in the meta-basalts, which are otherwise dominated by the blue colours of the blueschist facies minerals. The eclogite is post-dated by a normal garnet-lawsonite bearing blueschist facies assemblage (T-400⁰C; P_{min}-1.1GPa) and a late greenschist assemblage described by previous workers in the area. The geotherm during formation of the lw-eclogites studied by us was very cold and close to the “*forbidden zone*” (~5⁰C/km) with a temperature of only ca 350⁰C at 2.4 GPa peak pressure (Ravna et al. submitted, JMG).

By analogy to modern subduction zones, the exhumed high-pressure rocks of Corsica were strongly affected by co-seismic deformation evidenced by *pseudotachylites* (PST). We have identified hundreds of small (mm) and large (5-15cm) subduction-related PST fault and injection veins in both crust (gabbro) and mantle (peridotite) rocks in the ophiolite of the Cape Corse region. Most of the PST veins have been identified near the palaeo-Moho of the ophiolite. Extreme heating took place during seismic faulting and melting in the peridotite. The thermal energy required to form mafic and ultra-mafic PST can be used to determine the minimum stress-drop during seismic faulting. Because the radiated seismic energy is very small compared to the heating, we obtain much larger (order-of-magnitude) stress-drops than estimates based on seismology. We have used these high stress-drop-estimates to model and present an alternative mechanism to the commonly used dehydration embrittlement for intermediate to deep earthquakes. This new mechanism is referred to as “self-localizing thermal runaway” and is more favourable than ‘Byerlee-law’ faulting since it requires lower failure stresses for a number of conditions in subducting lithosphere.

Archaean layered ultramafic complexes and volcano-sedimentary cyclicity in komatiite flow sequences at Schapenburg, Barberton Mountain Land, South Africa

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Economic Geology Research Institute, School of Geosciences, University of the Witwatersrand, Johannesburg, South Africa

Mafic and ultramafic rocks of komatiitic affinity are distributed in a variety of geological settings in the ~3.5-3.2 Ga Barberton granite-greenstone terrane, South Africa. They occur (1) as komatiitic and high-Mg basaltic extrusives, developed throughout the stratigraphic column of the Barberton greenstone belt, but particularly in the lowermost formations of the Onverwacht Group; (2) as multiple compound cooling units in some greenstone xenoliths, such as Schapenburg; and (3) as ultramafic-mafic intrusions generally displaying pronounced magmatic differentiation and cyclical layering.

This paper highlights some of the more important relationships displayed by a cyclically repetitive volcano-sedimentary assemblage of komatiites, basaltic komatiites, and silicate-facies iron formations found in the Schapenburg greenstone remnant, located 30km south of the Barberton greenstone belt. Cyclic units, of which more than 20 have been identified, mostly consist of aphyric as well as spinifex-textured komatiite lava flow sequences or interlayered olivine-pyroxene cumulates. These rocks are overlain, in turn, by basaltic komatiites and metatuffs, the latter generally capped by thin layers of banded grunerite-chert iron formation. Sharp contacts separate the above rock types and evidence for structural repetition of the cyclical units is lacking. It is suggested instead that the alternating or cyclical extrusion of komatiites and komatiitic basalts resulted from a sill-like mafic magma chamber below being replenished from time to time by plume-related olivine-rich magma, some of which may have been expelled together with alternating pulses of basaltic magma.

By contrast the intrusive layered ultramafic complexes found in the Barberton greenstone belt consist of cyclically repetitive units of cumulus dunite, orthopyroxenite and harzburgite, and volumetrically subordinate websterite and anorthositic gabbro-norite units. Bulk compositional estimates have yielded high magnesian values (30.7-35.7 MgO%) comparable to those of neighbouring aphyric and spinifex-textured komatiite lava flows and thin porphyritic komatiite sills. The Barberton layered ultramafic complexes are interpreted as cumulative, gravitationally differentiated, sill-like intrusions injected penecontemporaneously into the developing pile of mafic and ultramafic lava flows. Other large-sized bodies appear to be the remnants of exhumed magma chambers that may once have acted as staging points for the periodic distribution of fractionated komatiitic and high-magnesian basaltic melts into the developing volcanic pile.

How representative are mantle xenoliths?

Irina M. Artemieva

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I use geophysical constraints to argue that xenolith data on densities and seismic velocities in the Archean-Proterozoic lithospheric mantle (LM) maybe non-representative of the intact (= unsampled by mantle-derived peridotite xenoliths) cratonic mantle. The first example (Artemieva, 2009) is based on the analysis of seismic velocity variations in the continental LM constrained by global seismic tomography models (S. Grand, 2002; N. Shapiro and M. Ritzwoller, 2002) which are corrected for lateral and vertical temperature variations. The resulting V_s velocity variations of non-thermal (compositional) are used to constrain 2D profiles through the cratonic LM of Europe, China, North America, Australia, and South Africa. In agreement with xenolith data, strong positive velocity anomalies of non-thermal origin (attributed to mantle depletion) are determined for all of the cratons. However, in kimberlite provinces cratonic LM has much weaker positive compositional velocity anomalies than the adjacent "intact" cratonic mantle, implying that (pre-)kimberlite magmatism has melt-metasomatised the cratonic LM. Another example (Kaban et al., 2003) is based on the results of global gravity modeling in which the effect of spatially differential thermal expansion has been eliminated from mantle residual gravity (density) anomalies. These results indicate a large scatter of density deficit in the cratonic lithosphere, uncorrelated with crustal differentiation ages. A comparison of compositional V_s and density anomalies with xenolith data indicates that variations in mantle densities and velocities constrained by xenolith data and parameterized solely in terms of iron-depletion are non-representative of the "intact" cratonic mantle. The discrepancy between major-element petrologic models and geophysical observations can stem from metasomatic modification of the cratonic lithosphere prior/during kimberlite magmatism. However, other factors such as underestimate of the effect of orthopyroxene on densities and velocities cannot be ruled out.

References

- Artemieva I.M., 2009. The continental lithosphere: Reconciling thermal, seismic, and petrologic data. *Lithos*, 109, 23-46.
- Kaban M.K., Schwintzer P., Artemieva I.M., and Mooney W.D., 2003. Density of continental roots: compositional and thermal effects. *Earth Planet. Sci. Lett.*, 209, 53-69.

Gravity-gradient fields in mapping unknown structures of the African plate

C. Braitenberg (1), A. Russian (1), J. Ebbing (2)

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2) Geological Survey of Norway (NGU), 7491 Trondheim, Norway, also at: Department for Petroleum Technology and Applied Geophysics, NTNU, 7491 Trondheim, Norway. Joerg.Ebbing@NGU.NO

The gradient tensor can be derived from the expansion of the gravity potential field in spherical harmonics. The recent release of the potential field up to degree and order $N=2159$ (Pavlis et al., 2008) allows to have sufficient spatial resolution to detect single structures as volcanic edifices and the density variations accompanying them. In remote areas this is a valuable tool to identify structures which are concealed below the surface. Areas involving magmatic products are of particular interest as they are generally denser than the surrounding rocks. One example is the Tibesti massif and the adjacent region, which includes several volcanoes and calderas and a series of structures which are assumed to be impact craters. Due to the inaccessibility of the region the extent of the magmatic areas in and beyond the massif is very uncertain.

We discuss which gradient components and derived quantities are most advantageous to enhance the near-surface geology. In a second step we calculate the field components and correct for the effect of topography. We find in general a good match between the known single volcanic edifices and our field analysis. In addition, our analysis indicates that some of the volcanoes are not isolated structures but connected by sub-surface high density masses. These might relate to magmatic products which extend to a greater area than the mere topographic expression. We furthermore compare the gradient fields with the present knowledge from geology and with satellite images of the region.

Reference

Pavlis, N.K., S.A. Holmes, S.C. Kenyon, and J.K. Factor, An Earth Gravitational Model to Degree 2160: EGM2008, presented at the 2008 General Assembly of the European Geosciences Union, Vienna, Austria, April 13-18, 2008.

Could subsidence in the Congo Basin be caused by the interplay of lithosphere deformation and mantle flow?

Susanne Buitter (1) and Bernhard Steinberger (2)

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The Congo Basin is a classic example of an intracratonic basin: it experienced slow subsidence over a long period of time, but a conclusive basin-forming mechanism has not been identified. The basin contains up to 9 km of unconformity-bounded sedimentary layers of Pre-Cambrian to Quaternary ages. The older sediments may have been deposited in response to thermal contraction after a late Proterozoic rift event [Daly *et al.*, 1992], but the upper 1-km thick sediment fill of Early Cretaceous to Quaternary age cannot be linked to clear basin-forming processes. Hartley and Allen [1994] have suggested that a downward dynamic force at the base of the lithosphere could explain the negative gravity anomaly over the basin and create the subsidence that allowed deposition of the uppermost sediments. The origin of this force is however an open question and points to the need to carefully consider the roles of the mantle and lithosphere in the formation of African cratonic basins.

Intriguingly, the global S-wave tomographic model of Simmons *et al.* [2006] shows a prominent fast anomaly at a depth of approximately 1000 km. This anomaly is well-resolved and unlikely to be an artefact of the tomographic model [Stephen Grand, pers. comm., 2009]. The fast anomaly may represent a high-density body which sinks in the mantle underneath the Congo Basin. This would offer a non-classic solution to the problem of subsidence in intra-cratonic basins. We speculate that this body may be a piece of lithosphere that detached from the overlying lithosphere. The delamination would first have led to an uplift signal at the surface caused by isostatic rebound, followed by subsidence caused by mantle downwelling as the detached body sinks into the mantle. As the body sinks further down, the downward directed pull on the base of the lithosphere diminishes. As the final result, subsidence is expected, because the lithosphere has been thinned by the delamination and because the load of sediments, which were deposited in the basin, will cause a surface depression.

We aim to combine processes in the deep mantle under the Congo Basin with models of lithosphere deformation and sedimentation- and erosion-processes at the surface. We will discuss observations from tomographic models and present first results of calculations of dynamic topography and simple models of lithosphere delamination.

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The uplift of the High Atlas Mountains

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The High Atlas Mountains of Morocco formed by shortening of a failed intracontinental rift which had developed in an oblique extension field associated with the opening of the Central Atlantic Ocean in the Jurassic-Triassic [Burke, 1976; Guiraud, 1998]. The duration of the postrift phase is uncertain but is likely on the order of 100 Myr, including the late Jurassic and the Cretaceous. This long postrift phase would have led to thermal equilibration and strengthening of the former rift area. The convergence of Africa and Europe in the Tertiary caused inversion and uplift of the High Atlas Mountains [Beauchamp *et al.*, 1999; Gomez *et al.*, 2000; Frizon de Lamotte *et al.*, 2000]. This indicates that the failed intracontinental rift still formed a lateral heterogeneity in the lithosphere that localised the contractional deformation, despite the long phase of postrift cooling. Inherited normal faults were reactivated in a reverse sense during the inversion, indicating that the normal faults could have helped to focus the convergent deformation [Buitter *et al.*, 2009].

The High Atlas Mountains have a high mean elevation of 2600 m with the highest peak at 4165 m, but this high elevation is underlain by an average thickness crust of not more than 40 km [Wigger *et al.*, 1992; Ayarza *et al.*, 2005] which is only a few kilometres deeper than the base of the crust of the surrounding areas. This lack of a mountain root indicates that the High Atlas are isostatically undercompensated. In combination with indications for a thin lithosphere [Seber *et al.*, 1996; Teixell *et al.*, 2005], this has raised the strongly debated question of how the elevation of the High Atlas Mountains is maintained. At least part of the uplift is caused by inversion, but several authors have argued for an additional contribution from a warm mantle source [Teixell *et al.*, 2003; Missenard *et al.*, 2006]. However, tomographic models, though admittedly of poor resolution in this region, show no indications of warm upwelling material under the High Atlas Mountains. As a contribution to the debate, I discuss dynamic models of basin formation by extension and basin inversion by contraction that show that high elevations can be maintained in contractional environments without requiring deep mountain roots.

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Is Plate Tectonics being forgotten?

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Old men are expected to lament that science is not as strong and exciting as it was in their hey-day. I like to believe (although I may be fantasizing), that I have so far escaped that fate. I think that science is now much more powerful, interesting and, certainly for me, at least as exciting as it was 40 years ago. My regret is specific. I discern a widespread lack of understanding of plate tectonics at anything more than a superficial level. I fear that the lack of appreciation of the power of plate tectonics is generating a lack of interest that is rapidly permeating the solid Earth sciences. I think that represents a tragic, and even a potentially crippling, loss for our community and our science.

There are reasons for a decline in interest: (1) When plate tectonic understanding emerged in 5 papers published in 1965, 1967 and 1968 research in seismology was generously funded because of political interest in distinguishing underground bomb-tests from earthquakes, and marine geology and geophysics were both well-funded because two nations had submarines carrying nuclear-tipped warheads sailing the world's oceans. This funding declined, particularly in the latter field, after about 1990. With that decline interest in plate tectonic research also declined. (2) Universities in the United States and Europe had loaded their faculty lists to saturation in the previous decade (1955-1965). Those professors are only now beginning to retire and die. In the four-year colleges in the USA mindsets had been established and plate-tectonics was perceived as an interesting add-on rather than as a radical change in the understanding of the Earth. Graduates of those programs who retain that attitude are now in positions of power in universities and in government. (3) Modern Structural Geology missed the boat. Appreciation of the power of understanding small-scale structures originated in Wisconsin in the 1880s and was carried to England by Gilbert Wilson in the mid 20th Century (See Dott GSA Bull.2001). It reached its acme in the work of Gilbert Wilson's student John Ramsey who exported it throughout the world including back to the United States but workers in that then and still largely dominant field were not excited by the plate tectonic revolution (See for example a standard text: Hobbs, Means and Williams 1973). (4) Isotope geochemists, who had much to offer in the plate tectonic field, were overwhelmed by the opportunities of the Apollo program and mainly studied the moon and meteorites. Igneous petrologists who also had much to offer were cowed in the early 1970s by the dominant isotope geochemists and had not yet developed opportunities to integrate the two kinds of study.

Saddest of all was the failure to take off of Tuzo Wilson's (1968) idea that plate tectonic understanding could be applied to the interpretation of the long-term history of the Earth by recognizing the existence of plate-tectonic processes far back in Earth history in the record of the life-cycle of the ocean basins which came to be called the Wilson Cycle. That was partly because Wilson's original exposition was in an obscure publication (Proc Am Phil. Soc 1968) and because his expanded version in Jacobs, Russell and Wilson (1973) attracted little interest because his fellow authors had not adjusted to the new ideas of plate tectonics. An example of failure to apply the Wilson Cycle concept is in the Barberton greenstone belt where rocks on either side of the Saddleback shear zone (which is a strike-slip fault zone) differ in age by 160 Ma. They may well have been on opposite sides of the Earth when they formed but the same "stratigraphy" continues to be applied to both sides. Practices of that kind only serve to delay understanding.

Alaskan-Uralian Intrusions in Africa and their Tectonic Significance

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Alaskan-Uralian (A-U) zoned ultramafic intrusions commonly form the roots and feeder conduits of volcanic arcs and these intrusions, first identified by Taylor (1967) in southeastern Alaska, are zoned intrusions consisting of a dunite core surrounded successively by clinopyroxenite, hornblendite and monzonite-gabbro rims. Several intrusions of this nature have been identified in Africa including the Yubdo Complex (Ethiopia; Johan, 2002), the Eastern Desert Complexes (Egypt; e.g. Ahmed *et al.*, 2008) and potentially the Kabanga-Musongti Belt (Burundi, Rwanda & Tanzania; Burke, 2003). We present petrological and geochemical data documenting a potential Alaskan-Uralian intrusive suite in the Andriamena Region of north-central Madagascar and evaluate the nature of other potential Alaskan-Uralian complexes in Africa.

The ultramafic bodies in the Andriamena region are crudely zoned, with dunite forming the cores, surrounded by harzburgite, lherzolite, pyroxenite, pegmatoidal pyroxenite and marginal fine-grained gabbroic rocks. The composition of the chilled basaltic margin of the Lavatrafo body is similar to volcanic lithologies from well-known continental arcs. This suggests that the liquid from which the differentiated Andriamena intrusions are derived has a composition similar to that of volcanics found in well-known continental Andean-type arcs, particularly in the Andes of South America. PGE data from the Lavatrafo intrusion in the Andriamena region show enrichment in the Pd-group PGEs and prominent negative Ru anomalies. These patterns are similar to A-U intrusions around the world and we propose that the generation of a negative Ru anomaly is a feature unique to magmatic arc settings.

The discovery of Alaskan-Uralian intrusions in north-central Madagascar, which has been tentatively positioned on the western margin of Rodinia at ~750 Ma provides new evidence in the form of ultramafic lithologies for an eastward-dipping subduction zone on the western margin of the Rodinian supercontinent and supports the ideas proposed by Handke *et al.* (1999), Torsvik *et al.* (2001) and Ashwal *et al.* (2002) that various continental fragments in Madagascar, the Seychelles and India (Malani Suite) represent the eroded remnants of a ~900-km-long continental arc on the western margin of Rodinia. The arc is proposed to have formed in response to subduction of Mozambique oceanic lithosphere beneath continental Rodinia as a result of rifting in central Rodinia and depending on the orientation of this rift in the southern part of Rodinia, the arc may extend into the Kalahari and Congo cratons.

When used in combination with palaeomagnetic reconstructions, the recognition of Alaskan-Uralian intrusions can provide important information regarding the geodynamic setting of poorly constrained terranes and can provide some control on the dynamics of supercontinental behavior.

Emplacement Geometry of the Pilanesberg Complex, South Africa

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The 25 km-diameter Pilanesberg Complex, South Africa, consists of felsic volcanics into which were intruded a number of syenitic and foyaitic facies. No mafic or intermediate compositions are present. It is currently considered to have formed as a series of ring dykes and cone sheets, sequentially emplaced from the centre outward, although very poor outcrop precludes identification of contact relations and dips between the different intrusive rock types [1]. Based on a number of observations and theoretical considerations of emplacement mechanisms, I reinterpret the intrusions as having been emplaced sub-horizontally, followed by subsequent centripetal subsidence. This structural reinterpretation was inspired by the revised geometry of the Ardnamurchan Complex [2], long considered the type locality for ring dykes. This overall shape for the Pilanesberg was originally proposed by Shand [3], but rejected by subsequent authors [1].

The originally described Inner and Outer Syenite are re-interpreted to be the cogenetic upper and lower marginal syenite. It was intruded by a small Red Foyaite, followed by the Inner and Outer White Foyaite, which are now considered to be the upper and lower facies of a single, inward crystallizing body. Emplacement of a number of relatively small foyaitic facies terminated the intrusive episode. A number of geochemical similarities between the two Syenite rings and the two White Foyaite rings suggest that each pair is consanguineous. However, as the White Foyaite sheet crystallized inward it liberated a fluid that caused extensive alteration of all overlying rocks, mainly the Red Foyaite, the upper White Foyaite and the volcanic rocks. Primarily, the alteration caused replacement of Na by K, a decrease in Zr, Y, Nb, Ce and La, and an increase in Ba and Rb. REE patterns in the unaltered rocks, specifically, the lack of an Eu* anomaly, and variably high Sr contents suggest that feldspars were not a significant component of the fractionating assemblage that produced these compositions. Extremely high concentrations of incompatible trace elements, the absence of any composition with more than 2% MgO and the enormous size of this intrusive complex create problems for the modeling of the genesis of the Pilanesberg Complex.

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The Bosumtwi impact structure, Ghana: Deep drilling unravels the formation and history of a well-preserved young impact crater

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The Bosumtwi impact structure, Ghana, was the subject of an interdisciplinary drilling program in 2004, conducted by the International Continental Scientific Drilling Program (ICDP). The crater was chosen as it is a young (1.07 Ma; Koeberl et al., 1997), small (10.5 km diameter) but complex structure, and is well preserved. Also, the lake sediments within Lake Bosumtwi are varved and allow the derivation of paleoclimate information over the past million years in a climatically sensitive area in the tropics for which so far only few data exist. Additionally, Bosumtwi is the source crater of one of four known tektite strewn fields (the Ivory Coast tektite strewn field; Glass et al. 1991; Koeberl et al. 1997, 2007). The purpose of the drilling was to 1) obtain a complete, 1 million-year record of the sedimentary fill and 2) to study the buried structure and crater fill of the impact structure (Koeberl et al., 2007). The cores were used to test predictions made by previously obtained geophysical data and numerical modeling studies. Prior to drilling, numerical modeling studies (based on predicted target characteristics and observations of suevites outside of the crater rim; Koeberl et al., 1998) expected a substantial volume of melt rock within the crater fill (Artemieva et al., 2004). The two hard rock cores, which have been used for impactite studies, have been assessed for their mineralogical, geochemical and geophysical characteristics (see various papers in *Meteoritics and Planetary Science*, volume 42). It has been shown that initial assumptions with regard to the predicted amount of shocked material were incorrect, as no melt sheet was intersected and shock pressures are lower for the impactites within the crater than expected (Coney et al., 2007; Ferrière et al., 2007). Drilling of the crater redefined the target rock composition: granite forms a more minor component than previously assumed (Koeberl et al., 1998); additionally, the petrographic and geochemical properties of the suevites outside of the crater differ to those within the crater (Coney et al., *in press*). The out-of-crater suevites contain a higher volume of shocked material than those within the crater. This is thought to reflect two different mechanisms for generation of the different suevites. Instead of the suevites forming from one homogeneous ejecta plume, it is thought that the within-crater suevites formed from either slumping off the crater walls or from lateral movement of material within the crater, with minor admixture from a heterogeneous ejecta plume (which produced the out-of-crater suevites).

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U-Pb ages, Pb-Os isotopes and PGE composition of Mailaka picritic basalt to rhyodacite volcanic sequence, West-Central Madagascar LIP

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The Mailaka lava succession forms the central-western part of the Madagascar Large Igneous Province (LIP). It is characterized by a sequence of basaltic lava flows and minor more evolved flows (andesites to rhyodacites). Sills and dykes cross-cut the Mesozoic sedimentary sequence just to the east. In situ U-Pb zircon geochronology for rhyodacites yields concordant ages of 89.7 ± 1.4 Ma and 90.7 ± 1.1 Ma. Therefore, the capping rhyodacitic unit of the Mailaka lava succession was emplaced contemporaneously with the underlying basalt sequence (see also Storey et al. 1995). Two geochemically different series are present. The transitional series, ranging from picritic basalts to basalts, has incompatible element abundances and Pb, Os and Nd isotopes that fall within the range of MORB (mid-ocean ridge basalts). In addition, the concentrations of PGE (< 350 ppt Ir, < 170 ppt Ru, 1000-1642 ppt Pd) in the transitional basalts are generally lower than in basaltic lavas from oceanic plateaus (e.g. Ontong Java and Kerguelen) and other continental flood basalt provinces (e.g. Deccan and Paranà-Etendeka). The tholeiitic series range from picritic basalts to rhyodacites, and have relatively high concentration of trace elements (e.g. Rb, Ba, Th and LREE), increasing Pb-Sr and decreasing Nd isotopes, characteristics of magmas that have assimilated upper continental crust. The rhyodacites have further interesting characteristics, in being peraluminous, thus cordierite- and orthopyroxene-bearing, clinopyroxene-free (Melluso et al. 2001), and have also inherited cores of the magmatic zircons indicating Precambrian ages. On the other hand, bulk-rock Pb isotope ratios of tholeiitic andesites found in the middle of the lava sequence, indicate involvement of a component depleted in radiogenic Pb, very likely old lower crust. EC-AFC modeling indicate that the rhyodacites may have the result of $\sim 25\%$ assimilation of upper continental crust with mass assimilated/mass cumulated ratio of ~ 0.35 . Tholeiitic andesites with low $^{206}\text{Pb}/^{204}\text{Pb}$ may have the result of assimilation of $\sim 8\%$ of lower continental crust with mass assimilated/mass cumulated ratio of ~ 0.1 . Therefore, interaction of mantle-derived magmas with differently reworked portions of the Madagascan continental crust is believed to be a significant petrogenetic process. This does not mean that interaction occurred at different levels in the crust, given the folded and thrust structure of the Madagascan basement. The data give further evidence that flood basalt sequences which are located on similar crustal domains (e.g., the Deccan Traps) may well have experienced interaction with crustal materials having different ages and petrogenetic histories (cf. Peng et al., 1994; Melluso et al., 2006).

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Physics of Silicate Melts at Deep Mantle Conditions

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The chemical history of the Earth is closely tied to its thermal history through fractionation during cooling of a magma ocean and melting of the mantle. Partial melting of the shallow mantle and lower crust associated with volcanism is but one of several settings where silicate liquids are present and play a central role. Seismic studies suggest that partial melt may in places overlie the 410 km discontinuity and the core-mantle boundary (Revenaugh and Sipkin, 1994; Williams and Garnero, 1996), while barometry and exolved textures in some mantle xenoliths require them to have reached the surface through melting of the transition zone (e.g. Haggerty and Sautter, 1990). Furthermore, a sufficient variety of heat sources in the early Earth have been identified to allow large parts of the mantle to have been molten to form a planetary magma ocean (e.g. Ruff and Anderson, 1980; Tonks and Melosh, 1993).

The high melting temperatures of silicate minerals, especially those of ultramafic compositions relevant to the mantle, makes experimental investigation of silicate melts very challenging. This problem is compounded at elevated pressures by restricted sample sizes, limited access to the sample for measurement, and even higher melting temperatures. While the thermodynamic properties at ambient pressure are well constrained for the majority of geologically relevant compositions (Lange and Carmichael, 1987), far less is known at high pressures, with most of our knowledge derived from shockwave experiments (e.g. Rigden et al., 1984).

First principles molecular dynamics (FPMD) simulations offer an accurate and reliable means by which to theoretically investigate the physics of melts at the extreme pressures relevant to the planetary mantle settings (e.g. Stixrude and Karki, 2005). The method is the state of the art in characterizing thermal effects in condensed phases, and is equally robust at ambient and extreme pressures, characterizing bonding directly from the electronic structure, computed via density functional theory (DFT; Hohenberg and Kohn, 1964; Kohn and Sham, 1965).

We have employed the FPMD method to study nine compositions on the MgO-SiO₂ binary (De Koker and Stixrude, 2009; De Koker et al., 2008). Using these results we developed a general, internally consistent description of silicate liquid thermodynamics, which includes electronic free energy contributions and correctly captures the limiting behavior as $T \rightarrow \infty$ or $\rho \rightarrow 0$. This description is constrained by a small number of free parameters, which can be directly related to thermodynamic properties at ambient pressure. In combination with FPMD simulations of MgO periclase, MgSiO₃ perovskite, and SiO₂ stishovite, these descriptions are used to investigate the melting phase diagram of the MgO-SiO₂ binary in the lower mantle. We also compute a variety Hugoniot loci for the ambient mineral compositions present on the join, and are able to make testable predictions for the pressures and temperatures at which melting should be observed in shock compression experiments, as well as the changes in thermodynamic properties associated with shock melting.

After adjusting the solidi for freezing point depression due to FeO, we find that the lowermost mantle eutectic composition is similar to that of the bulk mantle, with a solidus temperature of about 4500 ± 500 K. This implies that partial melt could be present in places

at the CMB today. Furthermore, combining this temperature with a reassessment of the adiabatic temperature profile of a planetary magma ocean, gives colder potential temperatures than previously thought, indicating that the entire Earth was likely molten during the later stages of accretion.

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Structural constraints on the generation of ultramafic pseudotachylites from Cima di Gratera, Corsica

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Ultramafic and mafic pseudotachylites (PST) are found within the Ligurian ophiolite of the high-pressure and low-temperature (HP-LT) metamorphic ‘Schistes Lustres’ in the Cima di Gratera area, Corsica. Ultramafic PSTs are preserved in lenses of preserved to hydrated peridotite surrounded by schistose serpentinites. Co-seismic faulting at high-stresses formed the PSTs (Andersen et al. 2008). Based on the close association with blueschist facies PST in gabbros (Austrheim & Andersen 2004), the ultramafic PSTs are assumed to have formed at blueschist facies, but exact PT-conditions during individual PST-events are not determined. Faulting probably took place at a range of PT-conditions during the Early-Alpine subduction when the ‘Schistes Lustres’ experienced initial HP-LT metamorphism (lawsonite-eclogite, 350°, 2.4 GPa, Ravna et al., in press) and subsequent exhumation on a cold geotherm to blueschist facies (400°, 1.1 GPa) and finally greenschist facies (Fournier et al. 1991). On map scale the PSTs appear to form a conjugate set: a sub-vertical and sub-horizontal pair of faults in the present frame of reference. On a smaller scale, the individual outcrops have a pattern of veins with 4 prominent orientations: 1) a principal orientation, which has the majority of the PST veins is interpreted as the generation surface. Subordinate veins include two sets of narrow veins found at angles of 2) ~30° and 3) ~45° to the principal vein orientation, and 4) injection veins at higher angles (70-90°) to the principal vein orientations. Crosscutting relationships indicate a sequence of PST generation and injection within this system; the principal vein set is oldest, succeeded by the thin veins at shallower angles. The high-angle injection veins crosscut the other vein sets and appear to be the youngest in an individual vein-generation and injection episode. These features are observed at both the outcrop and thin-section scale. Although the subordinate veins apparently have consistent orientations relative to the principal veins, these orientations are inconsistent with empirical predictions of Riedel (R, R’), and P shear orientations in fracture systems. The vein orientations are therefore difficult to fit directly with a Mohr-Colomb or Byerlee-type fracture law, and may suggest that other types of fault-mechanisms may have been important for the weakening that triggered runaway and seismic faulting (Kelemen & Hirth 2007, John et al. 2009). The poor fit with ‘normal’ fracture systems may, however, also be due to reactivations of the fault systems, re-orienting pre-existing PST veins, or generation of new PST veins with different orientations.

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New stratigraphic & volcanic architecture of the Onverwacht Suite, Barberton Greenstone Belt, South Africa: Fresh ferment for Mid-Archean tectonic models

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Synthesis of new and existing data identifies at least seven major shear zones and a major unconformity that separate the rocks of the southern Barberton greenstone belt into seven complexes with different complex geologic histories. The stratigraphic nomenclature presently applied to these sequences (e.g. formations) cannot incorporate these complexities. This requires changing the status of the traditional 'Formations' of the Onverwacht Group of the Barberton greenstone belt into 'complexes'. The complexes are referred to collectively as the Onverwacht Suite. The total age range and thickness of the suite is about 120 million years and 15 km, respectively, but the precise age ranges of each complex and their original thicknesses remain unknown. All the complexes include significant volumes of intrusions into their volcanic and volcanoclastic host rocks. The ages of the intrusions of the different complexes are different. In some complexes the intrusions and volcanic rocks have similar if not identical geochemistry, and are co-magmatic. Others provide 'stitching' ages between complexes. Six of the complexes have ophiolite-like affinities that suggest the complexes formed predominantly in oceanic spreading- and intraoceanic arc- environments with water depths of 2-4km. The complexes are tectonically stacked and the original spatial relationships between them can only be inferred in most cases.

At least one complex was uplifted by 2-4 km between about 3470 and 3460 Ma, giving a minimum uplift rate of some 2-4 mm/yr, similar to that in modern subduction zones and during emplacement of Phanerozoic oceanic crust as ophiolite complexes. Overlying coarse clastic sediments overlap in age with about 15 myrs of felsic-intermediate igneous activity dated between 3460 to 3445 Ma, that, in turn, relate in age to the intrusion of the tonalite-trondjemite plutons to the south of the greenstone belt. These sediments may therefore represent a sequence deposited in a tectonic basin associated with subduction and obduction processes. The emergence of the deep water complex above sealevel and the onset of subaerial clastic sedimentation (> 3455 Ma) probably best represents the start of obduction of the lowermost Onverwacht complexes across the older complexes (>3.5 Ga) that are now only preserved as remnants in the surrounding granitoid terranes.

Timing of a second major episode of subduction/accretion, dominated by folding, thrusting and exhumation of the Barberton greenstone belt, occurred between 3.230 -3.140 Ma. Early minimum cooling rates during more than 18 km unroofing were in the order of 1.5-5 mm/yr, similar to those recorded in modern orogenic zones. Oblique convergence ended in collision and strike-slip displacements around 3.1 Ga. The deposition of the Moodies Group sandstones and conglomerates has been linked to this period of deformation, again at rates comparable to those measured in modern orogenic belts and transcurrent plate boundaries. Thus within all crustal regimes for which reasonably robust rates of tectonic processes can be determined, these rates are similar to within an order of magnitude as those encountered today. By 3.0 Ga the region was part of a rigid peneplained continent.

The lithospheric structure of Northern Africa from seismological constrained gravity inversion

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Seismic information on the crustal structure of Northern African is relatively sparse. In southern Africa a series of seismic data has been acquired over the last decades, while in the central and northern part of Africa only few regional experiments have been carried out away from the East African Rift. In previous Moho depth estimates for Northern Africa, the depth estimates are based for large areas on gravity inversion and geological reasoning, e.g. West African Craton. The Moho depth estimates from such a method are relatively stable around 35 km depth, showing almost no local variations where seismic data are absent. Here, we analyze the effect of sub-crustal anomalies on the gravity field and consequently on Moho depth estimates.

For large scale gravity modeling it is important to consider the full thickness of the crust and possible mantle contributions as these contributions are of similar wavelength. To test the contribution of density variations in the mantle to the gravity field, we qualitatively evaluate the effect of compositional and temperature effect on mantle velocities and densities. In general, it is assumed that temperature and pressure exhibit the main control on velocity – density relationships (increase temperature, decrease density). Recent studies do however show the significance of compositional changes on the mantle densities. We use a recent shear-wave velocity model and convert it to a density model for the two cases: (1) In the temperature dominated case, we assume that an increase in velocity indicates also an increase in density. (2) In the compositional dominated case, we assume that an increase in velocity leads to a decrease in density. Both models show a long wavelength gravity field, which enhances the West African Craton and significantly changes Moho depth estimates by up to 8 km.

Without sufficient information on the deep structure it is difficult to distinguish between the effect of temperature and composition on sub-crustal domains. Comparison between velocity and conductivity might be used to differentiate between the two-end member models.

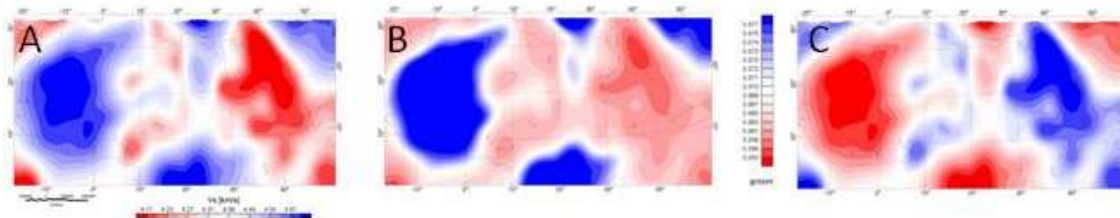


Figure 1 Velocities and density distribution in 150 km depth A) Shear-wave velocities, B) Densities from velocities assuming temperature control, C) Densities from velocities assuming compositional control.

The African plate: an overview of plate tectonic forces since the Jurassic

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Initially part of Gondwana and Pangea, and now surrounded almost entirely by spreading centres, the African plate moved relatively slowly for the last 200 million years. Yet both Africa's cratons and passive margins were affected by tectonic stresses developed at distant plate boundaries. Moreover, the African plate was partly underlain by hot mantle (at least for the last 300 Ma) - either a series of hotspots or a superswell, or both - that contributed to episodic volcanism, basin-swell topography, and consequent sediment deposition, erosion, and structural deformation. The interaction between lithosphere and mantle is playing an important role in shaping and modifying the sedimentary basins and the related hydrocarbon accumulation, but a systematic analysis of timing and effect of all these key factors upon the African plate is presently lacking.

Tectonic forces that act on the margins of a plate (mainly ridge push and slab pull) are transmitted through the plate interior and contribute to changes in regional tectonic regimes (e.g. *Cloetingh, 1988, Guiraud and Bosworth, 1997*). As the relative importance of loads applied to plate margins and plate base and those created internally can be very different from one location to another, we aim to quantify these loads for both present day and selected time frames in the geological past.

A systematic study of the African plate boundaries since the opening of surrounding oceanic basins is presently lacking. This is mainly because geophysical data are sparse and there are still controversies regarding the ages of oceanic crust. The publication of individual geophysical datasets and more recently, global Digital Map of Magnetic Anomalies (WDMAM, EMAG2) prompted us to systematically reconstruct the ages and extent of oceanic crust around Africa for the last 200 Ma. Location of Continent Ocean Boundary/Continent Ocean Transition and older oceanic crust (Jurassic and Cretaceous) are updates in the light of new data and models of passive margin formation. Reconstructed NeoTethys oceanic crust based on a new model of microcontinent evolution in this area, will be added to palaeo-oceanic grids following the method of *Heine et al. (2004)* and *Gaina and Müller (2007)*.

The new set of oceanic palaeo-age grid models constitute the basis for estimating the dynamics of oceanic crust through time and will be used as input for quantifying the paleo-ridge push and slab pull that contributed to the African plate palaeo-stresses and had the potential to influence the formation of sedimentary basins .

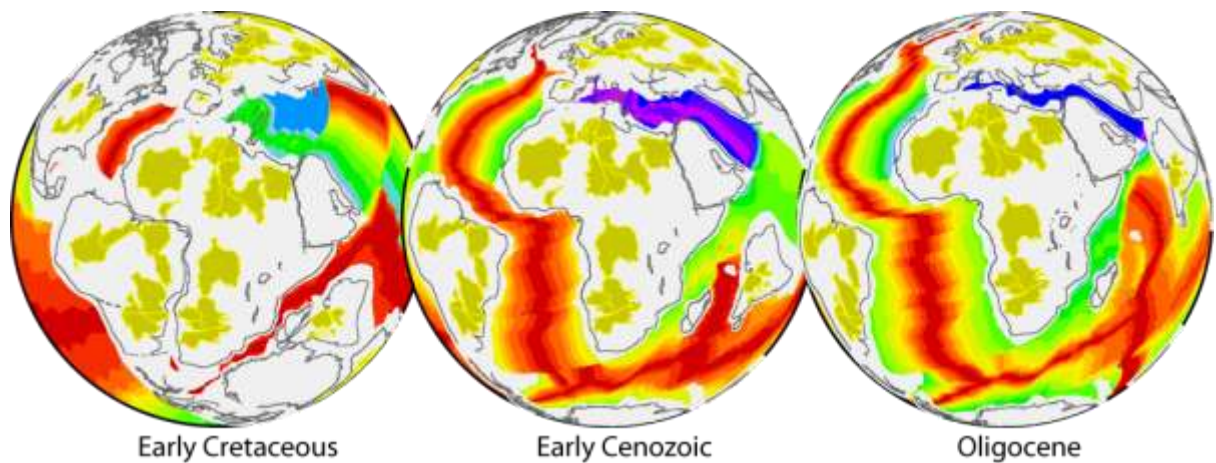


Figure 1. Palaeo-age grids of the African Plate and surrounding areas (warm colours-young oceanic crust, cold colours-old oceanic crust) and the location of selected intra-continental basins (light olive) for three time slices. Ridge push and slab pull are forces which are dependent on the age of oceanic crust, they can propagate into continental interiors and potentially affect the sedimentary basins.

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Paleoposition of the Seychelles continent in relation to the Deccan Traps and the Plume Generation Zone in KT boundary time

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The Late – Cretaceous to Early – Palaeogene magmatic rocks of the North and the Silhouette Islands in the Seychelles contain clues to the Cenozoic geodynamic puzzle of the Indian Ocean, but have suffered from low precision geochronological data and no paleomagnetic constraints. This contribution sets out to fill this gap by a paleomagnetic and $^{40}\text{Ar}/^{39}\text{Ar}$ study on these volcanic complexes. The $^{40}\text{Ar}/^{39}\text{Ar}$ analysis demonstrates that these rocks were emplaced during magnetochron C30n to C26r. A weighed mean of several samples from the North Island gave 63.1 ± 0.4 Ma. The striking resemblance with previous dating attempts (among U-Pb) points to a rapid cooling of this complex. The ages obtained from the complex of the Silhouette Island indicate a prolonged magmatism. The trachytic tuffs gave an age of 66.9 ± 0.6 Ma while the youngest unit (syenite) gave a weighted mean age of 61.4 ± 0.6 Ma. All ages from the different units are distinguishable at the 95% confidence level and we interpret this as related to distinct magmatic pulses. The order of the apparent ages correspond to their cross cutting relationship identified in the field. This indicates that the volcanism on the Silhouette was contemporaneous with the Deccan Trap volcanism. The paleomagnetic results from the Island of Silhouette indicate that the magnetic remanence carries normal polarity for all units apart from the microgranites. Their place in the geomagnetic timescale (GTS2004) corresponds very well with the observed magnetic polarities. The paleomagnetic pole obtained in this study has co-ordinates 57.55°S and 114.22°E ($A95 = 12.3^\circ$, $N = 14$) and corresponds very well with poles of similar ages from the Deccan Traps. The paleomagnetic mean remanence direction implies that the Seychelles has rotated $29.4^\circ \pm 12.9^\circ$ anticlockwise after their formation, sometimes between or after magnetochrons C30n and C27n. We propose that part of this rotation has been accommodated while the Gop/Laxmi basins were formed north and northeast of the Laxmi Ridge/Seychelles composite block. After magnetochron C27r, when Seychelles have been isolated from the Laxmi Ridge by seafloor spreading, the Seychelles might have continued to rotate as an individual plate, therefore creating limited extension to the N – NE just south of the Arabia Sea, and compression S – SW, in the NW Mascarene Basin. Earlier work has demonstrated that practically all reconstructed LIPs of the past 300 Ma project down to the Plume Generation Zone at the edge of the large low shear-wave velocity provinces on the core-mantle boundary. Our reconstruction confirm that India and the Seychelles lay nearly vertically about the Plume Generation Zone during the eruption of the Deccan Traps and can be linked to the active Reunion hotspot.

Towards establishing a 'bar code' for the southeastern terrane of the Kaapvaal Craton in northern KwaZulu-Natal, South Africa

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The Archaean basement of the Kaapvaal Craton in northern KwaZulu-Natal consists of several granitic inliers. These inliers can be subdivided according to locality, into the: Hlabisa, Nseleni, Ilangwe, Mfule Gorge, Buffalo Gorge, White Mfolozi and Mvunyana granitoids. The granitoids have been described as granodioritic to tonalitic gneisses [1], which are comparable to the 3.44 to 3.23 Ga tonalite-trondhjemite-granodiorite (TTG) suite of the Barberton region [2]. These granites are intrusive into the Nondweni Greenstone Belt, and have yielded a Rb-Sr, Pb-Pb and U-Pb age of *ca.* 3290 Ma [3]. Nearer the margin of the craton, larger amounts of orthoclase is present, yielding granites and granodiorites in addition to the TTG suite, which are comparable to the 3.10 Ga granodiorites from the Barberton area [2]. The age of these granites indicate strong resetting to *ca.* 980 Ma by Rb-Sr due to the influence of the *ca.* 1000 Ma Natal Thrust Front [4]. These inliers present the opportunity to further define the terrane boundaries proposed for the Kaapvaal Craton with geochemistry and isotopic data, such as Sm-Nd and Lu-Hf [5]. The area also needs to be compared with the Archaean terranes further to the north, particularly in the Swaziland and Barberton regions. Further refining of the age data of this area of the craton is also possible, with some of the granites having never been dated by U-Pb [6]. Also, a Archaean to Proterozoic cratonic reconstruction is possible, by comparing data in this area, with data from the Grunehogna Craton of Western Dronning Maud Land in East Antarctica [7,8,9]. To assist in possible cratonic reconstructions, palaeomagnetic work on the mafic sills and dykes that have intruded the granites may provide a palaeopole and age for the Kaapvaal Craton back into the Archaean. In this regard, dykes and the Hlagothi Complex, which is a sill that has a Pb-Pb age of between 2980 and 3050 Ma [10], provide a opportunity to obtain a palaeopole for the Kaapvaal Craton in the Archaean during the deposition of the Pongola Supergroup.

The basement of the craton in northern KwaZulu-Natal is generally poorly exposed, and deeply weathered, making mapping and sampling difficult. However, samples were gathered from the granites, as well as the mafic dykes and sills hosted within them from river valleys, where fresh samples could be located. Palaeomagnetic samples were also collected from selected dykes and the Hlagothi Complex. Sampling was carried out within 100 m of the Natal Thrust Front to approximately 100 km from the front. The Mvunyana and White Mfolozi granites represent the largest exposures of granite in the area and are located furthest from the Natal Thrust Front. Only a weak foliation is seen in the rocks further from the thrust front, whereas closer to the thrust, the granites become gneissic to migmatitic.

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Deep Carbon Repositories: Evolution and Dynamics

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Carbon is the 4th most abundant element in the solar system, and carbon (~3,000 ppm), among other light elements (e.g. H, N, O, S) is a candidate constituent dissolved in the core to account for the core's 10% excess in density for a mass dominated by iron with minor nickel. Graphite and calcite (CaCO_3) are the major carbon-bearing minerals at shallow levels (50-180 km) in the upper mantle (C=100-200 ppm) and are replaced by diamond and magnesite (MgCO_3) well into the lower mantle (>660 km, C~2,000 ppm), with possible extensions to the core-mantle boundary at 2,900 km. Diamonds are natural antiques that formed early in Earth's history (>2.5 billion yrs) in deep cratonic mantle reservoirs that are cool, rigid and keel-shaped, below the very earliest formed continental crust. Well beyond drilling or mining capabilities, diamonds are transported to Earth's surface in kimberlitic volcanoes of opportunity with two major, globally synchronous events at ~1.1 billion yrs. and again at ~100 million yrs; both were accompanied by large igneous provinces (LIPS), gigantic volcanic eruptions with huge volumes of magma over short periods of time, and both occurred at critical stages in supercontinent evolution: the earlier event during assembly of Rodinia, and the latter during the breakup of Pangea. These events correlate with superchron behavior (extended periods of single magnetic polarity) of the Earth's magnetic field and linked to heat loss in the outer core with changes in convective circulation, the conclusion is that volcanism is driven by thermal plumes that erupted from the D'' layer at the core-mantle boundary. Diamonds have had a long and complex history, are zoned, corroded, fibrous and polycrystalline; and are magmatic, metasomatic, and sulfidic in origin. Approximately 6,000 kimberlites and compositionally related lamproites are known; very few are economic but an extraordinary 600 tonnes or more of diamonds have been mined from primary hard rock sources and alluvials since ~1900. Upper mantle derived carbonatites (magmatic Ca & Mg carbonates) by contrast amount to just over 500, are in circum cratonic rift zones, increase exponentially with decreasing time, originate at shallower levels (60-80 km depth), host significant ore deposits of Nb, REE, Zr, Ti, Fe, P, lime and vermiculite, and with eruption linked to crustal tectonics. Kimberlites, carbonatites and the accompanying eruption of LIPS liberated enormous volumes of carbon to the atmosphere as CO_2 , CH_4 , and possibly CS_2 + CH_4 . Carbon in kimberlites, carbonatites and diamonds is primordial based on stable isotopes and in a comparison with meteorites. With primitive signatures in carbon, the antiquity of diamonds, and the age and volume progression of carbonatites globally, there is simply no room for latter day bio-carbon into deep mantle reservoirs by plate tectonic subduction!

Origin of low $\delta^{18}\text{O}$ magmas in South African large igneous provinces

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Low $\delta^{18}\text{O}$ magmas are 'out of Africa' in that the first recognized were 750 Ma granites from the Seychelles (Taylor, 1969), a continental fragment that was once part of Gondwana. Igneous rocks crystallized from low $\delta^{18}\text{O}$ magmas ($\delta^{18}\text{O} < 5.7\text{‰}$) are extremely rare and form either by partial melting or assimilation of rocks that previously interacted with meteoric water at high temperatures. Although their formation is often presumed to be related to extension, which allows deep circulation of fluids, some low $\delta^{18}\text{O}$ magmas formed via the interaction of crustal rocks whose ^{18}O -depletion significantly pre-dates magma generation (this probably includes the Seychelles, Harris and Ashwal, 2002).

Large volumes of felsic magma ($>35\,000\text{ km}^3$) were produced in the Karoo large igneous province and although clearly related to crustal extension, large volumes of significantly ^{18}O -depleted felsic magma were not produced. However, most Karoo felsic magmas have lower $\delta^{18}\text{O}$ values than the associated mafic magmas. This feature is also seen in the Bushveld Complex, where the mafic and ultramafic rocks formed from magmas with generally higher $\delta^{18}\text{O}$ values than the granites and granophyres. One explanation is that the initially formed mafic magmas were much hotter and were therefore able to assimilate significant amounts of the crust while stalled at or near the crust-mantle boundary. By contrast, the felsic magmas were produced by partial melting of relatively uncontaminated underplated mafic material. However, an alternative explanation is that these felsic magmas acquired lower $\delta^{18}\text{O}$ values at some stage during their evolution by assimilation or melting of hydrothermally altered material, without becoming *bona fide* low $\delta^{18}\text{O}$ magmas.

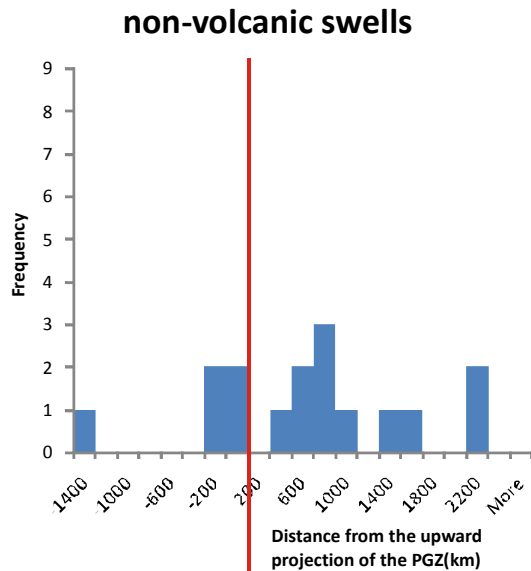
Quartz porphyry dykes from the 133 Ma Koegel Fontein complex on the W coast, about 300 km N of Cape Town crystallized from magmas having $\delta^{18}\text{O}$ values as low as 1.2 ‰. Low- $\delta^{18}\text{O}$ magmas are not known from the similar aged plutonic and volcanic rocks of the Parana/Etendeka large igneous province. At Koegel Fontein, mineral and whole-rock δD values together with quartz vein $\delta^{18}\text{O}$ values as low as -1.7 ‰ indicate magmatic-hydrothermal fluids with a $\delta^{18}\text{O}$ value of about -10 ‰. This seems too low for ambient meteoric water, given the latitude at the time of intrusion of 40°S and, together with its apparent uniqueness, suggests a role for old hydrothermally altered crust.

It has recently been suggested by Bindeman (2008) that low- $\delta^{18}\text{O}$ magmas ought to be much more common than presently realised. However, the generation of low- $\delta^{18}\text{O}$ magmas appears to be strongly favoured by highly ^{18}O -depleted ambient meteoric water. Similar processes to those which produce truly low $\delta^{18}\text{O}$ magmas may have operated during production of felsic magmas in the Karoo and Bushveld large igneous provinces, but the probable absence of ^{18}O -depleted meteoric water at the time of formation of the Bushveld and Karoo large igneous provinces meant that the production of low $\delta^{18}\text{O}$ magmas was not favoured.

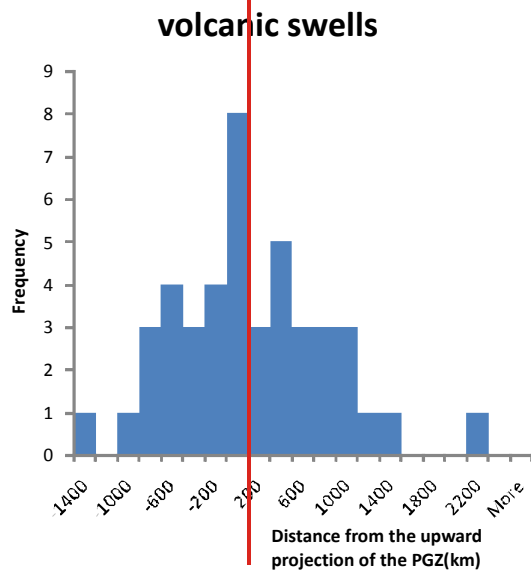
African 30 Ma and younger volcanism and its relationship to the Plume Generation Zone

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African 30 Ma and younger volcanic activity has been most continuous on the spreading centers that almost surround the continent and abundant in numerous hotspot volcanoes on the ocean floor. Hotspot volcanoes on the continent are mainly on crests of swells but some are close to sea level in areas where there has been substantial erosion keeping pace with elevation and related to heavy rainfall. Several hotspots within and on the margins of the Sahara, one of the driest places on the planet, are not on high ground. This can be explained by wet conditions prevailing until 2.8 Ma. None of the hotspots occur on cratons.



Many of the hotspot volcanoes of the last 30 Ma have now been found to lie vertically above the Plume Generation Zone (PGZ) at the Core-Mantle boundary, or at least within less than 1000 kilometers from its projection on the surface. The non-volcanic swells typically lie within the Plume Generation Zone, and so do the sedimentary basins of the last 30Ma.

Plumes from the Plume Generation Zone lay beneath the African lithosphere before the plate slowed down but their tops were smeared out and they showed no surface display. When the plate slowed down or stopped they penetrated the lithosphere and were assimilated into the new plate-wide shallow mantle convection. The Afar plume is distinctive. It appears to have found the newly forming Red Sea, Gulf of Aden and Ethiopian rifts by 'upside down drainage'.

(Outside) **PGZ** (inside)

The Palaeoproterozoic Transvaalide Orogeny

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The Transvaalide Orogeny project aims to study the deformation and metamorphism of a previously unknown orogenic belt located mainly between the Bushveld Complex and the Vredefort Impact Structure while unraveling the tectonic setting and framework of the central parts of the Kaapvaal craton during the Palaeoproterozoic. A structural model will aid in the understanding of geological hazards (e.g. sinkholes, unstable ground and active faults). The core study area is located between the world's two largest economically important deposits (Bushveld Complex and Witwatersrand Supergroup) and the study will contribute in unraveling the structural control of mineralisation in these deposits. The Cradle of Humankind World Heritage Site, the Vredefort Dome World Heritage Site and other tourism attractions (e.g. the Pilgrim's Rest area) are within and adjacent this poorly understood orogenic belt.

Existing geochronology data for the Witwatersrand Supergroup, Transvaal Supergroup, Bushveld Complex, Barberton Supergroup and Archaean Granitoids reveals two low-grade metamorphic-deformation events at ~2150–2120 Ma and ~2042 Ma. The latter event, the Transvaalide Orogeny, clearly is distinct from the Bushveld Complex emplacement (~2055 Ma) and Vredefort Impact Event (~2020 Ma) that might extend as far as the early Limpopo Belt deformation.

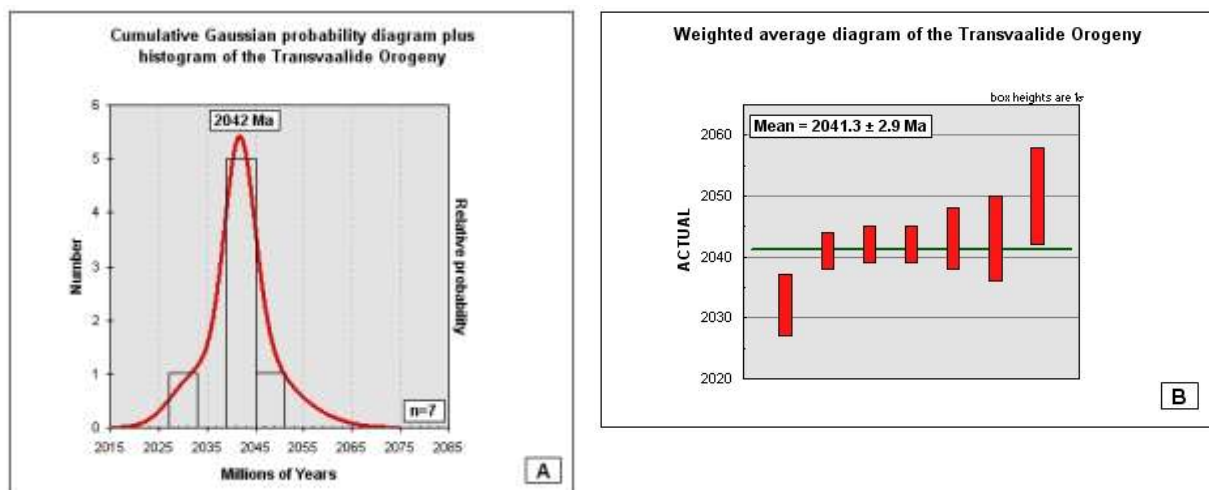


Figure 1. Cumulative probability, histogram and weighted average plots of available ages and uncertainty margins attributed to the Transvaalide Orogeny event.

From Africa with vents

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The Toarcian Karoo Large Igneous Province (KLIP) formed about 183 Ma ago. Doleritic sill intrusions cover an area of nearly 400,000 km², and caused widespread contact metamorphism of marine, fluvial and aeolian sediments. Widespread hydrothermal vents (Fig. 1) are interpreted as fluid release structures generated during contact metamorphism. Conservative estimates of the carbon loss from metamorphic shales, suggest a gas generation potential near 25000 Gt. 13 sill intrusions from localities spread across the entire Karoo basin give U-Pb ages with a total age range of 182.2-182.9 Ma (with a mean of 182.65±0.22 Ma). The dolerite ages are indistinguishable from the start of the lower Toarcian carbon isotope excursion, as constrained by new U-Pb data from bentonite layers in the Argentinian Neuquen Basin. This provides strong circumstantial evidence that the Early Jurassic global warming was triggered by the expulsion of contact metamorphic greenhouse gases associated with the subvolcanic intrusives of the KLIP. A similar explanation may also apply to the Early Eocene and Permo-Triassic climatic excursions.

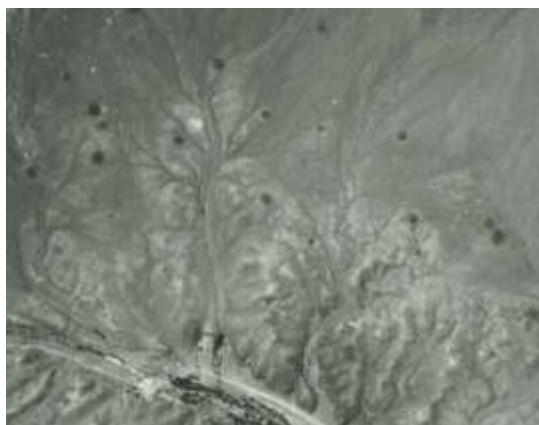


Figure 1. Aerial photo showing breccia pipes in the Lorisfontein area. Black circles are breccia fill, brighter 'halos' are contact metamorphic sedimentary rocks. Field of view ca. 5 km.

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Implications of the Strong Isopycnic Hypothesis for Cratonic Evolution

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The isopycnic hypothesis states that the temperature difference between the cratonic tectosphere (thermochemical boundary layer) and the convecting mantle is density-compensated by the depletion of the tectosphere in Fe and Al relative to Mg. Global inventories of seismic, gravimetric, thermometric, and petrologic data generally support a weak form of this hypothesis: averaged over cratonic scales, the in-situ density of the present-day tectosphere matches that of the convecting mantle to within a fraction of the compositional density difference required to compensate cold tectosphere.

This paper explores the implications of a much stronger version of the hypothesis: at sublithospheric depths (> 100 km), isopycnic balance has been dynamically maintained on length scales smaller than the maximum tectospheric thickness (~ 300 km) throughout the history of the cratons. The strong isopycnic hypothesis, first put forward by the author in 1978, implies that thick tectosphere must be compositionally stratified, with the more depleted peridotites at shallow depths grading downward to more fertile peridotites near its base. Peridotitic xenoliths with equilibrated textures are generally consistent with this prediction.

The strong isopycnic hypothesis places stringent constraints on the process that forms the thick tectosphere of the cratons; e.g., it must lead to an approximately isopycnic state by the time of large-scale tectonic stabilization. Single-stage and continuous-growth models don't work, including those based on single-stage plume-head differentiation, slab underplating, and conductive cooling. The most acceptable models are multi-stage, involving the advective thickening of already cool and depleted mantle in regions of convective downwelling. Crustal and mantle evolution must be strongly coupled; in particular, the stabilization ages of the cratonic crust and keel should be approximately the same. The latter prediction has been verified by the dating of diamond inclusions and by the Re-Os model ages of mantle xenoliths. Advective thickening is also consistent with the petrologic constraint that the garnet lherzolites in the tectospheric mantle were depleted by shallow magmatism, above the garnet stability field.

Continental evolution has involved the interplay between large-scale convective flow that advectively thickens the tectosphere (especially during supercontinent aggregations) and small-scale double-diffusive instabilities that disrupt it (in some cases, leading to rifting and drift). Over the long term, the two mechanisms interact to stabilize the cratonic tectosphere in isopycnic balance. This iterative process provides an explanation for one of the most puzzling aspects of continental evolution—why the tectonic stabilization of a craton can precede its magmatic stabilization by hundreds of millions of years. Regions of fertile mantle entrapped by thickened tectosphere during convergence will conductively cool, subside to form epicratonic basins, and eventually go unstable, leading to decompression melting and basaltic magmatism, which depletes the mantle and thus locally thickens the tectosphere. This endogenous mechanism may provide a better explanation for many large magmatic events—dike swarms, continental flood basalts, and mafic intrusions (e.g., Bushveld)—than the exogenous mechanisms of impacts and plumes. In any case, the endogenous model is more testable, because the magmatic events are predicted to involve basin subsidence and inversion governed by the instability time scale for epicratonic basins. Owing to the cold sidewalls of the thickened tectosphere that surrounds the fertile mantle, this instability time is

substantially longer (~300 My) than that for oceanic plates (~70 My). A second type of double-diffusive instability—eclogite draining of the lithosphere—is also important in the dynamic evolution towards isopycnic balance.

The strong isopycnic hypothesis implies that tectospheric thickness is regulated by the potential temperature T_1 of convecting mantle and the degree of tectospheric depletion, as measured by the average Mg#. Highly depleted peridotites are required to build a thick tectosphere; under current mantle conditions ($T_1 \approx 1350^\circ\text{C}$), the average Mg# must be greater than 92 to support tectospheric thicknesses greater than 200 km. Xenoliths with this degree of depletion are invariably of Archean age. Subsequent Proterozoic and Phanerozoic magmatism has not generated large volumes of such rocks. Therefore, the Proterozoic transition from thick to relatively thin tectosphere can most simply be explained by the exhaustion of mantle peridotites depleted to very high Mg# by higher fractions of melting during paleo-Archean and Hadean magmatic events.

The most challenging test of the strong isopycnic hypothesis relates to the long-term evolution of the cratons during secular cooling of the Earth. Any substantial decrease in T_1 with time will generate a buoyancy excess in the existing cratonic tectosphere, moving it away from isopycnic balance. At the time the strong isopycnic hypothesis was proposed, this appeared to be a major problem, potentially a fatal flaw. However, recent thermal history calculations by J. Korenaga have shown that the classical scaling relation between Rayleigh number and Nusselt number ($Nu \sim Ra^{1/3}$) overestimates the rate of secular cooling. His “plate-tectonic” $Ra-Nu$ scaling, which accounts for chemical differentiation of the oceanic lithosphere, reduces this cooling rate to $dT_1/dt \approx 50\text{-}100^\circ\text{C/Gy}$. Accounting for the decay in heat production within the cratonic tectosphere (which produces most of the present-day surface heat flow) reduces the post-Archean buoyancy imbalance to a small fraction of the total chemical buoyancy. It is likely that dynamic processes, such as convective erosion of the cratonic keels, also act to reduce the chemical buoyancy of the tectosphere over time. The residual imbalance can be compensated by a low rate of tectospheric uplift ($< 1 \text{ km/Gy}$)—a convenient explanation for why most cratons are shields.

In summary, the strong isopycnic hypothesis has survived over 30 years of testing and remains a viable principle for further investigations of cratonic evolution.

Deformation of the forearc wedge along the obliquely convergent Chilean margin

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The forearc wedge along the Chilean margin between 37° and 42°S, which results from oblique convergence between the Nazca plate and the South American plate, is characterized by a major margin parallel strike slip fault, the Liquiñe-Ofqui-Fault-Zone (LOFZ). Field studies show a recent dextral movement along the LOFZ of approximately 10 cm/a.

We present 3D numerical models that investigate the conditions in which the models develop the typical deformational pattern observed in nature. The numerical models are constrained by seismic profiles geometrically and by gravitational and seismic velocity models rheologically. The model setup includes a kinematical modelled subducting Nazca plate and a dynamically modelled South American plate, both lithospheres have an elasto-plastic rheology. The two converging plates are coupled by a frictional interface. The friction at the interface drops abruptly at the downdip end of the seismogenic zone.

Several parameters (e.g., coupling strength, obliquity, convergence rate, rheological properties of wedge material), which potentially govern the style of deformation, were varied in order to study their impact on forearc deformation and to most accurately match natural observations. We found that the frictional structure at the plate interface plays a key role for the segmentation of the strain in a trench normal and a trench parallel component. Without the sharply changed frictional conditions at the plate interface it would be not possible to obtain strain partitioning. This sharp transition in the strength of coupling between plates is attributed to the mainly thermally controlled updip and downdip end of the seismogenic zone. The strength of the material, which is itself highly controlled by temperature, is also an important factor controlling the style of deformation. Comparison of model results with GPS data shows a good conformity with velocities in trench parallel direction, but modelled velocities for the trench normal component are somewhat smaller than observed. In order to render the results of our modelling, we constructed a similar model for the northern part of the Chilean margin. Despite almost equal plate kinematic conditions along the entire Chilean margin, the style of deformation of the forearc wedge differs significantly between the north and the south. This comparison allows us to extract the parameters that control variations of styles of deformation along the Chilean margin.

Is the D'' layer a very early sunken mafic crust? problems solved and new ones created.

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Some highly diverse (and apparently unrelated) fundamental problems in Earth Sciences may be addressed by the hypothesis that a thick mafic crust, capped by a regolith rich in accumulated chondritic matter, sank to the core-mantle boundary in earliest Earth history and stayed there as the D'' layer (Tolstikhin and Hofmann, 2005). These are: (1) the mass balance of incompatible elements of the continental crust and depleted mantle cannot be reconciled with chondritic relative abundances of the lithophile elements in the silicate Earth, if the mass of the depleted mantle is greater than about 1/3 of the total mantle. Meanwhile, the geophysical evidence for whole mantle convection becomes stronger and stronger. (2) The same mass balance problem besets the Nd and Hf isotope systematics of crust and depleted mantle. (3) primordial ^3He is present in the deep mantle in much greater quantities than can be expected in a convecting mantle. (4) The early degassing time scale for a one-reservoir mantle calculated from radiogenic ^{129}Xe (from ^{129}I , half life 15.7 Ma) is ~ 130 Ma, while that calculated from fissiogenic ^{136}Xe from ^{244}Pu (half life 81 Ma) is > 700 Ma, this is a paradox. (5) The global heat flux is greater than calculated on the basis of U, Th and K content of the depleted mantle, and there appears to be a strong temperature gradient along the core-mantle boundary.

The D'' hypothesis of Tolstikhin and Hofmann (2005) was originally motivated by the noble gas problems (3) and (4). They envisaged that a regolith-laden mafic crust could have sunk and remained at the base of the mantle because of the great density of chondritic matter, making up the regolith portion of the crust. In geochemical modeling, Tolstikhin et al. (2006) found that with a D'' mass of $\sim 2.3 \times 10^{26}$ g (estimated from seismic data, and about $10 \times$ the present continental crust mass), consisting of mafic magmatic rocks (incompatible element-enriched relative to the mantle) the geochemical mass balance problems could also be solved. The hypothesis received a boost by the discovery (Boyet and Carlson, 2005) that chondrites had on average 20 ppm lower $^{142}\text{Nd}/^{144}\text{Nd}$ ratios than the silicate Earth, showing that the latter had lost or sequestered an incompatible element-enriched component within the first 100 Ma of its existence (half life of ^{146}Sm : 103 Ma), and that D'', if representing sunken mafic crust, could fit the characteristics required.

Accepting the above, the constraints on the time scale for the formation of this reservoir, as given by Nd and Xe isotope data and the context of the moon forming giant impact as well as the earliest terrestrial zircon data, still appear somewhat contradictory, and we attempt to resolve these issues here.

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Insights on the deep structure of the conjugate East African and Madagascan margins

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The rifted and transform margins created by the separation of Madagascar and Africa offer an opportunity to jointly investigate the structural and geodynamic evolution of conjugate continental passive margins. It is generally accepted that the continental breakup of Gondwana in the East African region initiated, probably during the Middle Jurassic, with the onset of the southward drift of Madagascar (then connected with Antarctica and India) along the Davie Fracture Zone, and subsequently led to the opening of the Somali and Mozambique oceanic basins. Although published kinematic models are able to explain and date some of the broad scale features of these oceanic basins, the exact paleoposition of Madagascar relative to Africa prior to breakup, the timing of rifting, the onset of seafloor spreading (as well as the end of seafloor spreading) in the Somali Basin remain unclear. A better understanding of the early geodynamic evolution of the margins and consequent depositional settings require a reassessment of the crustal structure and tectonics.

We revisit available geophysical datasets, including multichannel seismic reflection, gravity and magnetic datasets, to investigate the evolution of the Somali and Mozambique basins. A re-interpretation of preexisting vintage seismic lines, combined with potential field data helps to better constrain the composition and crustal architecture of the margins. Special effort is made to reconstruct the geometry of the salt layer, as the chronology of deposition of the evaporites relative to the chronology of the margin formation is a key issue in reconstructing the tectonic evolution of the margins.

We present a preliminary interpretation of the crustal structure of the East African margin, along Somali and Mozambique basins and of its conjugate Madagascan margin. We also discuss the location of the continent ocean transition zone, and its kinematics implications.

Constraining the timing of deformation, metamorphism, and crustal recycling in the Central Zone of the Damara Orogen, Namibia

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The Central Zone of the Damara Orogen, Namibia preserves a record of polydeformation and high-temperature, low-pressure metamorphism associated with the Pan-African collision of the Congo Craton with the Kalahari Craton. Three phases of deformation are observed: An early D1 event formed a regional bedding-parallel fabric, with rare intrafolial folds, but is largely overprinted by an intense D2 fabric, formed during S- to SE-verging D2 folding and thrusting, with late development of extensional features. This was followed by gentle upright, NE-trending D3 folding. Fold interference between km-scale D2 and D3 structures resulted in the domal structures characteristic of the Central Zone. Peak upper-amphibolite to granulite facies metamorphism is coeval with D2; migmatitic D2 shear zones, leucosome-filled extensional shear bands, and leucosomes developing along D2 fabrics are all indicative of this relationship. Grey granites widespread in the study area have also intruded during D2, as indicated by their close association with D2 structural features. Emplacement of uraniumiferous granites appears to have been controlled by D3 folding. SHRIMP dating of migmatites and granites from the Central Zone reveals that D2 deformation and peak metamorphism occurred between 520 and 510 Ma, with D3 upright folding slightly later at 506-508 Ma. Additionally, Hf-isotope analyses of zircons from 520 Ma syn-D2 granites and 2 Ga Abbabis Complex basement gneisses reveals that these gneisses formed from recycling of Archaean material, but that grey granites were sourced from recycled Palaeoproterozoic crust, possibly crust from the Kalahari Craton which was subducted below the Congo Craton.

Neoproterozoic DARCs in the Damara-Lufilian-Zambezi and Ubendian belts and the Western Rift Rise- relics of Rodinia fragmentation at 750 ± 50 Ma

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The Greater Congo Craton (GCC) was assembled by the late Mesoproterozoic, although whether or not it formed an integral part of Rodinia is still debated [1, 2]. Initial post-Irumide rifting of the GCC at c. 880 Ma resulted in the deposition of the Roan Gp of the Katanga Sgp, and the Nossib Gp of the Damara Sgp. A palaeopole for the 880 Ma Nchanga Granite, indicating a palaeolatitude of $\sim 40^\circ$ [3], supports reconstructions where GCC was part of Rodinia [1]. In both Sgps, a major unconformity marks the onset of rifting, uplift and ocean opening, when terrains to the south rifted away to form the Khomas Ocean, with development of an extensive Damaran-Katangan passive margin on the GCC. The rifting, which coincided with Rodinia breakup, occurred within the collage of Irumide accreted arc terranes [1], which extended from central Malawi and E. Zambia to central Namibia [4]. It may have been triggered by a mantle plume, which generated a triple junction (Damara and Zambezi rifts and Kundelungu Aulacogen) [4].

The rift succession is represented by c. 765-735 Ma mafic lavas and pyroclastics, olistostromes and breccias of the Mwashya Subgp, and 746 ± 2 Ma ignimbrites and acid lavas of the Naupoort Fm (U. Nossib Gp) and 747 ± 2 Ma rhyolites of the Ugab Subgp [4, 5]. In northern Namibia, deformed alkaline rocks and carbonatites (DARCs [6]- a Burkean acronym!) have similar ages to the rifting event. The Oas quartz syenite is dated at 756 ± 2 Ma [5]. New dating of various intrusive phases of the Oas syenites has given U-Pb ages of 765 ± 4.5 Ma (subvolcanic alkali granite) and 762 ± 12 Ma (syenite) [7]. At Lofdal there are many carbonatite and nepheline syenite intrusions of similar age (762 ± 2 Ma [7]; 765 ± 16 Ma [8]). The Mwashya rifting event produced the 800m-thick Lwavu lavas (W. Zambia), tuffs and agglomerates of the Mwashya Subgp and the Kibambale volcanics flanking the Kibaran Belt NW of the Kundelungu Aulacogen. This rifting may have continued N towards the Western Rift Rise of the Kivu region of eastern DRC, where an alignment of c. 800-740 Ma DARCs, varying from alkaline granite to nepheline syenites to carbonatites, flanks deformed Neoproterozoic Itombwe Sgp rocks [9]. DARCs intruding and flanking the Ubendian Belt are also of this age- the Mbozi Ne-syenite, S. Tanzania (748 ± 6 Ma); the Songwe syenite, N. Malawi (718 ± 20 Ma), and the Nkombwa Hill carbonatite, N. Zambia (675 ± 29 Ma) [4, 9, 10]. Coeval alkaline magmatism in the Ubendian Belt during the Kundelungu Aulacogen development means that the Bangweulu Block must have been rifting away from the Kasai Block, producing sinistral strike-slip reactivation of the Ubendian Belt. The rifting event has recently been recognised in central Malawi, where a deformed nepheline syenite gneiss contains zircons with cores dated at 730 ± 4 Ma [9]; in eastern Zambia, where metarhyolites are dated at c. 750 Ma [Siegfried & Armstrong, unpubl., pers. comm.], and western Zambia, where there are 750 ± 5 Ma subvolcanic porphyritic alkaline granites (Kasempa), and 749.5 ± 3.4 Ma quartz syenites (Mwombezi Dome) [7]. The DARCs were deformed during the Pan-African Damara-Lufilian-Zambezi Orogeny, at about 550-522 Ma, during the collision of the Congo and Kalahari cratons, coinciding with Gondwanaland assembly [4,11].

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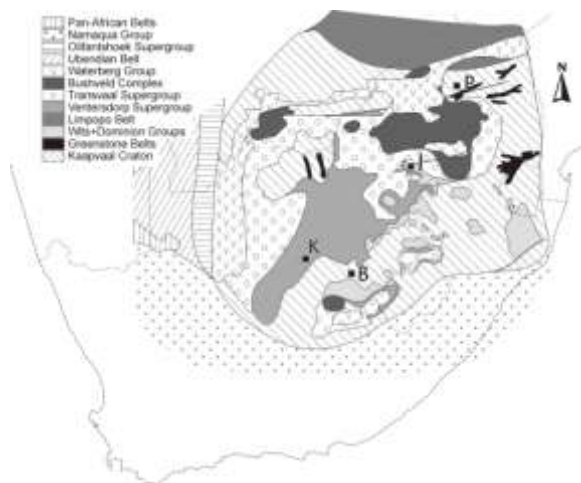
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The Pre-Karoo geology of the southern portion of the Kaapvaal Craton

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The pre-Karoo geology of the northern portion of the Kaapvaal Craton is well-known either as a result of surface exposures or because of exploration drilling, especially for the Witwatersrand Basin. However, the region between the southern margin of the Witwatersrand Basin and the southern boundary of the craton is covered by in excess of 1 km of Karoo and is poorly known. A synthesis of information obtained from drilling logs, examination of cores, gravity and magnetic modeling, seismic profiling and dating of core samples has enabled us to compile the geology of this region. The southern margin of the Witwatersrand Basin is defined by a northeasterly striking basement arch (here termed the Bloemfontein anticline). To the southeast supercrustal rocks again appear. Three apparently separate basins of Witwatersrand Supergroup are preserved (from west to east here termed the Colesberg, Bethlehem and Swaziland Basins). In the Colesberg and Bethlehem Basins, Witwatersrand rocks are overlain by Ventersdorp and Transvaal Supergroup rocks, the latter including an iron formation which is a correlative of the Penge Formation. The Transvaal Supergroup rocks overlying the Colesberg Basin have been intruded by the Trompsburg Complex, which thus appears to be an outlier the Bushveld Complex in terms of its setting, although dating suggests a slightly younger age. To the southeast of the complex is a sequence of red beds of Waterberg Group age. The supercrustal rocks have been deformed into broad folds, which lie sub-parallel to the southern craton boundary, possibly as a consequence of deformation during the Namaqua-Natal orogeny. It is evident from this synthesis that the Archaean and Proterozoic supercrustal rocks of the craton are far more extensive than previously supposed.



Pre-Karoo geology of the Kaapvaal craton: Locations of Kimberley (K), Bloemfontein (B), Johannesburg (J) and Polokwane (P) shown.

Distribution of meteoritic material in the Morokweng crater, South Africa: an unique African impact

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Highly siderophile elements (HSE; including the platinum-group elements (PGE)) are key tracers for meteoritic material in impact craters and distal ejecta. Impact melts at very large craters (e.g. Sudbury, Vredefort, Chicxulub) are typically poor in HSE, indicating a very small (<1%) meteoritic component. Morokweng is a >80km wide impact crater in South Africa, with an age of 144 ± 1 Ma and is unique among large to very large (>30km diameter) craters due to the exceptionally high concentration of meteoritic debris recorded by HSE found in the impact melt¹. Analysis of PGE data and Cr isotopes initially indicated the impactor was an ordinary chondrite asteroid^{1,2} and this was confirmed with the discovery of a 25cm wide clast of a highly equilibrated LL-6 chondrite, plus numerous smaller chondrite clasts in core from a diamond drillhole (designated M3) that traversed the impact melt and intersected the basement³. Distribution of HSE in the impact melt is not uniform and the lower portion of the melt sheet hosts more Ni, Cr and PGE than the upper 200 meters. Siderophiles increase dramatically to maximum values between 350 and 400m depth where partially melted chondrite fragments have been observed⁴. Beneath this, HSE generally decline with depth towards background values in the basement granite/gneiss. A thin impact melt dyke, carrying high concentrations of HSE and “magmatic” sulphides, is observed in the basement rocks ~140m below the base of the impact melt sheet proper. Lithophile elements are anti-correlated with the HSE, and elements like Mg and Fe (which are strongly correlated with the HSE). Analysis of early released Ar isotopes in plagioclase from the large chondrite clast produced an inverse isochron with an age of 143 ± 16 Ma that records the impact age⁵. However higher temperature steps produce older ages, including a statistically valid inverse isochron at 625 ± 163 Ma, that suggest that the impact did not completely reset the Ar isotope systematics and the clast may still record an earlier collisional event on the parent asteroid. Furthermore the very low concentration of cosmogenically produced ³⁸Ar_c suggests that the clast formed part of the interior of the asteroid and was shielded from cosmic rays during its transfer through space⁶. These observations place important constraints on the impact velocity and the disruption of the asteroid during post-impact shock. Hydrocode simulations designed to investigate the survivability of a silicate projectile during impact have shown that the proportion of the projectile surviving as solid fragments is strongly influenced by impact velocity, impact angle and projectile shape (i.e. whether the projectile has a shape that is longer in a direction normal, rather than parallel to the target surface)⁷. These results suggest the Morokweng projectile most likely struck the Earth at close to escape velocity (12km/s) and that the clast was derived from at least a few meters inside the trailing edge of the asteroid.

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Geochemistry of 2.63-2.49 Ga impact spherule layers in Western Australia and South Africa.

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Thin layers rich in spherules formed during impacts by large extraterrestrial objects have enormous potential to help understand impact processes on the early Earth and also aid in the long-distance stratigraphic correlation of Precambrian successions¹. Previous workers have recognized similarities and suggested correlations between early Archean spherule layers in Australia and South Africa^{2,3}. This study deals with 7 formations in the Hamersley Group of the Pilbara craton (Western Australia) and the Transvaal Group of Kaapvaal craton (South Africa). These formations are clustered around the Archean-Proterozoic boundary and each contains a single spherule layer⁴ with one exception (see below). Available age dating constrains deposition of these layers to the period between ca. 2.49 and 2.63 Ga. Geochemical analyses (including analyses for platinum-group elements (PGE) and Cr isotopes) have recently been carried out on samples from 6 of the 7 spherule layers along with samples from closely associated strata that were free of spherules⁵. These revealed an extraterrestrial component (ETC) in all six layers, based on PGE ratios and/or Cr isotopic composition. A detectable ETC was missing from the non-spherule layers. The amount of ETC varies from <1% in the Monteville spherule layer to a remarkable 40% in the only available sample of the Reivilo spherule layer. Both PGE ratios and Cr isotopic anomalies indicate most if not all of the impactors were ordinary chondritic in composition⁵. In contrast, all the early Archean spherule layers that have been analyzed were apparently produced by carbonaceous chondritic impactors⁶. Normalized rare earth element patterns suggest that the target rocks for some of the late Archean impacts were basaltic in composition and may record impacts into oceanic crust. Variability in PGE ratios favors ballistic emplacement of melt droplets rather than spherule formation via vapor condensation, as suggested by previous studies⁷. The geochemical data also provide a means to test proposed intra- and intercontinental stratigraphic correlations⁸ and models invoking the formation of giant impact basins with associated environmental and tectonic consequences at this time in Earth history⁹. Cr isotopic compositions are consistent with the formation of the oldest layers on both cratons by a single impact event about 2.63 Ga. In contrast, clear geochemical differences between the middle layers, both deposited ca. 2.54 Ga, suggest they were not produced by the same impact event. This interpretation is supported by the recent discovery of a layer in the Hamersley succession from a 4th major impact that is petrographically similar to and on a similar stratigraphic level to the middle layer in South Africa.¹⁰

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Estimations of stresses within the African Plate

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Several mechanisms control the state of stress within plates on Earth. The list is rather long, but well-known and includes ridge push, mantle drag, stresses invoked by lateral variations of lithospheric density structure and subduction processes. We attempt to quantify the influence of these mechanisms and to construct a reliable model to understand modern and palaeo-stresses using the African plate (TAP) as an example. Previous studies explained stress patterns and their evolution solely by assigning different rheological properties to sub-domains and their boundaries. Such an approach often leads to unrealistically high variations of properties within a modeled plate. In our approach we find the best possible agreement with observations before differentiating between sub-domains of TAP. The finite-element based suite ProShell was utilized to calculate stresses on the real geometry of TAP (non-planar). The approach allows us to combine several data sets and to estimate stresses caused by lateral and vertical distribution of properties within the lithosphere, to quantify the in-plane and bending stresses, to account for forces due to ridge push and mantle heterogeneities and mantle flow. The modeled results are tested and iterated to match the observed stress pattern and potential fields as good as possible. The starting model is based on the CRUST2 data set to construct the model crust and half-space cooling model to approximate properties of the lithospheric mantle. The results however, are not satisfactory, and might be related to the unrealistic representation of the CRUST2 model in certain areas of TAP, as was also shown by simple evaluation using gravity forward modeling of the model boundaries. The model implementation of the crustal structure calculated from simple gravity inversion or derived through isostatical considerations agree better to today's observed stress pattern.

Platinum-group Elements in the chromitites of the Bushveld Complex: New evidence on how the PGE got there

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The Bushveld Complex contains 75% of the world's resources of Pt, and of this, 58% occur in one unit, the UG-2 chromitite. Most of the other 20 chromitite horizons of the Bushveld are enriched in PGE to varying degrees. However, in contrast to other major PGE hosts, the Merensky Reef and Platreef, in which the PGE are closely associated with Fe-Ni-Cu sulfides, most of the chromitites contain very little sulfide. This paper reports preliminary results of a study of the PGE contents of the 21 chromitite horizons in the Bushveld complex, in 6 specific locations that have been chosen to represent the main "sectors" (troughs) of the Eastern and Western lobes of the complex. The compositions of the chromites themselves fall into a series of 3 groups comprising the LG-1 to LG-4, LG-5 to MG-2c, and MG-3 to UG-2 chromitites. There is a progressive change from one group to another that is attributed to differentiation and an increasing degree of contamination of the magma.

Overall, the average PGE concentrations in massive chromitite increase upward. The LG-1 to LG-4 chromitites have low (Pt+Pd)/(Rh+Ru+Ir+Os) ratios (0.1 to 0.3), above which there is an abrupt jump to higher ratios in the LG-5 (0.9 to 10) and all overlying chromitites (Fig. 1). The Pt/Ru and Pd/Ru ratios are very variable, but the Ru/Ir, Ru/Rh and Ru/Os ratios of all chromitites are relatively constant, indicating that Pt and Pd respond to different concentration mechanisms to the other PGE. Rh, Ru, Ir and Os were likely concentrated by chromite itself, probably as grains of laurite and alloys incorporated in growing chromite crystals, but the bulk of the Pt, Pd along with lesser proportions of the other PGE were concentrated by sulfide liquid. Most chromitites now have very low contents of S, but mineralogical and chemical data from the UG-2 at the Lonmin-Limpopo mine, and the UG-1 at Jagdlust support the suggestion of Naldrett and Lehmann (1988) that vacancies in chromite forming above 900°C were filled by Fe²⁺ derived from the destruction of interstitial sulfide liquid. As sulfide was destroyed, much of the Cu, Ni and Pd was lost, but the Rh, Ru, Ir and Os were protected as inclusions in the chromite. Pt also seems to have formed an immobile mineral at high temperature.

Eales et al.'s (1988) data on En composition through the Bushveld Critical Zone, indicate that the LG-1 to LG-4 chromitites formed at a stage when influxes of magma into the chamber were rapid and primitive, and overrode the effect of fractional crystallization, whereas above this, fractionation mostly overrode influxes of new magma. Irvine's (1977) model of mixing of resident magma with influxes of more primitive magma is invoked as the origin of the chromitite horizons. It is shown, using Li and Ripley's (2009) equation for sulfur solubility and the programme MELTS, that influxes and mixing of fresh primitive magma from depth with that in the chamber (i.e. as envisaged for the LG-1 to LG-4) would not have caused sulfide immiscibility along with chromitite crystallisation, but that influxes

and mixing of slower-ascending magma, that fractionated en route, could give rise to sulfide liquid segregating along with the chromitite (i.e. the scenario for the LG-5 and overlying chromitites). The modeling also shows that the more fractionated the magma in the chamber becomes, the more sulfide will form, accounting for the overall upward increase in Pt and Pd above the LG-5.

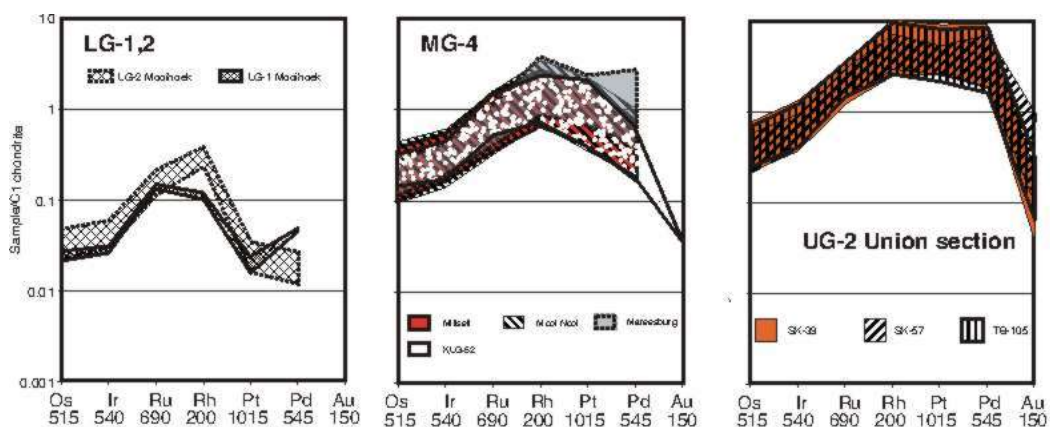


Fig. 1 Chondrite-normalised PGE profiles of some Chromitites

Note: The shaded areas represent the range in PGE concentrations in different samples collected continuously across massive chromitite at each location. The number below each element is the concentration in C1 chondrite in ppb, and is the number with which the concentration in the sample was normalised.

New Constraints on Mesoarchean Crustal Development in the Vredefort Dome, South Africa: Quantitative Phase Equilibria Modeling in THERMOCALC

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Mesoarchean Basement Complex rocks exposed in the core of the impact-generated Vredefort Dome in the central Kaapvaal craton comprise scattered greenstone fragments (pelitic and greywacke sediments, ironstones, komatiitic to tholeiitic lavas) enveloped by trondhjemitic and granodioritic gneisses and granites. Metamorphic grade ranges from upper amphibolite to granulite facies, however, these high-grade rocks are juxtaposed against mid-greenschist facies greenstones along a major NE-trending shear zone in the southeast. Both terranes and the shear zone are overlain unconformably by a volcanic and sedimentary succession at the base of which lies the $3\,074 \pm 6$ Ma Dominion Group.

Field evidence indicates that the metamorphic peak in the high-grade rocks was achieved during development of an intense, subvertical, NW-trending S3 fabric that is interpreted as the product of dextral transpressional tectonics. SHRIMP single zircon U-Pb dating indicates that the metamorphic peak occurred at between 3080 and 3090 Ma. Phase equilibria modeling of metapelitic and metagreywacke garnet granulites constrains peak conditions of 870-885 °C and 7.1-7.7 kbar. Inclusion relationships in garnet and cordierite constrain a prograde up-pressure trajectory dominated by heating from 6.5 to 7.5 kbar and 700 to 850 °C. The stability of cordierite and the absence of orthopyroxene in some peak assemblages constrain the post-peak suprasolidus evolution to a weakly decompressive to isobaric path. Phase equilibria constraints on the prograde and suprasolidus retrograde evolution suggest a clockwise P-T path associated with tectonic and magmatic thickening between 3.10 and 3.08 Ga.

The combined structural, metamorphic, geochemical and geochronological data suggest a juvenile island arc setting for the Vredefort terrane along the southwestern edge of the proto-Kaapvaal craton. Oblique east- to northeast-ward directed collision of the arc with the craton led to crustal thickening, partial melting and emplacement of 3100-3080 Ma granites and granodiorites and high-grade metamorphism. This was followed immediately by collapse of the thickened crust, leading to rapid exhumation of the midcrustal rocks by ~14 km prior to the deposition of the rift-related Dominion Group within 10 Myr of the metamorphic peak.

Petrogenesis and mode of emplacement of the Doros Complex, Namibia, with implications for early Cretaceous continental reconstruction

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The Doros Complex is a relatively small (~ 8 km × 4 km), funnel-shaped, layered gabbroic intrusion that forms part of the Damaraland suite of igneous complexes in Namibia (Hodgson & Botha, 1974; Marsh & Duncan, 2008). The Doros intrusion consists of several gabbroic units with varying textures and compositions that are stacked to form a concentric ring structure with a core of gabbro (Marsh & Duncan, 2008). The complex intrudes the contact between the Doros (Salem-type) granite-syenite pluton and the Zerrissene Group metasedimentary rocks (630-700 Ma) of the Damara Belt and the Karoo sedimentary sequence in this region (Hodgson & Botha, 1974; Passchier *et al.*, 2007; Marsh & Duncan, 2008; Miller, 2008). Intrusive activity in the Damaraland Complexes forms part of the greater Paraná-Etendeka magmatic event, which is attributed to the activity of the Tristan mantle plume and the associated rifting of West Gondwana during the Early Cretaceous (Milner *et al.*, 1995; Le Roex & Lanyon, 1998; Miller, 2008).

This study aims to examine the magma sources, emplacement dynamics and processes (number, nature and timing of magma pulses, mixing, contamination, differentiation) involved in the formation of the Doros intrusion, via comprehensive petrographic, geochemical, isotopic and palaeomagnetic analysis. This will assist in improving our understanding of the processes operational in the formation of layered mafic complexes, as well as make an important contribution to elucidating the role of mantle plumes in continental rifting and the associated magmatism, with implications for regional tectonics in the Early Cretaceous.

Fieldwork, sample collection and preliminary petrographic analysis have already yielded some important results. The dominant minerals in all lithological units are olivine, clinopyroxene, plagioclase and magnetite. Distinct variations in the proportions of these minerals were observed across the units, with localised modally-graded and grain size-graded layering. The lower units are very mafic, dominated by cumulus olivine and clinopyroxene, while the upper layers are more leucocratic, with strongly aligned cumulus plagioclase. The strongly foliated units show chaotic disruptions to the foliation within the contact zones. Leucocratic veinlets and xenoliths of both lower and higher units are common, decreasing in abundance away from the contact zones. These observations suggest that many of the gabbroic units were emplaced as crystal mushes, indicating the presence of a second magma chamber deep below the complex. This, together with the lack of orthopyroxene throughout the sequence, suggests that very little contamination of the Doros magmas has occurred. The time interval between magma pulses was not sufficient to allow earlier units to completely solidify, allowing for magma mingling and the entrainment of solid fragments during emplacement. The olivine contains melt inclusions, with potential for analysis. A phenocryst-bearing glassy basaltic chill margin was observed in contact with the Damaran metasediments.

A synopsis of recent contributions on the Neoproterozoic tectonic evolution of NW India

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The NW Indian block has a well-documented geological history from Archean to the Phanerozoic beginning with the 3.3 to 2.5 Ga Bundelkhand - Aravalli craton that forms the Archean protocontinent with geological record analogous to other parts of the world (Canada, Australia etc.) including Kaapval craton in South Africa. Following the cratonization and development of paleosols, the supracrustal rocks of Paleo- to Neoproterozoic Aravalli – Delhi Supergroup were deposited over this Archean basement. The western margin of this Aravalli – Delhi terrane is marked by the Delhi Fold Belt which is the 1 Ga Grenvillian event as seen in the development of subduction related granitoid intrusions (Sendra – Ambaji and Erinpura Granites).

To the west of the Delhi Fold Belt occurs a >50,000 km² Malani Igneous Suite, one of the largest felsic magmatic terranes in the world. For a long time the MIS magmatism was described as ‘anorogenic’ or ‘rift-related’ tectonic event, probably in the frame of the 750 Ma break-up history of the supercontinent Rodinia. The recent paleogeographic reconstructions based on more robust paleomagnetic and geochronologic data have shown the MIS to be a part of a larger Neoproterozoic terrane along with northern Madagascar and the Seychelles with Andean type subduction setting. Between the MIS and the Delhi Fold belt occurs the Erinpura Granite terrane, which has been conventionally attributed to the Delhi Orogeny and relatively younger Mt. Abu granite as ‘late-orogenic’. The previously observed features such as migmatization and shearing in Erinpura Granite and emplacement and fabric development of Mt. Abu granite can be attributed to the same time-frame as MIS magmatism. Recent geochemical and geochronological evidence have shown that the emplacement of granitoids and shearing was coeval with MIS magmatism. This implies that a) the MIS continues further east than previously envisaged and b) the easternmost part of the MIS shows deformation imprints (pervasive fabric to localized shear zones). The spatial and temporal status of the MIS, therefore, needs to be redefined before attempting any large-scale paleogeographic reconstructions for the Supercontinent Rodinia.

The Bouvet Hotspot, South Patagonia and the initiation of Gondwana Dispersal

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Animations of Gondwana dispersal indicate the importance of the outbreak of hotspots or mantle plumes in initiating rifting within continents. The subsequent history of magma production is preserved in volcanic relics on the floor of the oceans, such as with Kerguelen, Tristan, etc as the plates drift with respect to the hotspot reference frame. The decline in hotspot activity can be protracted and the latter-day output rather precisely focused (e.g. Reunion).

The established movement of Africa with respect to the hotspot reference frame back to 130 Ma has been simply extrapolated backward, heading towards a polar position for southern Africa at the time of the Permo-Carboniferous glaciation at, say, 300 Ma. In such a model, the Bouvet hotspot falls below the lower Limpopo valley at the time of Karoo-Ferrar volcanism (182 Ma) and the emplacement of the giant Botswana dyke swarm (178 Ma). It has often been remarked that a further 10-20 million years then elapsed before discernible Gondwana dispersal got under way.

The model presented here supposes that the initial outburst of the Bouvet hotspot expelled the 1100 Ma 'Grenvillian' terrane of South Patagonia from a starting position between the Natal coast of Africa and Dronning Maud Land, Antarctica. This created space between Africa and Antarctica into which magma could be ventilated from the Bouvet plume to build, initially, the Mozambique plains and the Mozambique Rise. The latter initially followed Antarctica when it started leaving Africa at about 167 Ma, leaving more space in which to grow the Falklands Plateau and, eventually, the Agulhas Plateau, Maud Rise, Maurice Ewing Bank, etc. It is further proposed, to conform with the shape of observed transforms offshore, that the earliest triple junction off the Natal coast jumped offshore, beyond the Mozambique Rise, at about 120 Ma. After this time Antarctica pursued an increasingly westward path with respect to Africa with modest, and complex, relative motions between Antarctica and (by now consolidated) South America. The three pieces of ocean around the triple junction and hotspot created during the Cretaceous Normal Superchron (120-83 Ma) now produce magnetic anomalies observable at satellite altitude.

This simple model with minimal new hypothesis explains the 'exotic' (to South America) rocks of South Patagonia and allows the geology of the Falklands to be matched initially with the Natal coast, as indicated by geological evidence. Close to the early triple junction the Falkland rocks at first followed Antarctica south before being rafted off to the South America plate at a later stage during repositioning of the triple junction. Ample opportunity for rotation of the Falklands continental microplate exists during this phase.

The whole concept fits elegantly within a carefully improved model of Gondwana-wide dispersal released in September 2009 and now available as an animation at www.reeves.nl.

Polyorogenic tectonic setting for gold mineralization in Nigeria?

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Geologically, Nigeria is one of the least understood countries of the African continent. Despite an enviable history of petroleum and tin production and large existing coal/lignite/tar sand resources, an understanding of the geology of the country's pre-Mesozoic geological evolution (ie. outside the Niger/Benue rifts and the Jos Plateau) has moved on little since the Nigerian days of Kevin Burke and John Truswell. Nigeria is also located at the heart of a West African domain that is underlain by Archaean, Palaeo- and Neoproterozoic orogenic terranes with a gold endowment second only to the Witwatersrand Basin, and yet is virtually unknown as an exploration venue or producer of gold.

The western half of Nigeria is underlain by a series of sub-parallel, NNE trending, meta-volcanosedimentary schist belts (in which sediments typically dominate over volcanics) that are intercalated with granitoid gneiss and collectively intruded by a variety of granite bodies of undoubted Pan-African age. This poly-orogenic basement complex is made up of minor, but reliably-dated, Archaean remnants (such as the 3500 Ma old Kaduna gneisses) and a more widely developed Eburnian assemblage comprising poorly-dated volcanosedimentary belts with associated granitoid gneisses – a Palaeoproterozoic age for the latter assemblage is supported by the likely pre-Neoproterozoic coherence between the well-dated Borborema Province of NE Brazil and the Nigeria/Cameroon block. In addition, Pan-African intrusions underlie a significant proportion of western Nigeria and are well-dated in both Nigeria/Cameroon and NE Brazil. The tectonic setting and structural evolution of western Nigeria is little studied but the authors' observations suggest that schist belts preserve early (Eburnean?), syn-metamorphic, bedding-parallel, ductile shear zones that are cut by later (Pan-African?), more brittle and often bedding-discordant, fault lines. Eastern Nigeria and northern Cameroon witnessed a more voluminous Pan-African granitoid overprint, although it is likely that auriferous Eburnian schist belt remnants are still preserved in this region, as suggested by gold exploration activities in Cameroon. There is little support for purported Mesoproterozoic crustal remnants in Nigeria (nor have they been documented in NE Brazil), despite evidence for such 'ages' from the former.

Primary gold mineralization in western Nigeria is orogenic in character. Prevailing mineralization models favour a late Pre-Cambrian-early Palaeozoic (Pan-African) timing for the formation of most of the gold occurrences in the region. Models also implicate a late tectonic, predominantly metamorphic fluid that was focused along conjugate structures associated with major NE trending composite fault sets such as the Anka and Kalangai faults. Recent work at the Paimasa prospect (Niger State) and the old Bin Yauri gold mine (Kebbi State) show that gold mineralization is associated with major quartz-tourmaline-sulphide vein sets (Figure 1) that are sometimes discordant, have been emplaced in a brittle regime and which are, in several instances, spatially linked to, or cut, Pan-African aged granitoid intrusions. A genetic link to granite intrusions has not, however, been demonstrated and at Bin Yauri magmatic fluids have been ruled out as a source for the tourmaline in the gold paragenesis.

Recent exploration in the Kushaka schist belt (Kaduna State) and also at Malele in Zamfara State suggests that an earlier (pre-Pan African?) episode of gold mineralization may, however, also exist. The Kwaga prospect, for example, is associated with a bedding-parallel ductile shear zone comprising thin, dismembered, anastomosing vein sets (Figure 1) that are particularly well mineralized where they cut graphitic metasediments. It is suggested that gold mineralization in Nigeria may, therefore, be polyorogenic in origin and that a possible Eburnian, event created early concentrations of shear zone-hosted gold that were subsequently remobilized and enriched in brittle structures formed during the ubiquitous Pan-African overprint. A detailed study aimed at comparing the structural, fluid-related and geochronological characteristics of these differing styles of gold mineralization is being planned for the near future – a better understanding of the origin of gold mineralization in this hitherto under-explored terrane will contribute significantly to the success of future gold exploration ventures in Nigeria.

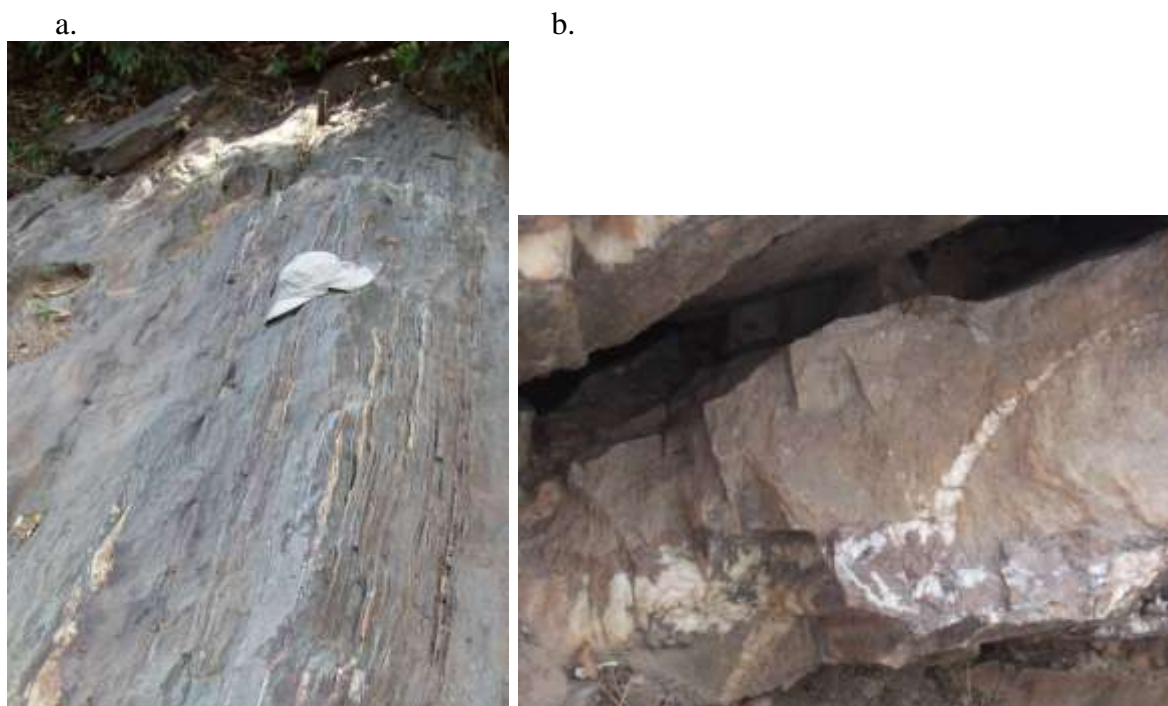


Figure 1: Contrasting styles of gold mineralization in NW Nigeria; a. Shear zone at Kwaga showing thin, dismembered auriferous quartz veins cutting meta-argillite; and b. Quartz-tourmaline vein cutting hornfels formed adjacent to a Pan-African aged granite intrusion at Bin Yauri.

Late Cenozoic Evolution of the Hellenic System

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Subduction of variably buoyant lithosphere is a common phenomena in many geologic settings. For example, the recent evolution of the Apennine, Banda and Hellenic subduction systems all provide excellent opportunities to observe how spatial and/or temporal variability in foreland buoyancy is reflected by changes in rates of subduction. This talk focuses on the evolution of the Hellenic subduction system, and the interconnection between subduction dynamics, trench retreat and deformation of the upper plate lithosphere.

The Hellenic subduction zone displays well-defined temporal and spatial variations in subduction rate and offers an excellent natural laboratory for quantifying the relations between slab buoyancy and tectonic deformation. In space, the active Hellenic subduction front is dextrally offset by 100-150 km across the Kephallonia transform zone, coinciding with the junction of a slowly subducting Adriatic continental lithosphere in the north (5-10 mm/yr) and a rapidly subducting Ionian oceanic lithosphere in the south (~35 mm/yr). Subduction rates can be shown to have decreased from Late Eocene time onward, reaching 5-12 mm/yr by Late Miocene time. Subsequently, entry of Ionian oceanic lithosphere into the southern part of the subduction system has resulted in an increase in trench retreat rates from ~10 mm/yr to ~35 mm/yr over a period of less than 10 m.y.

Application of a semi-analytic three-dimensional subduction model the Hellenic region provides a dynamically consistent means of quantifying subduction kinematics and trench retreat rates as a function of the buoyancy of the subducting lithosphere. Slab buoyancy through time can be largely reconstructed from the sedimentary facies of the external Hellenic nappes, the Hellenic (Pindos) ophiolite belt, and the modern foreland of the Hellenides. My results indicate that the post-Eocene evolution of the Hellenic system can be largely understood as a passive response to the subduction of a variably buoyant foreland lithosphere beneath the Hellenides. Subduction rates along the Hellenides appear to have slowed from perhaps 40-60 mm/yr during Eocene subduction of the Pindos ocean to approximately 5-12 mm/yr by Middle Miocene time as the result of the arrival and subduction of continental (transitional) lithosphere beneath the Hellenic trench system. Later, in Middle and Late Miocene time, subduction and trench retreat rates increased in response to the introduction of oceanic lithosphere into Hellenic trench system south of Kephallonia. Subduction rates remained slow in the north where continental lithosphere continues its slow subduction. Miocene rates of trench retreat increased first in the southern (Cretan) portion of the Hellenic arc, resulting in Middle to Late Miocene extension in the central Aegean, the eastern part of the Central Hellenic Shear Zone and the eastern Peloponnesus. Deformation was accommodated largely by slip along gently dipping detachment faults similar to those present in the Basin and Range Province. The entry of oceanic lithosphere into the southwestern (Peloponnesus) portion of the arc resulted in the Pliocene-Quaternary formation of the Kephallonia transform zone, the initiation of extension and strike-slip faulting in the western portion of the Central Hellenic Shear Zone, and development of a through-going deformation zone extending from the Kephallonia transform zone to the North Anatolian fault. This remains, in essence, the modern deformation pattern of the Hellenic and Aegean domains.

The excellent correlation between upper plate deformation and trench retreat rates, as determined by geodynamic modeling along the Hellenic front, enables a quantitative reconstruction of the post ~35 Ma evolution of the Aegean and Hellenic domains, whereby deformation of the upper plate lithosphere can be linked directly to the paleogeography and buoyancy of the Hellenic foreland through time.

Widespread denudation and uplift within a passive continental setting: geological and geomorphological insights into the late Mesozoic and Cenozoic evolution of southern Africa

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Defining the uplift history of southern Africa is of considerable importance to the geoscientific community as it can be used to unravel spatial and temporal variations in convective patterns within the mantle lithosphere. However, despite numerous endeavours, at present no model of post break-up landscape development has gained widespread acceptance. This paper proposes a new morphogenic model for the late Mesozoic and Cenozoic through the integration of geological and geomorphological evidence derived from records of post-emplacement alkaline volcanic pipe erosion, offshore sedimentary sequences, the form of key reference surfaces, and detailed topographic analyses. The latter of these includes a reappraisal of some of the data previously cited in support of substantial late Cenozoic uplift within southeastern Africa, including a more systematic analysis of longitudinal stream profiles derived from rivers in KwaZulu-Natal and the Eastern Cape. It is proposed that much of southern Africa was reduced to a surface of low relief by the end of the Mesozoic. Widespread epeirogenic uplift across the sub-continent elevated this surface to its present position during the Cenozoic, most probably during the Oligocene. Subsequent crustal unloading of the coastal periphery has led to the formation of a ubiquitous marginal bulge. Furthermore, it is suggested that the atypically narrow continental shelf and adjacent highly elevated landmass of southeastern Africa may result from the presence of “broken” crust associated with the Agulhas Falkland Fracture Zone. The nature, age, and origin of the southern African landscape has proved to be one of the most intractable and controversial problems within geomorphological research; taken together, these data provide significant new information on the morphogenic development of the sub-continent.

The Palaeo-Tethys and the Permian extinction: problems of tectonics and palaeontology

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The Palaeo-Tethys has long been portrayed as an easterly widening giant gulf of the late Palaeozoic Pangaea, separating the central and eastern parts of Gondwana-Land in the south from Laurasia in the north. This reconstruction assumed rigidly not only of the Gondwanian continents and North America, but also of Eurasia. Increasing data now show clearly that neither Europe nor Asia had their present outlines even outside the Tethyside superorogenic system in the Permian and in the Triassic. The Altaid evolution of Asia and post Altaid deformations have now been reasonably well understood and the Scythide Orogenic Belt has been recognized and the outlines of its evolution have been sketched out. This understanding requires that major right-lateral shear zones enter Europe. Indeed the Hercynian front in eastern Europe is right laterally displaced some 500 km and the Bohemian-Sardinian Shear (also called the External Massifs Shear Zone) displaces the easternmost Hercynian front some 1500 km westwards. Numerous other NW-striking shear zones cut Europe that clearly were active in the Permian and in the Triassic. All of these have a major influence on Pangaeon reconstructions and a shape possibly closer to Pangaea B may be possible. However, data from the United States and west Africa are not now conducive to such a view. Whatever the shape of the Palaeo-Tethys it is now clear that it was not a gulf, but an internal sea of Pangaea closed by the Cathaysian Bridge in the east as suggested both by the timing of collisions within the Chinese and Southeastern Cimmerides and by the distribution of Permian benthonic organisms and land tetrapods. Stratigraphic evidence from Upper Permian successions from within the Palaeo-Tethys indicates that it probably turned anoxic in the Permian. Anoxia seems to have started locally already in the late Carboniferous in the deepest basins and spread progressively to the entire ocean and then also invaded the shelves. This invasion wiped out aerobic life in step with the spreading of the anoxia in the Palaeo-Tethys and eventually poisonous gas eruptions seem to have created a killing halo around it in the latest Permian.

The Permian extinction was not a universal affair notwithstanding its immense magnitude. Its intensity was much smaller than commonly assumed and its G number falls below that of the end-Cretaceous event. In the Permian, organisms living in high latitudes were not affected and the chert gap seems not to be present in the Panthalassa. Therefore, the Permian extinction was a Tethyan affair including its terrestrial surroundings (extending as far south as South Africa through the Gulf of Malagasy) plus its spillways. Its immense magnitude is a result of the fact that in the latter half of the Permian, the Palaeo-Tethys and its surroundings included by far the densest biological niches.

The Source and History of the Sand River Gneisses, Limpopo Belt, South Africa

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The Archean polymetamorphic Sand River Gneisses in the Beit Bridge Terrane of the Central Zone of the Limpopo Belt, have calc-alkaline compositions and contain numerous generations of leucosomes. They are orthogneisses and may be divided into two phases, one grey with an enderbitic composition and the other white with a charnoenderbitic to charnokitic composition. Their igneous precursors were intruded at ~3.27 Ga into a package of sedimentary or metasedimentary rocks, the Beit Bridge Group (Messina Formation), and the 3.36 Ga Messina Layered Intrusion. The orthogneisses are intruded by and deformed with ~3.0 Ga tholeiitic dikes that postdate some ~3.07 Ga leucosomes and are intruded by other leucosomes at ~2.02 Ga, hence reflecting a period of extension between two high-grade metamorphic events. A third metamorphic event at ~2.66 Ga also affected these rocks to a lesser extent.

The major and trace element chemical composition of the Sand River Gneisses show both TTG characteristics as well as those of modern orogenic andesites. Their parental melt is interpreted to have been formed by slab melting and subsequent interaction with the overlying peridotitic mantle wedge (grey phase). In some cases, the melt was completely consumed by the mantle peridotite, which subsequently was remelted due to fluid injections (leucocratic phase). Trace element modelling indicates that different degrees of fractionation of the slab-derived as well as juvenile mantle melt could subsequently have led to further compositional variation in the Sand River Gneisses. Therefore, it is concluded that modern-style subduction processes were active in the Beit Bridge Terrane at ~3.27 Ga and Lu-Hf data suggest possibly even at ~3.6 Ga.

The older, ~3.07 Ga leucosomes are granitic in composition and formed, as indicated by REE modelling, by a small degree of fractional crystallization of a TTG melt of similar composition to the Sand River Gneisses. The younger, ~2.02 Ga leucosomes are granodioritic in composition and represent a more strongly fractionated TTG melt from which amphibole and garnet have been removed. None of the leucosomes studied are related to the ubiquitous, ~2.02 Ga in situ partial melting of the Sand River Gneisses

A geochronological, geochemical and petrographic study of granitoids from the Mt. Abu pluton and surrounds, SW Rajasthan, India.

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The Abu pluton is a composite body (45 km x 20 km areal extent) consisting of undeformed pink granite, foliated and porphyritic grey granite and augen gneiss, all of which may be juxtaposed. It has been classified as either Malani Igneous Suite (MIS; ~750 Ma) or as the older (~850 Ma) Erinpura granite-gneiss, depending on amount of deformation experienced. This apparent disparity in ages (~100 Ma) between granitoids of a single pluton is due to a paucity of robust geochronological and geochemical data available for this pluton.

Abu samples are hypersolvus monzogranites, predominantly metaluminous with LREE enriched profiles, similar to ~750 Ma granitoids from Seychelles. These differ from the Erinpura monzogranites (per- to met- aluminous), which show more primitive, shallower, less-enriched REE profiles. Spidergrams of both Abu and Erinpura are broadly similar, with Erinpura showing less well-developed -ve Ba, Sr, P and Ti anomalies. Most major elements show the expected negative trends with SiO₂, save MgO, which is level (Abu), and Na₂O and K₂O, which are scattered (Abu and Erinpura). Abu granitoids show strong positive Ti, Mn and P correlations with maficity, similar to Seychelles, while Erinpura is less clear cut. Radioactive U & Th (and Pb) show a negative trend with maficity while Sr (Abu) and V, Ni and Co (Erinpura) increase with maficity.

In thin-section, there is ample evidence that all samples have undergone some degree of solid-state deformation during a later metamorphic event. Deformation microstructures common to most samples include subgrain formation (quartz) and grain boundary recrystallization (quartz-k-feldspar), mymerkite (along margins of K-feldspar phenocrysts) as well as kinked deformation-twinning in plagioclase.

Three samples from the Abu pluton and one from Erinpura were dated using the U-Pb zircon (ID-TIMS) method. Samples dated varied in texture from undeformed to augen gneiss. The type-locality pink granite was dated at 766.0 ± 4.3 Ma (anchored at 0 Ma). The age calculated for the foliated granite was 763.2 ± 2.7 Ma; while that of the augen-gneiss was 767.7 ± 2.3 Ma (both anchored at 250 ± 50 Ma). These 3 Abu granitoids are tightly grouped in age despite evidence of disturbance in zircons from the latter two samples (reflected by Pb-loss on the Concordia diagrams). In comparison, the Erinpura granite is >90 Ma older, with a calculated age of 880.5 ± 2.1 Ma. Both Abu and Erinpura granitoids have been deformed due to a post-crystallization tectonothermal event as indicated by microstructures in thin-section, foliation in hand-specimen and discordance within the U-Pb age-data. ⁴⁰Ar-³⁹Ar age dating on the pink Abu granite yielded a weighted-mean plateau age of 508.7 ± 4.4 Ma (flat spectrum). Further confirmation of this Pan-African age was provided by the Erinpura granite with a weighted mean-age of 515.7 ± 4.5 Ma (disturbed spectrum). These are the first robust Pan-African ages reported for this part of Rajasthan and are likely the cause of the deformation within the Mt. Abu granitoids.

The U-Pb ages reported for the Abu granitoids fall within the range of ages (770-751 Ma) of the MIS and Seychelles undeformed granitoids and so should not be classified part of the Erinpura granite. The MIS and Seychelles (together with Madagascar) have been proven

spatially contiguous at ~750 Ma (palaeomagnetic poles). Seychelles and Madagascar have also been postulated to have formed in an Andean-type arc (contrary to the idea that they are anorogenic and extensional), while ultramafic-mafic volcanics (Punagarh & Sindreth) within the area dated at ~764 Ma are thought to be part of an ophiolitic assemblage. Additionally, Seychelles and Mt. Abu dolerite dykes have also been found to be geochemically similar. We propose the possibility (based on temporal and spatial contiguity as well as geochemistry) of the inclusion of the Abu pluton within this Andean-type arc on the western margin of Rodinia.

Magmatism and continental rifting

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Rifting is a fundamental plate tectonic process that creates elongated depressions in the Earth's surface, which become filled with sedimentary and volcanic material, as it is presently observed at the Baikal, East African, Rhine Graben and Rio Grande Rift Zones. All rifting models predict Moho uplift due to crustal thinning, and reduced seismic velocity in the uppermost mantle due to decompression or heating from the Earth's interior. However, recently acquired data from the presently active Baikal Rift zone in Siberia and the failed Dniepr-Donets rift zone in Ukraine are examples where there is no Moho topography that can be related to the rifting process. Further, data from the Kenya Rift Zone shows signs of less Moho uplift than expected from the actual extension. At all these rift zones, we observe a localized zone in the lower crust which has exceptionally high seismic velocity and is highly reflective. We suggest that rift-related crustal thinning took place, but the expected Moho upwarp was compensated by magmatic intrusion in the lower crust at the high-velocity zone. This finding has significant implications for modelling the evolution of sedimentary basins around rift structures.

Diamonds sampled by plumes from the core-mantle boundary

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Diamonds are formed under high-pressure more than 150 km deep in the Earth's mantle and have been brought to the surface mainly by kimberlites. Kimberlites, which are themselves derived from depths greater than 150 km, provide invaluable information on the composition of the deep sub-continental mantle lithosphere. We have shown that large igneous provinces of the past 300 My, rotated back to their eruption sites, project radially down to lie on narrow stable plume generation zones at the edges of time-invariant heterogeneities in the deepest mantle. We here use plate reconstructions and tomographic images to show for the first time that mantle plumes from the deepest mantle also explain the distribution of most kimberlites erupted in the past 540 million years. A remarkable pattern is observed when we plot kimberlites on our series of plate reconstructions. At practically all times, eruption sites plot close to the plume generation zones. For the last 320 My, Gondwana with Africa at its heart, has drifted slowly northward over the African plume generation zone, and this readily explains the dominance of African (Gondwana) kimberlites in the global record as having been sourced by heat from deep plumes. There are relatively few Phanerozoic dated kimberlites in the world older than 320 My; only about 200 are known between 540 and 320 Ma, and kimberlites were altogether absent from core Gondwana between 370 and 500 My -- Why? Plate reconstructions provide the answer: Over this time interval Gondwana was centred on the South Pole and the bulk of the continent, was located between and not over, the plume generation zones.

Geological expressions of subduction, collision, delamination and slab break-off in western Turkey: a record of a continuous process

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Although Greece and Turkey must share identical geodynamic boundary conditions during late Cretaceous to Present Africa-Eurasia convergence, their geological records have been interpreted in very different ways. Whereas Greece experienced continuous subduction and accretion of supracrustal nappes, western Turkey was characterized by collision of the Eurasian Sakarya and Pan-African Anatolide-Tauride continents in the Eocene. It remains unclear how convergence continued following postulated Eocene slab break-off. Here we synthesize the metamorphic and structural record of western Turkey and propose a new, continuous scenario. Convergence between Sakarya and the Anatolide-Taurides commenced around 90 Ma with intra-oceanic subduction and the establishment of a cool subduction channel in which the Tavşanlı and Afyon high-pressure, low temperature belts were metamorphosed and exhumed. Eclogite lenses in the Menderes are likely of Alpine age, reflecting deep underthrusting. Subsequent delamination of the crust from the subducting lithosphere led to crustal thinning by southward lower crustal flow, the formation of a penetrative sub-horizontal foliation and a regional high-temperature, low pressure metamorphic overprint. Shallower overlying crust experienced widespread Eocene granite intrusion. Delamination gave way to progressive roll-back of the Aegean-west Anatolian slab since the late Eocene, accelerating in the late Oligocene to form the Menderes metamorphic core complexes. Final break-off of the west Anatolian slab likely occurred in the middle Miocene, leading to the formation of the east Aegean subduction transform and compression of the Anatolian segment between the Aegean and Cyprus subduction zones, with vertical axis rotation of SW Turkey as a response.

New microbeam zircon dating insights on migmatites of the former Moirivier metamorphic complex and the Neuhof formation, Sinclair group, Namibia

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In the 1.4-1.0 Ga Sinclair Group and its basement, located in Namibia, the relations and chronostatigraphic succession are not fully understood. This is certainly true for the former Moirivier Metamorphic Complex (MMC) and the Neuhof Formation. Becker (2008) interpreted the MMC and the Neuhof Formation as part of the Kairab Formation (Hoal, 1990), a heterogeneous metamorphic basement overlain by metavolcanics that are intruded by subvolcanics. This basement is part of the Namaqua Metamorphic Complex and Hoal (1990) separated the metavolcanics from the apparently older basement. The comparison Becker (2008) made was based on the fact that the units lie close to each other and lithological similarities; the MMC seems to be dominated by gneissic intrusive rocks and the Neuhof Formation consists mainly of basic volcanic and sedimentary rocks with closely related intrusives.

In this study we used the NordSIM ion probe and a high resolution laser ablation ICPMS to date zircons from two migmatized samples and a red aplite dyke that cuts a migmatite from the MMC on Hauchabfontein farm. This migmatite location is interpreted by Becker (2008) as the gneissic Hauchab Granodiorite. He states that this body intrudes an amphibolite which is indicated by the presence of amphibolite xenoliths in the granodiorite. The second migmatite is located close by to the west. Our field interpretation is that the 'gneissic granodiorite' is the result of a migmatization event caused by a gabbro intrusion mixing with melted granitoid material. The two migmatite samples are hybrid rocks, consisting of a mixture of mafic and felsic components. Zircons from these hybrid rocks showed large CL-bright rims, indicating an overall metamorphic or migmatitic event. However most of the zircons show no age difference between rim and core. These dates are 1205 ± 6 and 1220 ± 8 Ma and reflect the gabbro intrusion and migmatization event. Since the cores of the zircons were probably reset, a migmatization event is favoured above a metamorphic one, since it requires very high temperatures. This also applies to the formation of hybrid mixtures between felsic and mafic components. The migmatization age is slightly older than the red aplite dyke at 1201 ± 16 Ma. The migmatization corresponds in age to the Barby Formation which formed during northwestward subduction prior to the ~1200 Ma Namaqua collision.

In the Hauchabfontein migmatite we found one concordant zircon core dated at 1367 Ma possibly related to tonalite intrusives at 1375 Ma like the Hammerstein (Becker, 2008) and the Aunis Tonalite (Hoal, 1990), that intrude the Neuhof and Kairab Formations respectively. The second migmatite sample contains four xenocrysts with a combined concordant age of 1748 ± 21 Ma. This age indicates the presence of a basement older than the Kairab Formation, like the Elim Complex and Gaub Valley Formation to the north.

South of Hachaubfontein on the border of Moirivier Farm, we sampled a metasediment from the Neuhof Formation. This is a low grade, quartz-rich gneiss, thought to be of volcanic origin. Becker (2008) interpreted fine grained quartz-feldspatic gneisses that occur in the Neuhof Formation as intrusives because of the young age (~1320 Ma) in comparison to the 1375 Ma Hammerstein Tonalite intrusive. However in our sample we found two age domains

at 1330 ± 5 and 1291 ± 9 Ma. This indicates that the sample was not an intrusive but more likely a metasedimentary rock containing detrital zircons derived from two magmatic units.

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Discovery of Komatiite – the 40th Anniversary

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Forty years have elapsed since the presentation of a two benchmark papers at the International Upper Mantle Conference held in Pretoria in July 1969. The first was entitled “The Geology and Geochemistry of the Lower Ultramafic Unit of the Onverwacht Group and a Proposed New Class of Igneous Rock” by M.J Viljoen and R.P. Viljoen. This together with a companion paper entitled “Evidence for the Existence of a Mobile Extrusive Peridotitic Magma from the Komati Formation of the Onverwacht Group”, by the same authors, was published at the end of 1969 in the Upper Mantle Project, special publication No.2 of the Geological Society of South Africa. The papers reported on the discovery of a new class of igneous rock and proposed a new name.

The proposed new class of igneous rock was termed komatiite and both a peridotitic and a basaltic variety were identified as widespread rock types belonging to the same clan, and occupying large parts of the Komati Valley in the southern portion of the 3.5 billion year old Barberton greenstone belt. The discovery of komatiite was the result of detailed mapping over 4 field seasons, starting in 1965, of large tracts of country underlain by the Onverwacht group, the lowermost stratigraphic sequence of the Barberton greenstone belt, as part of South Africa’s contribution to the International Upper Mantle Project.

The rationale behind the introduction of this new class of igneous rock, based mainly on field evidence as well as whole rock geochemistry, is outlined in this contribution. The recognition of pillow and other diagnostic, volcanic structures and textures and in particular the enigmatic, so called “crystalline quench textures”, which were later to become universally known as Spinifex texture, were of prime importance and helped in establishing the fact that komatiites were emplaced mainly as lavas. The geochemistry of the mafic and ultramafic rocks of the proposed komatiite clan was also highly distinctive with ultra high magnesium contents, high calcium aluminium ratios and low alkalis being diagnostic, making them totally unlike any other class of igneous rock previously described, at the time.

The Barberton greenstone belt is one of the best developed and exposed of all the Achaean greenstone belts of Africa and attracted and is still attracting researchers from all over the world. Many of the pioneer researchers visited the Komati Valley and were instrumental in assisting the authors and steering their lines of thought which led ultimately to the recognition and naming of komatiite. Professor Al Engel of the Scripps Institute of Oceanography in San Diego played an indispensable role in this regard and his work on the low potassium oceanic tholeiites and their significance with regard to early crust formation was of huge importance. Engel, on his visit to South Africa in 1966, drew analogies between the Onverwacht Group volcanics and mid Oceanic Ridge Basalts (MORB’s) the most “primitive” of volcanic rocks on the planet. He reasoned that in these times of early earth evolution, even more primitive volcanics could be found in the ancient greenstone belts as one proceeded down the stratigraphic pile. A seed had been sown.

Other visitors who assisted in the recognition and naming of komatiite were Prof. Preston E. Cloud Jnr. who drew attention to the possibility of early forms of life in cherts and related

sediments interlayered with komatiitic successions and Dr. Mike Ohara of the University of Edinburgh who alerted the authors to the significance of crystalline quench or Spinifex textures, one of the hallmarks of komatiite. Many other geoscientists helped in piecing together the story of komatiite with members of the Economic Geology Research Unit of the University of the Witwatersrand and particularly Professors D.A. Pretorius and CR. Anhaeusser contributing ideas as studies progressed.

Ultimately, Engel was correct in that volcanic rocks, even more primitive than low potash oceanic tholeiites, which he had been looking for, occurred in profusion in the lower stratigraphic sequences of the Barberton belt. Komatiites were the missing link of his jigsaw puzzle. They also completed the picture that Professor Harry Hess of Princeton had been piecing together throughout his distinguished career in the study of ultramafic rocks. On a visit to the Komati river valley in July 1969, he enthusiastically endorsed the evidence presented for a new rock clan and a mobile, extrusive ultramafic magma.

Being close to total melts, peridotitic komatiites provide important information regarding the composition of the Upper Mantle of the earth. They also provide vital clues as to the composition and nature of Archaean tectonics, the earth's first crust and how tonalite/trondjemite granites, so characteristic of the early Archaean, formed. A variety of mineral deposits and in particular nickel and gold is associated with komatiites which were the carriers of these and other elements from the mantle into the crust.

In the forty years that have elapsed since the announcement at the Pretoria Conference in 1969, and after a few early years of hesitation and perhaps skepticism, komatiites have been recognized in the greenstone belts of all the continents (most recently in China in the Mt. Taishan Granite Greenstone Geopark), as a significant new class of mainly ancient and dominantly volcanic, igneous rock.

The bibliography on komatiites is huge and growing and a second publication on the subject by N. Arndt (the first was by Arndt and Nesbitt, published in 1987) has recently appeared (2008) and further research and debate will undoubtedly continue into the future.

The writers were fortunate and privileged to have been approached to carry out studies on such a remarkably well exposed and developed sequence of rocks as those occurring in the Komati River Valley and to have been able, through extensive field studies in the first instance, to recognize a hitherto unknown class of igneous rock. South African geology has been firmly placed on the world stage by the recognition and naming of komatiites, described by Arndt and Nesbitt as "one of the most important petrological advances of the last century".

Magnetic modeling of the Bushveld Igneous Complex

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Magnetic modeling of the 2.06 Ga Bushveld Complex presents special challenges due a variety of magnetic effects. These include strong remanence in the Main Zone and extremely high magnetic susceptibilities in the Upper Zone, which exhibit self-demagnetization. Recent palaeomagnetic results have resolved a long standing discrepancy between age data, which constrain the emplacement to within 1 million years, and older palaeomagnetic data which suggested ~50 million years for emplacement. The new palaeomagnetic results agree with the age data and present a single consistent pole, as opposed to a long polar wander path, for the Bushveld for all of the Zones and all of the limbs. These results also pass a fold test indicating the Bushveld Complex was emplaced horizontally lending support to arguments for connectivity.

The magnetic signature of the Bushveld Complex provides an ideal mapping tool as the UZ has high susceptibility values and is well layered showing up as distinct anomalies on new high resolution magnetic data. However, this signature is similar to the highly magnetic BIFs found in the Transvaal and in the Witwatersrand Supergroups. Through careful mapping using new high resolution aeromagnetic data, we have been able to map the Bushveld UZ in complicated geological regions and identify a characteristic signature with well defined layers. The Main Zone, which has a more subdued magnetic signature, does have a strong remanent component and exhibits several magnetic reversals.

The magnetic layers of the UZ contain layers of magnetite with as much as 80-90% pure magnetite with large crystals (1-2 cm). While these layers are not strongly remanent, they have extremely high magnetic susceptibilities, and the self demagnetization effect must be taken into account when modeling these layers. Because the Bushveld Complex is so large, the geometry of the Earth's magnetic field relative to the layers of the UZ Bushveld Complex changes orientation, creating complications in the modeling. Anisotropic magnetic susceptibility may be related to demagnetization in the Bushveld Complex due to well defined, relatively thin layers. Aeromagnetic data are useful for imaging layered intrusions because they often contain highly magnetic layers. However, care must be taken to incorporate the effects of strong susceptibilities (AMS, demagnetisation) and remanence.

Rodinia breakup and Gondwana assembly in the Lufilian Arc, Central Africa: new tectonic stages revealed by syntectonic conglomerates

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Introduction

The Lufilian arc is a part of the Neoproterozoic-Lower Palaeozoic Pan-African network of orogenic belts composed of sedimentary succession of the Katanga Supergroup. The belt contains large bodies of fragmental rocks ('megabreccias') considered by previous workers as tectonic friction breccias extending at two regional decollement zones generated by thrusting during Lufilian orogenesis.

The present author has shown recently that that these fragmental rocks are complexes of syntectonic conglomerates deposited as elements of stratigraphic succession of the Katanga Supergroup (880-500 Ma) and supplied from uplifted source zones composed of Katangan rocks. The major lines of evidence for sedimentary genesis of the Katangan 'megabreccias' are: (1) lack of pervasive shearing or other textures that would point to tectonic fragmentation of brittle rocks; (2) derivation of clasts from identifiable Katangan lithostratigraphic units and provenance of clasts recording two major stages of unroofing of the source region; (3) lithological variations, bedding and lateral facies gradients; (4) sedimentary features diagnostic of deposition from sediment gravity flows and fluid gravity flows; (5) unconformable lower boundaries of 'breccia' bodies, which represent stratigraphic, not tectonic contacts; (6) soft-sediment injections of conglomerate projecting into open fractures in allochthonous blocks, recording loading of unconsolidated sediments beneath older, rigid Katangan rocks.

Sedimentary genesis revealed two previously unrecognized sedimentary basins and tectonic stages of the Lufilian belt evolution, which are reflected in the revised stratigraphy. The Katanga Supergroup is therefore subdivided into four groups: two syn-rift successions - Roan and Nguba, and synorogenic foreland units - Kundelungu, Fungurume and Plateau.

Newly recognised basins and tectonic stages

Significant uplift in the southern part of the Roan rift basin (≥ 765 Ma) closed the deposition of the first rift basin infill (the Roan Gp.). Thick olistostromes of the Mufulira Formation derived from the uplifted zone initiate sedimentation in the subsequent Guba rift, that expanded northward beyond the N boundary of the Roan rift. Thus the Roan and Guba Groups record two distinct rifting stages and a northward shift of the rifted zone.

The Kundelungu Group, fills the first synorogenic foreland basin and includes a proximal conglomerate wedge in the south of the Lufilian belt. In the second orogenic stage the Fungurume foreland basin was formed in the northern part of the belt and filled with subaqueous and subaerial conglomerates and allochthonous blocks derived from the orogenic source and deposited ahead of the north-advancing orogenic front. The late syn- to post-orogenic Plateau Group continental molasse (≤ 575 Ma) was deposited partly synchronously with the Fungurume Group in the basin that extended north of the Fungurume foreland.

Therefore, recognition of sedimentary genesis of the Katangan 'megabreccias' reveals two major rifting stages due to Rodinia break-up and two major convergence phases between the Kalahari Craton in the S and Congo Craton in the N, which lead to the Gondwana assembly in the central African sector of the Pan-African orogen.

The Lunar rayed-crater population – Characteristics of the spatial distribution and ray retention

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Global cratering statistics of young impact craters on the Moon is used to unravel potential spatial asymmetries, which may have been introduced due to the particular orbital constellation of a synchronously rotating satellite. Only craters that exhibit bright ejecta rays extending for several crater radii were considered in this study. This crater population is younger than about 750 Ma. The shape of the crater size-frequency distribution does not show strong dependence on the target properties (mare vs. highlands). However, slightly lower frequencies indicate a shorter retention of the visibility of rays in mare units when their visibility is purely due to immaturity and not due to composition. Rays of small craters fade away much faster. Large, old, rayed craters sustain their visibility longer than the average crater population because of the compositional contrast between rays and mare material, and thus obscuring the cratering record when investigated for spatial variations. Using the existence of rays purely based on optical maturity instead of visibility as marker horizon for the Copernican-Eratosthenian boundary, suggests a shift from 1.1 Ga to 750 Ma.

Evaluating the spatial distribution of lunar rayed craters, focusing on latitudinal and longitudinal density variations, no agreement is found when compared to previous analytical and numerical studies. Although there is an apparent hemispherical asymmetry centred close to the apex, the density distribution is patchy and no predicted spatial pattern could be confirmed. Spatial distribution corrections accounting for the lower frequencies in the mare areas did not result in a better agreement with the analytical estimates. Density variations are less than 15 % over vast parts of the lunar surface, and accordingly the uncertainties for absolute surface ages. However, variations of up to 50% are found even for the more numerous small craters. These extreme values are located at high latitudes.

An analysis of the older craters is more challenging (on the Moon) because earlier geological processes complicate the setting, and the orbital constellation of the moon-earth-sun-projectile system altered with time.

The 3.0 Ga Pongola Supergroup – the world’s oldest continental rift or the world’s oldest continental margin?

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The 3.0 Ga Nsuze Group of the Pongola Supergroup is relatively undeformed and arguably the best preserved and exposed volcano-sedimentary supracrustal succession of the Meso-Archean period. In 1985 Kevin Burke, with Kidd and Kusky wrote a paper entitled ‘The Pongola structure of southeastern Africa: The World’s oldest preserved rift?’ (Burke *et al.*, 1985). It generated a lot of debate. 25 years later we are still debating this topic. This would seem a simple topic with a simple conclusion. So why the continued debate? Part of the answer is that the Pongola SG does not clearly fall into any established continental environment and so the succession may be telling us something that we don’t fully understand about rocks in this setting of this period.

The Pongola Supergroup is located close to the eastern boundary of the Kaapvaal Craton in South Africa and in Swaziland. By 3 Ga southern African Archaean crustal development had established the granite – greenstone terrain of the Barberton greenstone belt and its southern equivalents, and had undergone intense deformation. Other greenstone terrains, such as in Zimbabwe, were yet to become established. In relation to the Kaapvaal Craton the Nsuze Group represents the start of a long period of major sedimentary deposits and therefore provides a critical glimpse of Earth history at the earliest stage of crustal stabilization and continent formation. For this reason the tectonic setting of the Nsuze Group is not well understood and may not have modern-day equivalents. Other volcano-sedimentary successions in the Kaapvaal Craton were also becoming established at the same time. The volcanic rocks of the Dominion Group (at the base of the Witwatersrand Supergroup) are located in the central part of the Kaapvaal Craton and are of the same approximate age (but also older), and have been lithologically correlated with the Nsuze Group. This simplistic correlation may not be correct.

This study presents detailed field observations and compositions of samples from several areas in which the volcanic rocks of the Nsuze Group are particularly well preserved. These include the type section of a thickness of over 10 km of volcanic stratigraphy that has a wide range of rock types from basalt to felsic volcanic rocks, as well as the White Mfolozi inlier some 100 km further south. Primary textures and structures (many indicative of shallow water and subaerial environments) include pillow lavas, pyroclastic deposits and pahoehoe lobes with exceptionally well preserved ropey lava tops (Fig. 1). There is also textural evidence of non-mixing of disparate lavas (previously described as liquid immiscibility structures). Over 300 carefully selected samples with well constrained and understood geological settings were analysed at high precision. A bimodal distribution of compositions is observed for the volcanic rocks (peaks at 0.7% and 5% MgO; 74% and 56% SiO₂), with the most abundant rock type being basaltic andesite to andesite (Fig. 2). While a strong crustal signature for Nsuze Group rocks is well established, various sections have quite different lineages and coherent fields for major and trace element and are also different to those of the Dominion Group. Previous data sets of limited extent showed broad and generally scattered trends which may have indicated AFC processes from a single primary magma combined with crustal contamination, but the new data (including ratios of highly incompatible elements and REE) show distinctly different fields relating to individual

volcanic vents tapping a wide range of source materials which include both underlying crustal rocks as well as Archean mantle.

The conclusion from this work is that the succession is not that of a continental rift system, and is also quite different to recent continental margin volcanic environments. It may represent a shallow dipping subduction zone with extensive melting of continental and subcontinental lithosphere.

Reference

Burke, K., Kidd, W. S. F. & Kusky, T. M. (1985). The Pongola structure of southeastern Africa: The World's oldest preserved rift? *Journal of Geodynamics* 2, 35-49.



Fig. 1. Intersecting pahoehoe lava lobes in the White Mfolozi inlier

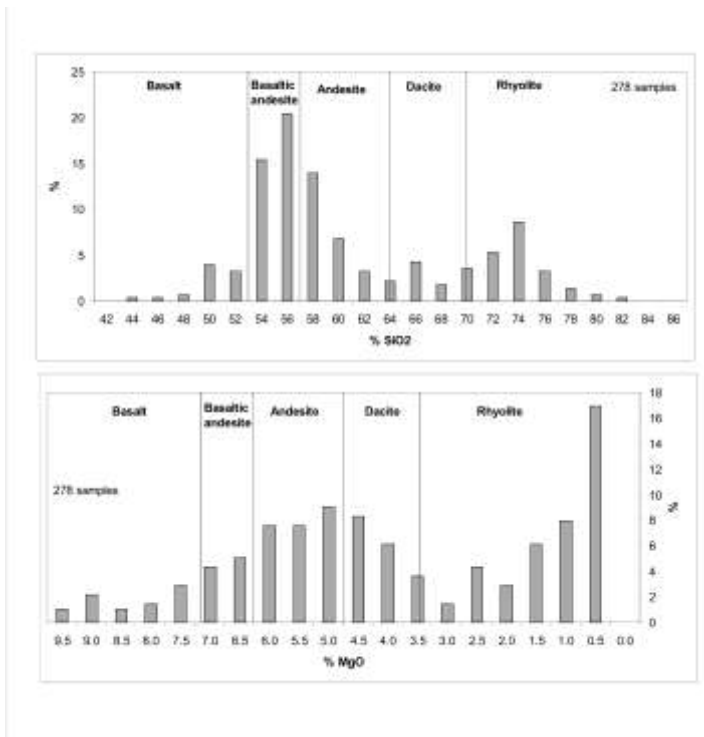


Fig. 2. The bimodal distribution of rock compositions for volcanic rocks of the Pongola Supergroup.

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