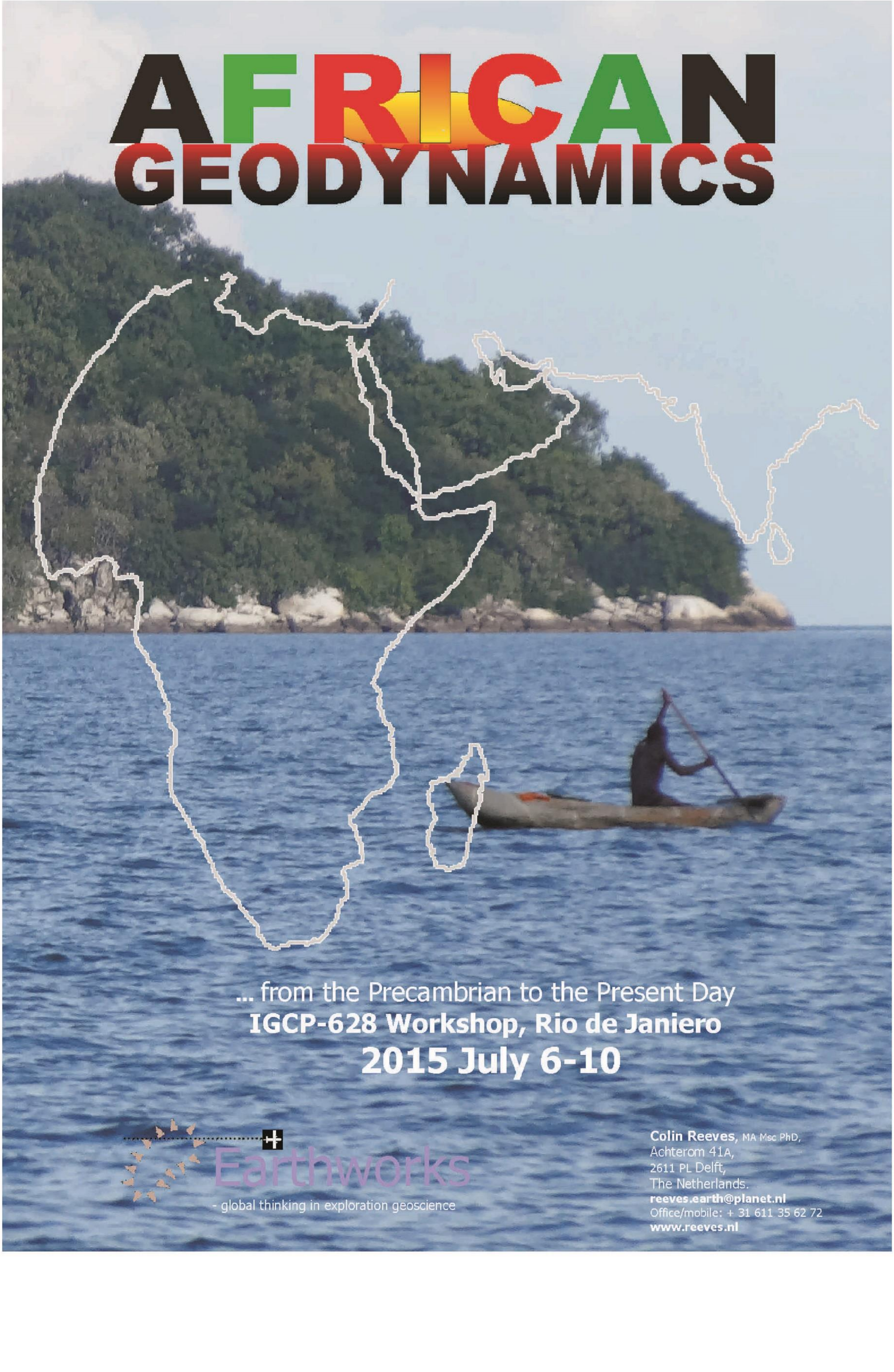
AFRICAN
GEODYNAMICS
... from the Precambrian to the Present Day
IGCP-628 Workshop, Rio de Janiero
2015 July 6-10
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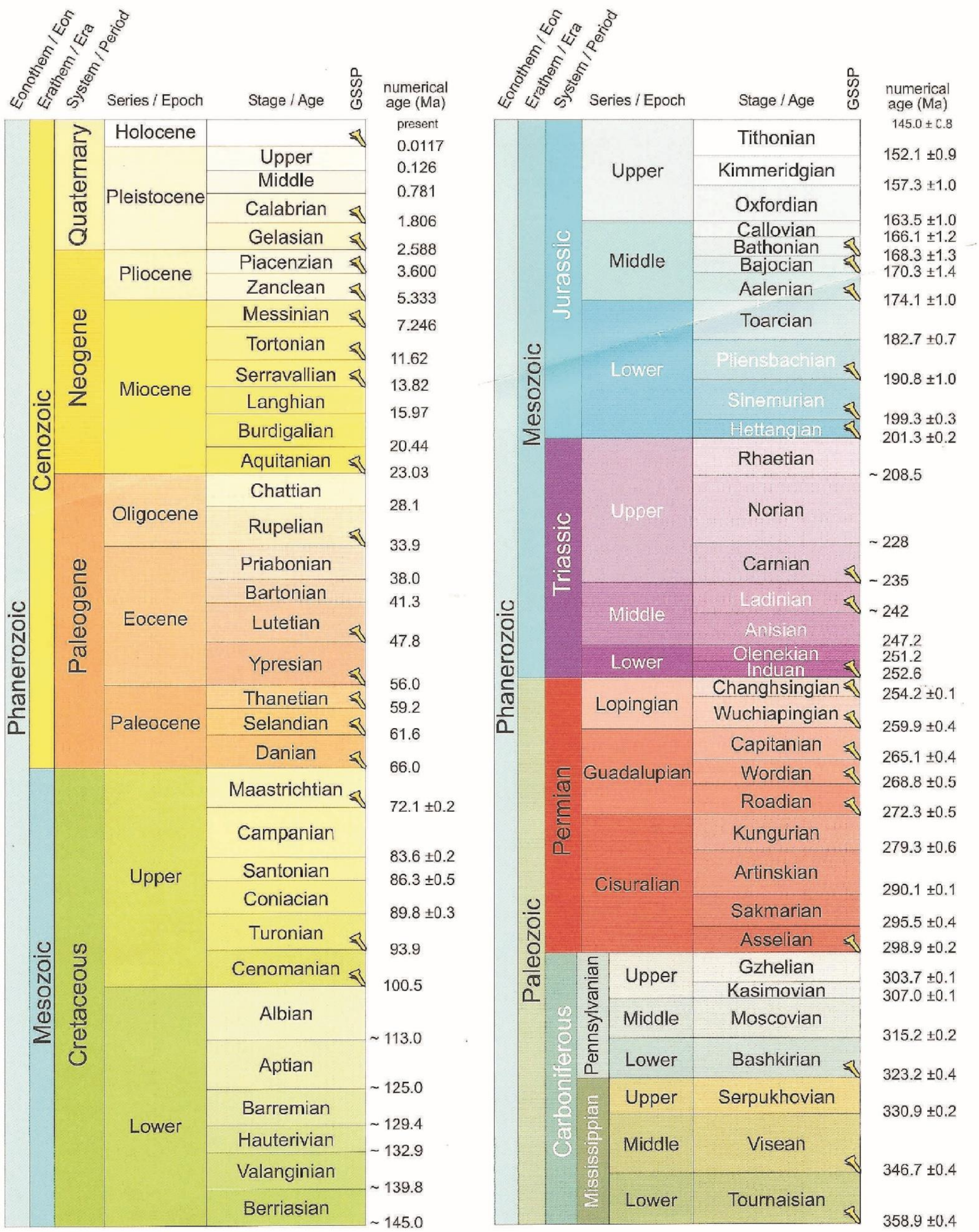

Part of the International Chronostratigraphic Chart reproduced for the 2012 Brisbane 34th International Geological Congress

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AFRICAN GEODYNAMICS

From the Precambrian to the Present Day

IGCP-628

Rio de Janeiro State University

2015 July 6-10

This course attempts to present a simple, credible model for (a) reassembled Gondwana and of (b) the tectonic events that describe Gondwana disruption and dispersal, working primarily from first principles. It is designed to be accessible to all with an interest in this area of earth science. The course draws on a career of regional geophysical mapping in Africa, Australia, India and elsewhere coupled with 20 years working with plate tectonic reconstruction software. It therefore builds on the (still limited) geological mapping and resource exploration of Africa, its extension through geophysics into areas devoid of surface outcrop and its further extension into the context of global tectonics, particularly through Phanerozoic time. It presumes that the correct model should be valid at all scales and be testable at each geological stage. It invites such testing from those with access to local data.

Many of the ideas started as elements of a postgraduate research programme at ITC, The Netherlands that set out in 1993 to investigate the power of geo-information management (GIS) in understanding the geology of the Gondwana continents when linked to the aeromagnetic data compilations of Africa, the Middle East, India and Australia and the magnetic anomaly map of the world (IGCP) that the course leader was involved with in the 1990s. The continued development of this perspective has been supported by many of the consulting projects for the petroleum industry carried out by Earthworks BV since its inception in 2001.

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Delft, June 2015

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Cover picture: A view of Lake Malawi, one of Africa's large rift lakes

Introduction

In this course, the tectonics of Africa through Phanerozoic time is described visually using GIS tools in an attempt to synthesize broad-scale plate tectonic ideas that can be tested against local geological knowledge.

After a long period of stability at the centre of Gondwana, departure of the continents surrounding Africa and the steady growth of oceans between them is quantified. The fracture zones of the ocean floor are critical constraints on continental movements and their growth is systematically rolled back in time from the present day to constrain earlier positions. Conclusions about the earliest phases of Gondwana disruption and the transition to ocean growth are deduced.

Maps, paleomaps and animations are central to conveying these ideas to the participants. The course progresses from the geometric principles of quantitative paleogeographic reconstruction on a sphere to the latest edition of the model for Gondwana dispersal. The presentations are organized into twelve Powerpoint sessions, totaling over 400 slides, as follows:

- **1. Africa Now – our Laboratory**
- **2. Undoing the oceans – Africa and Antarctica**
- **3. Paleozoic Africa – the Centre of Gondwana**
- **4. An African mosaic within Gondwana**
- **5. East Gondwana reassembled**
- **6. Evolution of the Indian Ocean**
- **7. Evolution of the South Atlantic Ocean**
- **8. Evolution of the Bouvet Triple Junction**
- **9. Three Episodes of Rifting in Africa**
- **10. Dykes, Hotspots and Large Igneous Provinces**
- **11. The Architecture of Precambrian Africa**
- **12. Synthesis and Summary**

Each session is followed by a discussion period to which all participants are invited to contribute. The whole of Africa is considered the area of interest, but the focus will be on sub-Saharan Africa where the course leader has had most hands-on experience.

The GIS context

From a starting point of practical resource exploration, we should consider the following statements:

- *We do not know enough about the geology of Africa – or its former neighbours*

- *No one person even knows all that is presently known*

- *Improved access to existing knowledge in convenient format might allow new insights and understanding without even acquiring new data (ICT-GIS approach)*

- *With a comprehensive database, new data-gathering (exploration) campaigns could be targeted at areas that are key to better understanding, from continental-scale to commercial exploration.*

GIS technology for computer map-making and data management, linked to the capability to prepare accurate continental reconstructions for times in the past, provides a powerful work-bench for displaying *x,y*-related knowledge and playing out 'what if?' scenarios that should assist in understanding geological history and testing ideas against data, in both research and education. The role of maps, paleomaps and animations is central.

The ideas presented grew from an initial research project within ITC (now a Faculty within Universiteit Twente, The Netherlands) to investigate the power of geo-information management in understanding the geology of the Gondwana continents when linked to the aeromagnetic data compilations of Africa, the Middle East, India and Australia that Reeves was involved with in the 1990s. The project ran from 1994 until 2000 when the activities of ITC came to an end in Delft. A summary of student theses from this period and refereed publications subsequently arising from the work is given later in these notes.

Previous presentations of the course

- University of the Witwatersrand, South Africa, October 2005
- Dublin Institute of Advanced Studies, Ireland, November 2006
- University of the Witwatersrand, South Africa, November 2007
- AAPG International Meeting, Cape Town, October 2008
- IASPEI Summer School, Cape Town, January 2009
- Private client, The Netherlands, May 2009
- SMMRP, Abuja, Nigeria, January 2010
- University of Kentucky, Lexington, February 2011
- Private client, India, October 2012
- Geological Society of Africa, CAG-24, Addis Abeba, January 2012
- South African Geophysicists Association, Skukuza, October 2013
- Private client, London, April 2014

Course Materials

The materials presented in the course have evolved from a number of talks and presentations given at various international meetings since about 1995. The digital approach to making maps and images matches handily with the capabilities of Powerpoint as a display medium in the classroom and to 'bring geodynamics to life'. As a means of conveying ideas and "mind pictures" this medium is hard to beat when coupled with the spoken commentary of the course leader. A brief summary of the main points of each presentation are presented in the following pages.

In addition, there are a number of formally refereed papers arising from the work that are available as PDF files. Participants are welcome to use all this material for their personal research and teaching as long as the source is acknowledged and some precautions are taken to protect the present author against incomplete referencing of source materials where this may be necessary. Any commercial use should be in consultation with the author. Opportunities and suggestions for future presentations of the course are of course welcomed.

Course Contents

Introductory remarks about the course and its objectives

Session 1. Africa Now – our laboratory

1.1 Topography of Africa and drainage
1.2 The geology of Africa – digital and in overlapping layers
1.3 Geophysics to reveal hidden geology
1.4 The real movement of Africa from GPS
1.5 Seismicity of Africa and the East African rift system

Session 2. Undoing the Oceans – Africa and Antarctica

2.1 The ocean of Africa – the entire African plate
2.2 Principles of plate movements and Euler rotations
2.3 The ocean that separates Africa and Antarctica
2.4 A model for Africa-Antarctica in eight intervals
2.5 Principles: Keep it simple!

Session 3. Paleozoic Africa – the centre of Gondwana

3.1 Prolonged stability, post-Pan-African
3.2 Reassembling Gondwana – the questions.
3.3 The Precambrian elements
3.4 How much separation between them?
3.5 A tight assembly around Madagascar

Session 4. An African mosaic within Gondwana

4.1 Closing the Red Sea and the Gulf of Aden
4.2 The assembly with modified location for Somalia
4.3 The fracturing of North Africa
4.4 South America in place and mega-fractures in Brazil
4.5 Some conclusions from the re-assembly

Session 5. East Gondwana reassembled

5.1 Not just a re-assembly, a working model
5.2 Retracing Indian Ocean fracture zones in four regimes
5.3 Regime 4
5.4 Regime 3
5.5 Regimes 2 & 1
5.6 The fit of Antarctica against Africa
5.7 The fit of Madagascar against Africa
5.8 Propagating rift before transform margin
5.9 The 2015 website animation

Session 6. The evolution of the Indian Ocean

6.1 In forward time: The Karoo-Ferrar igneous event
6.2 The three proto-oceans – Somali, Mozambique, Weddell
6.3 The initiation of dispersal
6.4 The rift between Madagascar and India
6.5 India goes north and the evolution of the Mascarene Basin
6.6 A new ridge system as Australia leaves Antarctica
6.7 The Red Sea and the initiation of rifting in Africa

Session 7. The evolution of the South Atlantic Ocean

7.1 Euler poles for Africa-South America opening
7.2 Issues when the fit becomes tighter in earlier phases
7.3 Ocean, continent and 'extended' crust
7.4 The mechanics of extension
7.5 Features of the early South Atlantic Ocean
7.6 The Atlantic opening animation

Session 8. The evolution of the Bouvet Triple Junction

8.1 Implications for the evolution of the South African south coast
8.2 South Patagonia, the Falkland Islands, etc
8.3 The animation of a triple junction
8.4 The 2012 Gondwana dispersal animation
8.5 Regime changes and the stratigraphic column around Africa

Session 9. Three episodes of rifting in Africa

9.1 Euler poles for the current rifting process
9.2 The mechanics of the Cretaceous rift system in central Africa
9.3 The Karoo/Gondwana rift system in a plate tectonic context
9.4 Hidden Karoo rifts? – Angola, offshore Namibia, …

Session 10. Dykes, hotspots and large igneous provinces

10.1 The aeromagnetic discovery of the giant Botswana dyke swarm
10.2 Extent of Karoo volcanics from aeromagnetics
10.3 Dykes in aeromagnetics and in the field
10.4 Earlier syn-rift injection in the Okavango?
10.5 Dykes in Tanzania and Uganda
10.6 When are dykes only faults?
10.7 The Bangui anomaly
10.8 Bangui and Morokweng (impacts)
10.9 Mozambique dykes - and Antarctica again

Session 11. The Architecture of Precambrian Africa

11.1 Magnetic anomalies and geological reconnaissance
11.2 Magnetic anomalies world tour
11.3 Crustal elements of African and Gondwana
11.4 Gondwana and Rodinia
11.5 What sort of a mosaic – tiles or lily leaves?
11.6 Fault systems at all scales in Africa
11.7 Many maps of African structure, no consensus

Session 12. Synthesis and summary

12.1 Geology and tectonics
12.2 Information and communications technology
12.3 ‘Atlas’ demonstration (time permitting)

Session 1: Africa now – our Laboratory

Maps are central to earth science. Information of value to earth science is increasingly becoming available in the form of digital maps, even via internet, e.g. Google Earth, OneGeology (www.onegeology.org) etc. Exploiting these possibilities should allow professionals to comprehend the geology of a region more easily and opens many new approaches to science and exploration through the sharing of geoinformation.

While geology is essentially three dimensional and located in the crust that makes up the spherical surface of our planet, 2D maps and images are familiar to earth scientists and can now be generated on demand, on screen or on paper, from digital source data at any desired scale and projection. Maps using orthographic projection ('satellite view') avoid the distortions of other projections when viewing large areas of the planet and perhaps help the viewer appreciate the consequences of true 'global tectonics' more readily. Most of the maps shown in this course are in orthographic projection, centred on the area of interest and often emphasize the role of the spherical surface as opposed to 'flat earth' maps.

Maps may show chosen 'themes' and combinations of themes as long as the data available is thoughtfully arranged in GIS layers. Bringing these advantages to African geology as a whole (in the absence of a single geological authority for the continent) needs to be considered for the general good of science and exploration.

Africa is about 20 per cent of the world's land area and is predominantly Precambrian terrane, though the exposure of Precambrian rocks at the surface is limited for many reasons. On a map, outlines of Phanerozoic cover sequences can be added as overlapping layers to indicate the succession of younger 'cover' rocks, where present. The paucity of exposure of the Precambrian 'basement' leads to the still-limited knowledge of Africa's Precambrian geology. Aeromagnetic surveys have been used widely in Africa to reconnoitre these vast unexposed areas.

The continents have moved over geological time, so present-day geography is not appropriate for (world) maps of the geological past. Fairly robust models of these continental movements are now available, along with the software to create 'paleomaps'. Geological information in GIS format can be linked to the relevant continental fragments (by way of a 'plate net') so that the information always moves together with its appropriate tectonic fragment. Geological features can also be 'time-windowed' to appear and disappear at the appropriate age (e.g. flood basalts). So, in principle at least, if the data base is carefully organized with appropriate attributes it is possible to create (world) geological maps for any time in the past.

2015 June 1

Session 2: Undoing the oceans – Africa and Antarctica

The record of recent continental movements (back to about 200 Ma) appears in the topography of the ocean floor (closely-defined only since about 1997) that was created in the process, transforms/fracture zones being normal to conjugate coasts and magnetic ‘stripes’ parallel to them. Geometrical models of continental movements may be checked against these real data. Mid-ocean ridges are seen in the topographic data to be precisely self-sustaining over long periods within close limits.

Relative movement of any two continental fragments may be defined geometrically by an ‘Euler pole’ (defined in present-day latitude and longitude for the reference plate) and the amount of rotation (degrees) about that pole (Euler’s theorem). Correct rotation parameters should show that ocean fracture zones from conjugate plates ‘telescope’ into each other as time is reversed since it may be assumed that such transforms have always been coincident and collinear at the mid-ocean ridge. Rifts and mid-ocean ridges tend to follow lines of Euler longitude, while transforms follow lines of Euler latitude, giving tectonic significance to an instantaneous Euler pole, for example at an active mid-ocean ridge or in an incipient rift zone through a continent poised to split into two continents.

The present world is divided into a small number of large plates (about 10 large ones) in relative motion. Present day motions may be measured directly (using geodetic GPS) but uncertainty increases with time into the geological past. There is no ocean-floor record before about 200 Ma (start of the Jurassic period). Before this time (less accurate) paleomagnetic data has to be relied upon.

Instantaneous rotation poles tend to be stable over long periods of time and so approximate well to ***interval*** poles for that entire period, evidenced from the fracture zone record. Elegant models, it is argued, should invoke only small numbers of interval poles that operate over long periods of time. Fundamental changes in Euler pole positions should therefore be few and far between and reflect some broader change in global tectonics, perhaps even quite remote from the ocean in question; ‘smoothly and without interruption’ is the norm. Mid-ocean ridges are prone to ‘ridge jumps’ when such hiatuses occur. The paths of continents as recorded in the ocean floor may therefore be simplified into a manageable number of *interval* poles to which instantaneous poles approximate over prolonged periods.

Central to understanding the dispersion of Gondwana is the relative motion of Africa and Antarctica – in many ways the most important and least understood movement for which data is also relatively sparse in the ‘Africa-Antarctica corridor’. The work described here has developed eight interval poles that are used to define the relative movement of Africa and Antarctica over the period from about 183 Ma to the present, accounting for almost 6000 km of ocean-floor growth. Theoretically-created ‘flowlines’ may be compared with the actual features of the ocean floor to check the model.

Building a rotation file to define the relative movements of all plate-pairs at all geological times over the whole world is a huge item of work. The work described here builds on decades of research by Alan Smith (Cambridge) and the software of Cambridge Paleomap Servcies Limited. Nearly all rotations of Gondwana fragments have been re-worked and refined by the present author. The file now being used (CR15GSCA.rot, February 2015) contains several hundreds of fragments and sub-fragments and over 1000 data lines with Euler poles and rotations. It is subject to on-going improvement as new constraints become available or when opportunities to make the model more elegant appear, driven by the need for overall economy of hypothesis and the ‘principle of least astonishment’.

One important principle is that subduction has a high threshold and is therefore not easily initiated. Credible models of continental dispersion should therefore be constrained such that new ocean crust, once created, is not subsequently consumed, even locally. If this is the case, then the dispersal of Gondwana should be modelled using only (a) rifting and ridge growth and (b) transform motion along common plate boundaries. This is an important constraint that is often overlooked by ‘blue sky’ thinkers.

Processes occurring at global scale should be reflected in the geology and tectonics observed at field scale, so the rotation model becomes a test-bed for structural interpretation and *vice versa*.

2015 June 10.

Session 3: Paleozoic Africa – the Centre of Gondwana

The earth's crust is commonly thought of as consisting as two types of crust: *continental* and *oceanic*. It may be more useful (within Gondwana, at least) to think of **four** types:

1. **Precambrian** crust that has retained its geometry and thickness since the widespread orogeny at the end of the Precambrian that created and consolidated Gondwana.

2. **Oceanic** crust that has been created during the period of ocean growth since the beginning of the Jurassic.

3. Precambrian **continental** crust that has been **extended** in the processes of rifting before ocean-floor spreading began and now forms a rim around each Precambrian fragment that adjoins an ocean and also occupies rift zones between otherwise still-adjacent Precambrian fragments.

4. Crust undergoing **compression**, shortening and eventually subduction. This category need not concern us greatly as collision and subduction is virtually absent from the pattern of Gondwana dispersal discussed in this course.

A model of Gondwana has been built with a mosaic of extant, rigid Precambrian fragments (Type 1 crust) separated by gaps of only 60 to 120 km. Within these gaps, Precambrian crust that was present at full thickness and exposed at the surface in Gondwana times has been stretched and lost below younger cover in rift zones and passive margins. The Precambrian shoulders of these rifts, it is argued, are (often) still to be found in outcrop or in geophysical coverage (such as aeromagnetic or gravity survey) and mark the boundaries between the rigid, non-extended parts of the crustal fragments and the extended margins. The merits of this model are presented and defended; many authors prefer wider separations of the fragments but this raises other, more difficult problems that the present approach avoids. Each of the 50-odd Precambrian fragments that make up Gondwana is assumed to have retained its shape throughout Phanerozoic time.

The evolution of thinking about the neighbours of Madagascar in Gondwana (Reeves *et al.,* 1987, Reeves *et al.,* 2004) shows the logic of the process which was subsequently extended to all of Gondwana.

If a starting Precambrian crust of 38 km thickness is imagined and a zone twice this width (i.e. 76 km) is stretched to half its thickness, the stretched zone becomes 152 km wide. This gives an extended crust of 76 km width and 19 km thickness on each of the two conjugate margins, assuming it divides equally down the middle (unlikely, in practice; rifting is often asymmetrical). The outlines of these extended margins will, of course, overlap by about 76 km when the fragments are re-assembled. Inspection of the aesthetically acceptable reassembly indicates a somewhat greater overlap, suggesting that the actual stretching may be closer to 3 times than 2. Of course, it will vary from place to place, depending on the structures involved. A strike-slip fault evolving into a 'transform margin' may create a particularly narrow zone of stretched crust, for example. But the overall result is not inconceivable and proves to be a profitable line of thought.

2015 June 10

Session 4: An African mosaic within Gondwana

Applying the approach outlined in Session 3 to the Red Sea, even a very tight closure between the existing traces of Precambrian outcrop does not cause Precambrian outcrops to overlap and so violate mapped geology. But even the tightest closure of the Red Sea does *not* close the Gulf of Aden. To do this requires the rotation of the Horn of Africa with quite large relative movement with respect to the rest of Africa. This occurred primarily in the Ethiopian rift accompanied by a small relative movement in the Anza graben in Kenya. Somalia is then an example of a sub-plate within Africa that can be imagined to have moved slightly with respect to the rest of Africa. (Even slight relative movement in a rigid crust is enough to cause a rift, as well as to change the outline of the continent.)

A tight closure of the conjugate geologies of Africa and South America south of the Niger delta is also possible (Reeves *et al.,* 2004; Reeves, 2010). We can make a reassembly that closely resembles the present-day East African rift in this way. But it leaves a tapering gap between the coast of Africa west of the Niger delta and the north coast of Brazil. This may be closed by rotating NW Africa through about 10 degrees with a pole near the Niger delta. The space so created within north Africa may be filled by adjusting the various sub-plates in North Africa, closing the Cretaceous rift system (see Session 9) that now separates them. Principally this involves moving NE Africa to the west, undoing the dextral strike slip on the main near-E-W fault. Extensions involved are comparable with the sedimentary sections observed in seismic data across the rifts. More of the sub-plates that make up the African mosaic are defined by the Cretaceous rifts. In practice, in reverse time, the north coast of Brazil is first closed against West Africa, then closure of the longer conjugate coasts proceeds south from the Niger Delta (see Session 7).

Large plates such as Africa should, then, be envisaged as a mosaic of smaller sub-plates with quite modest relative motion. The stable cratons and less stable mobile belts and rifts of Africa form a mosaic of about 20 fragments to which plate tectonic modeling may be applied – as with the continents. With the plates within Africa, no large stretches of ocean are created between them, except where a fragment such as Madagascar has actually become detached from the continent. The theory of plate rotation is unchanged. Rift and shear zones are typical markers of inter-cratonic pathways.

In general, extension during rifting is very slow and prolonged as compared to rates typical of ocean growth. This presents an additional uncertainty for accurate reconstructions and exactly how much separation to leave between the Precambrian parts at any given stage when rifting may already have been active. Some oceans turn from rifts to oceans very quickly, others are very slow to evolve, yet others become simply failed rifts. We cannot assume that the pattern of ocean growth established once rifting turned to drifting tells us everything (or anything!) about what happened in the earlier rifting phase.

Fragment movements (‘drifting’) must be driven by the sum of (a) the current of the underlying asthenosphere, (b) ‘ridge push’ and (c) ‘slab pull’. ‘Ridge push’, once established, should have a certain fixed value per unit length of ridge. (Transform offsets will provide friction that reduces the effect of the push). It would therefore operate most efficiently on a cylindrical earth where every line of (Euler) latitude would be an (Euler) equator. It is notable that many of the ‘big player’ ridge sections on today’s earth fall within the tropical latitudes of their Euler poles where ridge-push operates most efficiently. For similar reasons, it is difficult for large fragments to *rotate* (Euler pole within the fragment) rather than <u>translate</u> (Euler pole 90 degrees remote from the fragment). Rotations tend to be limited to small fragments (like Sri Lanka) that are at the mercy of the major players in the global regime at the time. There is thus a global tendency for large plates to have translational (rather than rotational) motions. On a sphere, the only difference is the distance from the Euler pole. The most efficient spreading pattern must be optimized over the whole globe.

Further reading:

Reeves, C.V., Sahu, B.K., and de Wit, M.J., 2004. A re-examination of the paleo-position of Africa's eastern neighbours in Gondwana. Journal of Africa Earth Sciences, **34**, 101-108.

2015 June 10

Session 5: East Gondwana reassembled

The means of making a 'paleomap' of the continents at a given time in the geological past has been demonstrated. An ***animation*** is a sequence of such reconstructions presented as a series of frames shown consecutively. Much may be learnt from building such sequences then observing them critically for credible, smooth movement. Some of these criteria are reviewed. Critical examination of results leads to incremental improvements in the model – a protracted process that hopefully converges – eventually!

First, it is to be expected that the movement of the continents is steady and virtually unstoppable, so abrupt events in an animation might be questioned as to their veracity. Judicious adjustment of parameters in the rotation file within the limits of uncertainty of the data can enable smoother, more credible movements to be achieved in any animation. Constantly seeking means of improvement and refinement means that the task is never truly 'finished'.

Second, the situation at each moment in time has to be compatible with the geological information for that time. The dynamic model can, therefore, be tested by observing local geology at times in the geological section when, for example, a rift starts developing.

Third, there appears to be a considerable threshold to overcome before subduction can be initiated. Outside of well-defined subduction zones, then, modeling is limited to constructive (mid-ocean ridge) and strike-slip (conservative) movements. Ensuring that no overlaps occur, even if they get opened again, is an additional powerful constraint on what can be modeled on the sphere of the earth – a fact often overlooked by those who want to propose new 'blue sky' reconstructions ignorant of the extensive framework of what is reasonably possible. In general I have invoked 'economy of hypothesis' as much as possible – also known as the principle of 'least astonishment'. Occam's razor: The principle states that among competing hypotheses that predict equally well, the one with the fewest assumptions should be selected.

The building of the latest (2015) Indian Ocean animation is illustrated by way of showing the reversal of transform creation in reverse time animation. Four distinct regimes of ocean creation are evident from the fracture zone data, despite the paucity of magnetic anomaly picks in the Indian Ocean and their total absence in the time interval 83 to 125 Ma (the Cretaceous Normal Superchron or Quiet Zone). The present regime (Regime 4) with India and Australia as essentially one plate has existed since about 47 Ma (mid-Eocene).

From ~47 Ma to ~88 Ma (Regime 3) India executed its rapid northward movement. Followed in reverse time, this brings the margins of the 'older' ocean around Sri Lanka into contact with its conjugate off Antarctica with a pattern of fracture zones matching very convincingly. Pre-88 Ma (or perhaps earlier), two mid-ocean ridges existed either side of India. That between India and Antarctica (Regime 2) developed more recently (almost entirely since the start of the Cretaceous) while that between India and Africa-Arabia (Regime 1) started at about 183 Ma in the Middle Jurassic and became defunct after about 100 Ma. The exact relationship between India and Madagascar is still unresolved in this model, but a credible, tight Gondwana reassembly is achieved for 183 Ma. Note the 'overlap' period during which Regime 1 dies out and Regime 2 takes over. During this overlap period we argue that India must have travelled to the south with respect to Madagascar by almost 1000 km with the development of an extensive transtensional rift between the two.

2015 June 10

Session 6: The evolution of the Indian Ocean

New (2010) ocean magnetic anomaly data off Mozambique demonstrate exact positions for Antarctica with respect to Africa in the early stages of their separation (150-127 Ma approx.), eliminating many degrees of freedom in models developed earlier. Of key concern here is the area of the Mozambique plains. Are they continental or oceanic? Or extended continental crust? What is the role of the Lebombo feature at the eastern margin of the Kaapvaal craton? And the dyke swarms evident around the South Africa-Zimbabwe-Mozambique border?

The Karoo-Farrar igneous event at 183-178 Ma (Karoo basalt, Giant Botswana dyke swarm) has often been cited as the key event in Gondwana disruption. A range of Euler poles that could effect the transition from the oldest credible Africa-Antarctica fit from the magnetic anomaly data (at about 150 Ma) to the Gondwana assembly advocated here was derived by geometrical construction.

The next assumption was that East Gondwana should be kept intact as long after initial disruption as possible. The path of Madagascar from its present position to its Gondwana 'fit' position was examined. This is defined by the arcuate 'original' Davie fracture zone (ODFZ) which describes the relative movement of Madagascar and Africa (apart from some reactivation during Eat African rifting?). Transcribing this path onto Antarctica (as a proxy for East Gondwana as one plate) in the Gondwana re-assembly shows that this fault trace will coincide with that on Africa at about 150 Ma, demonstrating that East Gondwana may indeed remain intact until at least this time.

So Madagascar may be moved from its present position back to a position where it ***is*** fixed within East Gondwana at about 150 Ma using the ODFZ. What is then needed to bring Madagascar from that 150 Ma position to its situation in the final reassembly? This may be calculated and the necessary Euler pole falls *somewhere* on a great circle bisecting two conjugate points (Madagascar and Africa) at their 150 Ma location. The intersection of this great circle with that drawn for the Antarctica-Africa reconstruction defines a unique Euler pole that brings the whole of East Gondwana against West Gondwana in the fit position advocated. The position of this pole indicates that the first Gondwana disruption was a reactivation (or continuation) of the Karoo rifting in eastern and southern Africa.

With this rationale, East Gondwana must start disrupting at about 150 Ma as Madagascar cannot follow *both* the ODFZ-defined path *and* East Gondwana at younger times. Relative movements are at first modest and we distribute them between dextral transtension between India and Madagascar and growth of an initial ocean between India and Antarctica-Australia. The start of this ocean is ill-defined by ocean magnetic strip data but growth would become several times faster after about 124 Ma when Madagascar became part of the Africa plate and the transition from Regime 1 to Regime 2 was complete. Before this time (about ~136 Ma) the Antarctica-Africa spreading ridge moved outboard of the Mozambique Rise and Antarctica followed South America more to the west. Note that both the Tristan and Kerguelen plumes broke out at about this same time.

The transition from Regime 1 to Regime 2 must have occurred as the Antarctica landmass cleared the obstacle of continental Africa and its attempts to move west became possible. Is there a role for Coriolis forces as Antarctica (East Gondwana) gets closer to the geographic pole of rotation than Africa (West Gondwana)?

Starting from our reconstruction of Gondwana, the main events in the creation of the passive margins of the east coast of Africa and both coasts of India are now described in forward time.

The east, west and south margins of Madagascar underwent distinctly different processes as India and Madagascar moved south. Any relative motion between India and Madagascar is still only poorly defined. We have chosen to confine this motion to the steady development of transtensional rifting along an old line of weakness that is now preserved as the east coast of Madagascar and the west coast of India. Madagascar came to rest as part of the greater African plate at about 125 Ma. The Madagascar Rise continued to move south for some time, even after India finally left Madagascar in its remarkable change of travel direction at about 88 Ma and the outbreak of the Marion plume.

After about 25 million years of operation, 88 to 63 Ma, the Mascarene Ocean basin between Madagascar and the Seychelles-Mascarenes became a fossil ocean in the Paleocene, shortly after the eruption of the Deccan Traps in India. A second mid-ocean ridge, already penetrating from north to south near the west coast of India took over as the principle source of future ocean-floor, though its precise location jumped several times in the process. The Seychelles and Mascarene fragments were peeled away from India by its initial action. The whole of the rapid northward motion of India, 88 to 43 Ma (Regime 3) can, nevertheless, be described quite accurately by a single Euler pole for the movement of India with respect to Africa.

At about 47 Ma, a major ridge reorganization occurred across the Indian Ocean as relative movement between Antarctica and Australia started at something like its present pace with India and Australia becoming (virtually/identically) a single plate. This most recent phase of activity (Regime 4) is punctuated only by the advent of the Gulf of Aden and Red Sea rifting and the initiation of the East African Rift system at about 24 Ma.

Animations illustrate the different character of the four regimes of ocean-floor spreading, three of them divided into two by sub-events. Major (and minor) regime changes are therefore suggested at about 183, (136), 125, 88, (65), 47 and (24) Ma.

2015 June 11

Further reading:

Reeves, C.V., and de Wit, M.J., 2000. Making ends meet in Gondwana – Retracing the transforms of the Indian Ocean and reconnecting continental shear zones. Terra Nova **12**, 272-280.

Reeves, C.V., Teasdale, J., and Mahanjane, E.S., (in press). Insight into the eastern margin of Africa from a new tectonic model of the Indian Ocean. Geological Society, London. Special Publication. Transform Margins.

Session 7: Evolution of the South Atlantic Ocean

Key points

The Atlantic Ocean includes two key elements that originally underpinned early thoughts about the operation of plate – or global – tectonics. In the North Atlantic, the magnetic anomaly 'stripes' attributable to geomagnetic field reversals during ocean floor creation are well revealed by numerous shiptracks. And, in the South Atlantic, the remarkable similarity between geometry of conjugate coastlines is supremely evident. The clear definition of ocean-floor topography (1997) and the evidently persistent coincidence and co-linearity of transforms provides a third, more recent, constraint on modeling continental movements precisely. We shall deal here only with the South Atlantic Ocean.

Ocean floor in the South Atlantic created since 83 Ma (when the Cretaceous Normal Superchron or quiet zone ended) is well endowed both with magnetic anomalies and transform faults/fracture zones revealed in their topographic expression. Together they form a set of natural 'coordinates' that may be used to reconstruct the relative positions of Africa and South America throughout that period with a high degree of certainty. Plotting Euler latitude and longitude lines about a published Euler pole for South America *vs* Africa (off SE Greenland) demonstrates excellent agreement of transforms with latitude lines and anomalies with longitude lines for the whole period from now back to about 79 Ma. Some slight systematic deviations are interesting but minimal.

Pre-79 Ma, the transforms are markedly more curved, indicating a rotation pole much closer to Africa. A pole off the NW coast of Africa may be found that shows a good fit to these older transforms (apart from the oldest parts of the Falklands Agulhas Fault Zone – see later) and, operated at a reasonable rate (the period is devoid of magnetic anomalies, of course), brings the north coast of Brazil against the coast of West Africa in a way consistent with reconstructions east of Africa at about 120 Ma. Note the continuity of long-distance fault features mapped in Brazil into Saharan and Central Africa in this South America-Africa reconstruction.

There remains a large misfit between the east coast of Brazil and the African coast south of the Niger delta which widens consistently to the south, from zero in the region of the Niger delta itself. To close this gap requires Africa to be broken into more than one plate (we use the sub-plates already described in Session 2) and for NW Africa to follow South America closely in the period from 120 to 140 Ma (these dates ill-constrained).

Using the edge of the extended continental crust mapped by industry we can assess the stretching of the Precambrian crust prior to rupture and arrive at a figure of about 2.5, not very different from that obtained for the East Gondwana reassembly. Note that it takes several million years for the zone of active crustal stretching to propagate northwards from the Cape to the Niger Delta. Note also that, whereas we can envisage the South Atlantic being initially 'levered apart' (probably by the actions of the Tristan plume), once the mid ocean ridge is established throughout its whole length (joining up via the Equatorial Atlantic with the pre-existing North Atlantic ridge), 'ridge push' tends to keep the separating sides of the ocean parallel to each other in later times. Note that a significantly different initial Euler pole (in the vicinity of the Niger delta) describes the first phase of South Atlantic opening. As with the East Coast of Africa, it would seem that a phase of rift propagation (in the case of the Atlantic, from south to north) preceded coast-normal ocean-growth.

The early activity of the Walvis Ridge/Tristan hotspot led to the damming of the South Atlantic and large volumes of subaerial volcanic material being deposited in the (dry?)

early rift floor. Meanwhile, marine incursion over the Sahara (perhaps assisted by waterways of the central Africa rift system?) filled the South Atlantic basin north of the Walvis Ridge intermittently, leaving an extensive salt basin. Movement of the later sediments resting on this mobile salt pillow is responsible for the development of oil-bearing structures of enormous economic significance in Brazil, Angola, Gabon, etc. Now the ‘pre-Salt’ sediment package is also of economic significance.

2015 June 11

Session 8: Evolution of the Bouvet triple junction

South of the Walvis Ridge, the situation is somewhat more complex and deserves closer study. As early as 178 Ma, the great Botswana dyke swarm indicates a clockwise rotational force was active on southern Africa relative to the rest of the continent. Jurassic rifting with N-S extension is evident in Patagonia and the extension of South America that resulted makes the present continent too long for a rigid reconstruction to fit the Falklands plateau to the Agulhas fault without first undoing this extension. This early movement may be fitted with the initial East-West Gondwana pole derived in Session 7.

Models built on sound evidence have been presented for the ‘panels’ of ocean that were created by relative movements of Africa and Antarctica and Africa and South America respectively. There is a similar set of movements (complex!) between South America and Antarctica that will not be considered here. The three ocean panels so defined surround the area of the Bouvet hotspot and its triple junction. All the levels of complexity typical of modeling triple junctions will only be touched upon.

Three large magnetic anomalies observed from the CHAMP earth-orbiting satellite appear to have a common origin in the crust created around this triple junction by its associated hotspot during the Cretaceous Normal Superchron. Constraints provided by all the most recent work are employed in an animation of the series of tectonic events that set the south coast of South Africa apart from either the east coast or the west coast of the continent to the north.

Ideas from 2008-9 suggested that (a) the various plateaus such as the Falklands Plateau, the Agulhas Bank, the Mozambique Plains and the Mozambique Bank are NOT of continental nature but have an origin in the early history of the Bouvet mantle plume and (b) the gap between South Africa and Dronning Maud Land, Antarctica, was originally filled within Gondwana by the ‘Grenvillian’ terrane of South Patagonia and the Falklands Island themselves. This allows an elegant solution for the start of Gondwana disruption and the growth of the early ocean around South Africa. These ideas are referred to in an extended abstract and a poster (both from 2009) appended at the end of these notes. The newer (2015) offers another, perhaps more credible, model of events off the south coast of Africa.

The March 2015 animation of the whole story of Gondwana dispersal is presented and discussed. An animation showing this dispersal with emphasis on the continuity of the ocean fracture zones is shown on the website www.reeves.nl. This is supported by a series of images in higher resolution images with the ocean shaded in the colours of the CGMW Geological Map of the World.

Finally, possible relations between events in plate dispersion and the sedimentary record are indicated. Plate tectonic events that occurred within the Indian Ocean, it seems, have their effects much further afield, including all the coasts of Africa and its internal basins. This underlines the truly global significance of global tectonics.

2015 June 11

Session 9: Three Episodes of Rifting in Africa

'No smoke without fire' – no plate disruption without rifting.

So far we have seen (a) long periods of continental stability (such as Gondwana in the Paleozoic), (b) rifting, sometimes prolonged, without more than a few tens of km of translational movement, (c) stretching of the Precambrian crust to half thickness or less prior to rupture, and (d) thousands of kilometers of ocean growth (e.g. South Atlantic Ocean) between passive margins. This session examines the evidence provided by three rifting episodes *within* Africa that occurred during the Phanerozoic: the present **East African Rift** (0-30 Ma), the **Cretaceous rifts of central Africa** (120-140 Ma) and the **Karoo rifting** of central Gondwana (200-300 Ma), the last-mentioned contemporaneous with similar events in India and Antarctica.

Rifting within a mature continent profoundly affects drainage patterns. Rift shoulders rise, tending to lead water *away* from the axis of any rift. As mature rift flanks, coastlines often include rift shoulders which similarly drain water inland, away from the coast, leading to only a few escape routes of the resulting internal drainage basins to the sea (Congo River, Zambesi, Nile…). Only a small number of major deltas are to be found around the whole coastline of Africa. A similar situation applies in India.

Apart from topography, rifts are characterised by seismicity and, sometimes, volcanicity. Rift extension rates may be measured directly but are generally very small, 1-2 mm per year (1-2 km per million years) in East Africa, for example. The pre-existing fabric of the continental crust seems to influence the location of rift valleys profoundly, at least on a regional scale. The older cratonic areas seem to be unfavourable for the propagation of rifting. The Ethiopian Rift (the third arm of the Gulf of Aden and Red Sea trio) bifurcates elaborately to avoid the Tanzanian craton, for example.

While the East African rift runs N-S, the fabric of the crust imparts NE-SW and NW-SE fault directions that become local rift basins and accommodation zones respectively. Repeated bifurcation towards the SW and approach to a suggested Euler pole in the South Atlantic reduces the rift from a clear unity in Ethiopia to an array of minor rifts, such as the Okavango, in southern Africa.

In many cases, the lines of weakness exploited by rift systems are long-lived and may find a role repeatedly (even with differing senses) as stress systems change over geological time (resurgent tectonics – "once a weakness, always a weakness"). No role exists for the 'second-weakest link' in any system; sufficient weakness directions pre-exist such that there is always one 'close enough' to the optimum direction to fail again when the stress field is appropriate.

The extents of the Cretaceous rifts in north and central Africa are examined. They are not exposed at the surface but have been mapped largely as a result of geophysical exploration. They host oil supplies that are currently in production in southern Sudan and in Chad. Maps from several different sources reveal the pattern of faulting associated with the rift system.

Taking the Gondwana reassembly on the east and west of sub-Saharan Africa as fixed, the position of north Africa can be reviewed by a rotation of it about a pole in the Congo craton to indicate an optimum position, compromising between rotation of West Africa and rotation of Somalia. Uncertainties arise where there has been more than one phase of rift activiation, or even – as in the Benue trough – a compression phase following extension.

The rifts of the Karoo system pointedly avoid the cratons of Zimbabwe and Tanzania. The time-equivalent 'Gondwana' rifts of India do likewise for the Indian cratons. The Gondwana reconstruction of Karoo rift basins between East Africa and Madagascar demonstrates the continuity of the whole rift system through India and into Antarctica. The alignment of rifts from Somalia to NW Botswana (the southern trans-Africa shear system, STASS) is the manifestation of a major shear zone that bisects the whole of Gondwana. It may be extended across the Tethys Ocean where it unites with the Ural mountains which were formed by the collision of Asia with Europe at about 250 Ma. The two plate-systems Europe-West Gondwana and Asia-East Gondwana across the Tethys Ocean were slightly independent since Gondwana was not entirely rigid, thanks to adjustments along the STASS and consequent rifting in adjacent regions. This is a particular example of how events at a global tectonic scale have consequences at the scale of local sedimentation.

The whole of Gondwana may be interpreted as crisscrossed by major linear features with affinities to small circles – and perhaps lines of Euler latitude at times in the past? Such features are not easy to see in the field and they can be easily concealed below younger cover. But we should remain alert to their possible existence. Even small weaknesses in large plates can become the locus of rifts and sedimentation. And, as in North Africa, the whole outline of large plates may be adjusted by modest internal movements across internal rift zones.

2015 June 12

Reeves, C.V., 2013. Global tectonics, Rifting and the fabric of Africa. Extended abstract. Society of Exploration Geophysicists, 'Exploration of Continental Rifts' workshop, Houston, September 26.

Session 10: Dykes, Hotspots and Large Igneous Provinces

Aeromagnetic surveys are very good at revealing dykes since the latter are often strongly magnetic, in contrast to their host rock. Such surveys reveal the geometry of dyke swarms in a way that is not easy for conventional geological field mapping. A case in point is the giant Okavango Dyke Swarm that crosses north Botswana that was first recognized from aeromagnetic surveys carried out in 1975-6.

By contrast, large expanses of flat-lying lava and extrusive volcanic rocks are usually only weakly magnetic, especially when surveyed from the air. They tend to impart only 'noise' on magnetic profiles. Even so, this noise has enabled the extent of Karoo age basalts to be mapped extensively across large areas of central southern Africa where they lie hidden below Kalahari sand cover.

The dykes and basalts of southern Africa are mostly attributable to the activity of the Bouvet/Karoo hotspot which 'struck' at about 183 Ma. This is often referred to as the Karoo or Ferrar (in Antarctica) plume. More will be said about hotspots at the end of this session.

Dyke swarms are recognized from aeromagnetic surveys elsewhere in Africa. A vast semi-circular dyke swarm has been recognised in Tanzania and Uganda and could perhaps extend into DRC where there is, as yet, no aeromagnetic coverage. Attempts at finding one of these dykes in outcrop have so far failed, but from the aeromagnetics they appear to predate Proterozoic sedimentary cover.

Coast-parallel dykes are a feature of many areas – southwest Africa, Red Sea, Indian west coast, etc. They are presumably associated with early stages of rifting that turned eventually into passive margins.

In the detail of the highest-resolution aeromagnetic surveys, dykes are evident, as well as some faults revealed by the *destruction* of magnetite in the vicinity of faults. The main difference between a dyke and a fault is the injection of magmatic material into the fault plane that is associated with dyke formation. Note, interestingly, that such injection thoroughly seals the fault so that, unlike other faults, it is almost never re-activated. A result is that dykes appear in swarms where many dykes follow similar but different paths, often almost regardless of the country-rock geology.

A word about impact structures and their relation to geoinformation. The Bangui anomaly in the Central African Republic has been recognized since the earliest satellite magnetometer missions as one of the biggest anomalies on earth. Its relationship to other types of geological map data is demonstrated and geophysical limits on its physical dimensions mentioned. Its geological origin is still unexplained.

A large impact has been recognized at Morokweng in southern Africa. Again it is a geophysical discovery, but it has been drilled (including fragments of meteorite) and dated. It occurred precisely at the boundary of the Jurassic and Cretaceous eras. It can be speculated that this – and the start of full-blown dispersal of the Gondwana continents – is not purely coincidental but this is far from proven. Even large meteorite impacts can be no more than a trigger to plate-tectonic events.

Returning to dykes, by way of a recent example, attention is drawn to the new aeromagnetic coverage of Mozambique that was achieved 2000-05. The extensive dyke swarms of Botswana and South Africa could be expected to extend into Mozambique. The fact that they don't suggests that the Precambrian rock into which they were injected is missing east of the Lebombo monocline – or is at least buried very deeply below younger sediment below the plains of Mozambique. The new data draws attention to the relationship between Africa and Antarctica in the early Jurassic. The 2010 ocean magnetic anomalies (Konig and Jokat, 2010) refine the possible solution for ANT-AFR movements in this period. It is suggested here that the Lebombo monocline was a pre-existing strike-slip feature when the first relative movement of Antarctica against Africa occurred at about 183 Ma. The dispersal model discussed in Session 8 suggests that this became a major dextral transtensional feature with the first substantive movement of East Gondwana against West Gondwana, one of three elements making up a triple junction.

Finally we return to hotspots and mantle plumes. A small number of plumes punctuates the geological history of the last 200 million years and evidently had considerable influence on the break-up and dispersal of Gondwana and, consequently, present day geography. Their activity is illustrated again by reference to the animation of Gondwana dispersion. Note how their output loads the ocean crust with vast quantities of magma. Usually a mantle plume starts with material erupted or injected over a wide radius (1000 km or more) but continues with decreasing output and finally has a long-lived phase with a rather precise vent location. The animation shows this for the Tristan, Bouvet, Marion, Reunion and Kerguelen plumes. The plumes are thought to have their origin at the core-mantle boundary.

2015 June 12

Session 11: The Architecture of Precambrian Africa

We set out (in part) to see what we could learn about Precambrian geology using GIS and plate reconstruction software. It is this part that is reviewed in this penultimate session.

Aeromagnetic coverage is pre-eminent worldwide in frontier geological exploration and it works well, even over regions obscured by younger cover. A brief tour of the magnetic anomaly maps of the northern continents and Australia is presented. The coverage of Africa is less good and less complete, but a large part of the value of what exists has still not been exploited. The coverage of aeromagnetic surveys in Africa is reviewed briefly.

The first magnetic anomaly map of the world was published in 2007 and is available digitally. A first world magnetic susceptibility map was presented in rough form in 2008. Access to such data sets is facilitated by internet tools such as Google Earth. GRACE world gravity data also gives new insights. Some examples are shown of attempts to interpret aeromagnetic data in different parts of the world to give deeper understanding of the structure and lithology of the Precambrian crust.

In the plate-tectonic approach presented here, the African Precambrian crust is perceived as fragmented into about 20 sub-plates, fragments or mosaic elements. Their behaviour is likened to that of a mosaic under stress. But analogy to the behaviour of lily-leaves on a pond may prove instructive. Immense crustal strength to transmit pressure over long distances is not needed if movement of the substratum is the main source of stress (an underlying current in the mantle). Each element has a Precambrian core – ‘craton’, provided we are careful to understand what we mean by it – that has remained rigid throughout the Phaneorzoic. Various stresses applied to the mosaic have led to rifting and/or shearing in the corridors between cratons with the result that the margins have become extended – to half or less of the original thickness where the rifting has continued into the creation of a passive margin.

Various sources of information on the occurrence of faults such as satellite imagery, geophysical data, published interpretations, etc. are shown. While they all differ in detail (and scale!) they also tend to support the idea of a mosaic of cratons. Fracture patterns are well established in a few key directions across large areas of Africa.

2015 June 12

Session 12: Summary and Synthesis

We set out by seeking (1) to see African geology in its Gondwana context and (2) to see what ICT could do to help us see things more clearly.

1. Geology

The simplicity of global tectonics serves us well, but describing the whole world in just ten plates is overly simplistic, particularly if we seek to find manifestations of tectonic processes at field scale and *within* continents. From the point of view of Africa, it is more informative to think of the continent in terms of about 20 plates or fragments (sub-plates, or in some senses, cratons). For the whole of Gondwana this becomes about 50 fragments. The exact number is uncertain as there are some likely boundaries that have not actually moved, at least as far as the current model is concerned.

Each fragment has a piece of Precambrian crust that we have assumed has the same size and outline shape today as it had at the end of the Precambrian. The margins – often rift 'shoulders' of some earlier time – can be found on geological maps and in geophysical surveys such as aeromagnetic and gravity.

Some of these fragments have Archean 'cores'. In some cases, Proterozoic mobile belts have formed around these ancient cores, building defences that help ensure the longevity of the cratons. Not surprisingly, rifting between cratons is often along these zones; the cratons themselves are resistant to fracture. Studies in southern Africa suggest that the mantle below the Kaapvaal craton to a depth of about 400 km has remained attached to the craton for a long time.

Where shearing and/or rifting has occurred, the pre-existing Precambrian crust in the rift zone has been extended and lost from surface view below younger cover. Where rifting has gone as far as the generation of passive margins, the Precambrian crust was probably reduced to half or less of its original thickness, producing margins to the fragments, some of which have been shown in some of the animations. The fabric of the initial Precambrian crust – weakness zones, solid Archean cratons, a pre-existing pattern of faults and fractures – has influenced profoundly the way in which Africa has responded to different stress fields through the Phanerozoic. *Resurgent tectonics* involves repeated re-activations of the same weakness. The changing of the shape of the continent by small adjustments between the elements of the 'African mosaic' is important when making global plate tectonic reconstructions. Most often, these changes occur by way of strike-slip movements, rifting or – more generally – a combination of both in oblique rifts. Compression following rifting (as in the Benue Trough) is exceptional.

The importance of aeromagnetic and gravity surveys in exploring the Precambrian fabric of the many unexposed areas of Africa is emphasized (CVR's talk at Gondwana-15 addresses this). Many areas still need to be surveyed; existing survey data is not sufficiently accessed in current studies. Gravity coverage of India (for example) is good (onshore) but systematic aeromagnetic coverage to modern specifications (onshore and offshore) is still lacking.

2. ICT and Geological GIS.

Geological maps can be built up in ways that mimic the overlapping nature of the younger cover sequences. Stripped away, we may then show what is known or interpreted of the older rocks hidden by sedimentary or volcanic cover (or water, ice…).

Each piece of geological information should include a *fragment number* amongst its attributes and a *time-window* to indicate the period of geological time in which it should be displayed. With access to 'rotation files' that define the movement of the fragments over geological time (e.g. the dispersal of Gondwana since the start of the Jurassic) and suitable software, the information may then be displayed in a 'paleomap' for any chosen time in the geological past. Critical comparison of geological data in reconstructions is a powerful method of testing reconstructions and improving them. The global tectonic context – and the structure of the underlying crystalline basement – is important for understanding basin development.

The principle of building a geological map in which all this information can be stored in logical layers and on which further interpretation can be built has been demonstrated for southern Africa. Wisdom suggests that this is an endeavour that merits serious attention to avoid duplication of effort and to accelerate the distribution of knowledge. Merely adding fragment identification and a time-window to each element of information allows the data to be used in making paleomaps that give extra insight into paleoenvironments and paleo-tectonics at times in the past.

Not all the items we would wish for are currently accessible generally, but rapid progress is being made. Developments in OneGeology (for example) are unfolding rapidly. Africa is in danger of getting left behind; take up of IT in geological surveys there falls way behind the rest of the world (CVR's talk at IGC, Brisbane). Many issues of data custodianship and ease of access need to be addressed in the context of the new world of ICT and the role of national geological surveys within it. National geological surveys often need to re-think their role if they are to remain relevant in an information-oriented society.

Plate rotation models should be published so that they may be used by others. Local data should be used to assess the validity of the model. New local information may help improve the accuracy of the model by 'fine tuning' fragment rotations over prescribed intervals. Those attempting this should always be aware that small changes made locally in the relative position of two continents may have profound effects in the distant reaches of the same fragments and their relation to neighbouring fragments there. Awareness of the constraints of working on a finite sphere is paramount.

The ease with which genuine maps with located data in precise projections can be made for times in the past should spell an end to sketch maps and cartoons in serious geology. In cartoon films, characters can be made to do things that would be simply impossible in real life. Making geological animations based on factual map information should avoid doing this for the movements of the earth's crust. There should be an end to cartoons and sketch maps.

CVR

Delft, 2015 June 12

Gondwana Animations

One message from this workshop is that reconstructions should be judged critically from the animations produced from their rotation models. For example, motions in nature are likely to be smooth (without sudden stops, starts and direction changes). New ocean crust, once created, should not be destroyed again unless there is sound evidence for this. Only in this way can a truly critical appreciation of the consequences of the model in terms of the smooth motion of the fragments and the absence of intermediate inconsistencies be made. Just trying to enforce these conditions (in addition to keeping the fracture zones coincident and co-linear) has forced repeated adjustments to the model shown here over many years. Where there are no physical constraints, it is important not to invent (deliberately or unwittingly) unlikely situations for which there is no evidence.

A number of examples of recent animations that are used in the sessions are accessible for download from the website www.reeves.nl/gondwana. These include updated animations of Gondwana dispersion and the creation of the Indian Ocean, incorporating many new refinements of plate motions that were prepared for publication in 2015. In future, new examples will be placed on this webpage as they become available.

Some explanatory notes to accompany the animations are available at http://www.reeves.nl/gondwana/sp1. You are welcome to make educational and research use of all these items, provided due acknowledgement of their source is made. Where there is involvement of commercial interests, however, the author would appreciate being informed as he is still active in his professional consulting practice. Paleogeographic reconstructions can also be made to order for various purposes by Earthworks BV in collaboration with Cambridge Paleomap Services Limited.

Another resource, now rather dated, is the animation of Gondwana dispersion that was first launched in the year 2000. This first edition is still available at: http://kartoweb.itc.nl/gondwana. This website and animation attracted a great deal of interest in its early years, ranging from the general public through school and educational users to researchers in earth science and floral and faunal evolution. In total, over 200 000 'hits' from 48 000 different users had been registered by June 2004.

Those wanting to get involved in paleo-reconstruction themselves are advised to make contact with Alan Smith at Cambridge Paleomap Services Limited (ags1@esc.cam.ac.uk) and help support another small enterprise while getting the best possible software and advice backed by decades of research and hands-on professional experience.

Publications

The main publications arising from the project that are relevant for researchers on Gondwana dispersal are as follows, in chronological order of publication:

Reeves, C.V., 1999. Aeromagnetic and gravity features of Gondwana and their relation to continental break-up: more pieces, less puzzle. Journal of African Earth Sciences, 28, 263-277 (Gondwana-10 conference).

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Reeves, C.V., 2010. A simple model for the tectonic history of the South Atlantic Ocean. (Not published, PDF available).

Reeves, C.V., 2010. Bouvet Plume poster (and withdrawn paper).

Reeves, C.V., 2011. Some new thoughts on the early opening of the South Atlantic Ocean. Extended abstract, Geological Society of Houston/Petroleum Exploration Society of Great Britain, London, 2011 September 7-8

Reeves, C.V., 2012. Global thinking, geophysics, Gondwana - and India. Extended abstract. Association of Exploration Geophysicists meeting, Hyderabad, October.

Key, R.M., and Reeves, C.V., 2012. The post-Gondwana development of East Africa's coastline with emphasis on the development of the Rovuma Basin. Extended abstract. Geological Society meeting, London, October 24-26.

Reeves, C.V., 2013a. African Geology and Tectonics through aeromagnetics: from Botswana to Gondwana. Extended abstract. 24th Colloquium of African Geology. Addis Ababa, January.

Reeves, C.V., 2013b. The global tectonics of the Indian Ocean and its relevance to India's western margin. Journal of Geophysics, vol 34, 87-94.

Reeves, C.V., 2013c. The position of Madagascar within Gondwana and its movements during Gondwana dispersal. Journal of African Earth Sciences. Volume 94, p 45-57.

Reeves, C.V., and Mahanjane, E.S., 2013. Mozambique and its role in the downfall of Gondwana. Extended abstract. Geological Society of Houston/Petroleum exploration society of Great Britain, London, September 11-12.

Reeves, C.V., 2013d. Global tectonics, Rifting and the fabric of Africa. Extended abstract. Society of Exploration Geophysicists, 'Exploration of Continental Rifts' workshop, Houston, September 26.

Reeves, C.V., 2013e. Lebombo: Are we on the edge of Africa? Extended abstract. South African Geophysical Association meeting, Skukuza, South Africa, October.

Reeves, C.V., Teasdale, J., and Mahanjane, E.S. (in review). Insight into the Eastern Margin of Africa from a new tectonic model of the Indian Ocean.

Except where indicated, these items are available on request as a PDF file from the author (e-mail reeves.earth@planet.nl).

The items highlighted in grey appear in the Appendix to these notes.

Student theses

The ‘Gondwana’ Project that gave rise to the original animation and website was supported through ITC Internal Research funds from 1994 to 2000. In addition to the journal articles listed above, the following theses and reports (in alphabetical order of author) have appeared as a result of student work related to the project.

Abdelaziz, A.M.S., 1996 (Egypt). A GIS database of faulting and fracturing in eastern and southern Africa based on published geological maps and new aeromagnetic interpretation. MSc thesis, ITC.

Ahwireng, T.N., 1996 (Ghana). Generation and interpretation of a regional lineament database for West Africa. MSc thesis, ITC.

Chavez Gomez, S., 2000 (Cuba). A database of dykes in eastern and southern Africa supported by aeromagnetic survey interpretation. MSc thesis, ITC.

Chavez Gomez, S., 2000* (Cuba) – A catalogue of dykes from aeromagnetic surveys in eastern and southern Africa. ITC Publication No. 80. Including CD.

Kassa Mekonnen, T., 2004 (Ethiopia). Interpretation and geodatabase of dykes using aeromagnetic data of Zimbabwe and Mozambique. MSc thesis, ITC.

Mubu, M.S., 1995 (Zambia). Aeromagnetic mapping and interpretation of mafic dykes in southern Africa. MSc thesis, ITC.

Nyakaana, J., 1994 (Uganda). Ground geophysical studies near the Kilembe mine, Uganda, and their relation to the interpretation of regional aeromagnetic data in central Africa (SW Uganda, Rwanda, Burundi, NW Tanzania). MSc thesis, ITC.

Perera, A.G.S.R., 1997 (Sri Lanka). Aeromagnetic interpretation of the geology of SW Sri Lanka and its comparison with northern Mozambique. MSc thesis, ITC.

Reeves, C.V., 2003*. East Africa and Western India: Passive margins from the evolution of a complex ocean. Poster presentation (5 posters), American Association of Petroleum Geologists meeting, Barcelona, September 2003.

Rosendaal, E.A., 1997 (Utrecht). A method of checking existing models for continental motions using topographic features on the ocean floor of the Indian Ocean derived from satellite altimetry data. Internal report, ITC.

Sahu, B.K., 2001* (India). Aeromagnetics of selected continental areas flanking the Indian Ocean with implications for geological correlation and reassembly of central Gondwana. PhD thesis, University of Cape Town/ITC.

Van Heiningen, P.S., 1997 (Utrecht). The pre-disruption tectonics of Gondwana: evolution of Karoo basins in southern and eastern Africa and Madagascar. MSc thesis, University of Utrecht.

Yardimcilar, C., 1998 (Turkey). An examination of the evidence from magnetic anomaly mapping for the fit of Madagascar against East Africa. MSc thesis, ITC.

Student theses are notoriously difficult to obtain from academic institutes for various reasons, but I do make an effort to assist in this where I can. Some of the above theses exist in digital formats, though all would involve some time and expense to reproduce fully.

Acknowledgments

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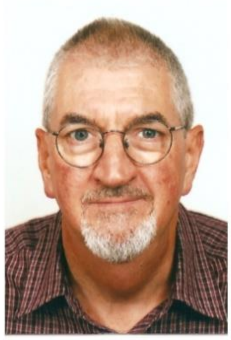
Most of the illustrative material used in this course was created using the “Atlas” software of Cambridge Paleomap Services Limited in Cambridge, U.K. Many years of support from Alan Smith and Lawrence Rush there is gratefully acknowledged. More information on their products can be found on the CPSL website.

Suzanna Reeves assisted in 2010 with the digitizing of the 2010 Geological Map of the World (scale 1:25 000 000) with permission of the Commission of the Geological Map of the World.

About Colin Reeves



Colin Reeves is the principal of Earthworks BV, an independent consultancy. He has more than 40 years’ experience in the instigation, execution and interpretation of regional geophysical surveys in Africa, India, Australia and the Americas, spread across the government, commercial and educational sectors. He has been based successively in Botswana, UK, Canada, Australia and The Netherlands where he was professor in Exploration Geophysics at ITC in Delft from 1983 until 2004. Several hundred geoscientists from Africa, Asia and South America followed postgraduate programmes in Delft during his tenure. His interests include the global-tectonic context of exploration geoscience and national airborne geophysical mapping programmes in Africa, India and elsewhere. He may be reached at: reeves.earth@planet.nl A fuller CV appears on the website www.reeves.nl

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Earthworks
- global thinking in exploration geoscience

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