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We gratefully acknowledge the support of the sponsors for making this meeting possible.

TSG
Tectonic Studies Group
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Plate Tectonics: The Dan McKenzie Archive

Through storytelling, and illustrated by the papers and photographs McKenzie kept throughout his career as well as recorded interviews, the new *Plate Tectonics* website acknowledges Dan McKenzie's unique contribution in the most important discovery in the Earth sciences of the 20th century, documents his interactions with many collaborators and co-workers and includes work which continues today.

https://www.mckenziearchive.org

Exhibition - 50 years of plate tectonics

To coincide with the *Plate Tectonics at 50* conference and the launch of *Plate Tectonics: The Dan McKenzie Archive* website, a special exhibition showcasing items from the Dan McKenzie archive is on display at the Geological Society until December 2017.

50 Years of Plate Tectonics concentrates on McKenzie's early work in plate tectonic and includes a selection of his research notes, papers and letters. If you have a smartphone you can also listen to excerpts from interviews with McKenzie about various aspects of his life and career.

CONFERENCE PROGRAMME

Tuesday 3rd October 2017	
09.30	**Registration and tea & coffee (Main foyer and Lower Library)**
10.20	**Welcome** **Malcolm Brown** (President of the Geological Society)
	Session 1: Session Chair: Rob Butler (University of Aberdeen, UK)
10.30	**Introduction** Tony Watts (University of Oxford, UK)
11.00	**KEYNOTE: Morgan's and McKenzie's discovery of plate tectonics** Hank Frankel (University of Missouri, USA)
11.30	**Why Wegener missed plate tectonics** Wolfgang Jacoby (Mainz University, Germany)
11.45	**KEYNOTE: Rigidity and Plate Tectonics** Xavier Le Pichon (Collège de France)
12.15	**Discussion**
12.30	**Lunch and posters (Lower Library and Main library/Fellows Room)**
	Session 2: Session Chair: Jim Briden (University of Oxford, UK)
13.30	**KEYNOTE: Plate Tectonic Evolution during the Last 1.3 Billion Years: The Movie** Christopher R. Scotese (Northwestern University, USA)
14.00	**True Polar Wander and The Origin of the Hawaiian-Emperor Bend: New Evidence** Richard G. Gordon (Rice University, USA)
14.15	**The Development of a Deformable Plate Model: A Fundamental Requirement for the Reconstruction of Extensional and Compressional Tectonic Environments and for Data Constrained, Global, Palaeogeographic Mapping** John Watson (CGG Robertson)
14.30	**Role of the Equatorial Atlantic reconstruction in deducing palaeogeographic and continental margin evolution in the Gulf of Mexico and Caribbean** Jim Pindell (ION Geophysical)
14.45	**Reconstructing Phanerozoic and Proterozoic Earth Evolution: building on pre-existing efforts and data** Bruce Eglington (University of Saskatchewan, Canada)
15.00	**Discussion**
15.15	**Tea, coffee, refreshments and posters (Lower Library & Main Library/Fellows room)**
	Session 3: Session Chair: Nicky White (University of Cambridge, UK)
15.45	**KEYNOTE: Rifting and the Wilson Cycle: New Plate Tectonic Perspectives from Africa and N. America** Cynthia Ebinger (University of Rochester, USA)
16.15	**Active Tectonics in Turkmenistan and the South Caspian region** Richard Walker (Oxford University, UK)
16.30	**How do the continents deform?** Tim J Wright (University of Leeds, UK)

16.45	**The Spreading Plate Boundary across Iceland: Rifting and Volcanism** Robert S White (Bullard Laboratories, University of Cambridge, UK)
17.00	**Intra-ocean Ridge Jumps, Oceanic Plateaus & Upper Mantle Inheritance** Nick Kusznir (University of Liverpool, UK)
17.15	**Discussion**
17.30 – 18.30	**Reception and posters (Lower Library & Main Library/Fellows room)**
Wednesday 4th October 2017	
	Session 4: Session Chair: Gareth Roberts (Imperial College London, UK)
08.30	**Registration and tea, coffee & refreshments (Main Foyer & Lower Library)**
09.00	**KEYNOTE: Plate Tectonics, mantle convection, and the dynamics of subduction zones** Peter van Keken (Carnegie Institution for Science, Washington DC, USA)
09.30	**Residual Depth Anomalies and the Nature of Mantle Convection** Nicky White (Bullard Laboratories, University of Cambridge, UK)
09.45	**Robust measurement of anisotropy in the mechanical strength of oceanic lithosphere** Lara M. Kalnins (University of Edinburgh, UK)
10.00	**Depth through time in the South Atlantic** L. Pérez –Diaz (Royal Holloway University London, UK)
10.15	**Large-Slab Obducted Ophiolite Complexes and their role in the Plate Subduction Inception, Arc Plate Growth and Crustal Evolution** John F. Casey (University of Houston, USA)
10.30	**Discussion**
10.45	**Tea, coffee, refreshments & posters (Lower Library & Main Library/Fellows room)**
	Session 5: Session Chair: Karin Sigloch (University of Oxford, UK)
11.15	**KEYNOTE: Insights into subduction zone dynamics from seismic anisotropy** Michael Kendall (University of Bristol, UK)
11.45	**Subduction-transition zone interaction: a review** Saskia Goes (Imperial College London, UK)
12.00	**Seismic probe of mantle mixing/unmixing in the Earth's transition zone** Teh-Ru Alex Song (University College London, UK)
12.15	**The Atlas of the Underworld: a catalogue of slab remnants in the mantle imaged by seismic tomography and their geological interpretation** Douwe G. van der Meer (Utrecht University, Netherlands & Nexen Petroleum)
12.30	**Discussion**
12.45	**Lunch and Posters (Lower Library & Main Library/Fellows room)**
	Session 6: Session Chair: Lidia Lonergan (Imperial College London, UK)
14.00	**KEYNOTE: Plate Tectonics and the geology of plate boundary zones** John Dewey (University College Oxford, UK)
14.30	**Plate Tectonics in the Andes: old paradigms and new insights** Victor A. Ramos (University of Buenos Aires, Argentina)
	The plate tectonic Approximation: An Update Richard G. Gordon (Rice University, USA)

15.00	**The East African Transform Margin: - a major new interpretation using potential fields geophysics** Andrew J. Long
15.15	**From inland-sea basins to confined orogens: An example from the Neoproterozoic Araçuaí-West Congo orogeny and implications for Plate Tectonics** Antonio Pedrosa-Soares (Federal University of Minas Gerais, Brazil)
15.30	**Discussion**
15.45	**Tea, coffee, refreshments and posters (Lower Library & Main Library/Fellows room)**
	Session 7: Session Chair: Mike Daly (University of Oxford, UK)
16.15	**KEYNOTE: Cenozoic growth of the Tibetan Plateau and its influence on Asian climate: One opinion about 21st century continental tectonics and its role as an environmental agent** Peter Molnar (University of Colorado Boulder, USA)
16.45	**Intraplate orogenesis: Eurekan Orogen** Randell Stephenson (University of Aberdeen, UK)
17.00	**Intraplate Mountain Building in Non-Cratonised Continental Interiors: Lessons from Central Asia** Dickson Cunningham (Connecticut State University, USA)
17.15	**Revolution in the Earth Sciences: An African plate perspective** Chris J.H Hartnady (Umvoto Africa (Pty) Ltd)
17.30	**Tectonic roles of South America tectonostratigraphic terranes in the Brasiliano collage** Benjamin Bley de Brito Neves (S. Paulo University, Brazil)
17.45	**Discussion**
18.00 – 19.00	**Wine reception and posters (Lower Library & Main Library/Fellows room)**
Thursday 5 October 2017	
08.30	**Registration and tea, coffee & refreshments (Main Foyer & Lower Library)**
	Session 8: Session Chair: Alan Roberts (Badley Geoscience Ltd)
09.00	**KEYNOTE: Sedimentation and tectonics in the plate tectonic era** Nicholas Christie-Blick (Lamont-Doherty Earth Observatory Columbia University, USA)
09.30	**Kilometre-scale burial and exhumation of passive margins and continental interiors: an overlooked consequence of plate tectonics?** Paul F. Green (Geotrack International)
09.45	**How important are intrabasement structures in controlling the geometry of sedimentary basins? Insights from the Taranaki Basin, offshore New Zealand** Luca Collanega (University of Padova, Italy)
10.00	**Tectonic causes of Cenozoic thin-skin deformation in the Gulf of Mexico** Teunis Heyn (BP America Inc)
10.15	**The Aleutian Trench, a study of sediment sourcing and delivery that emphasizes the cyclic nature of plate tectonic processes** M.R Dobson
10.30	**Discussion**
10.45	**Tea, coffee, refreshments and posters (Lower Library & Main Library/Fellows room)**

	Session 9: Session Chair: Jonathan Turner (Radioactive Waste Management)
11.15	**KEYNOTE: Plate tectonics and the petroleum industry – a 50 year symbiosis** Tony Doré (Statoil, UK)
11.45	**Plate tectonics in hydrocarbon exploration – From time-animated 2D maps to data-rich Paleo-Earth models as next generation exploration toolkit** Christian Heine (Shell & Institute for Geology, Germany)
12.00	**Plumetectonics nature forming geological structure of Kazakhstan with large deposits and basins** Adilkhan Baibatsha (Kazakh National Research Technical University, Republic of Kazakhstan)
12.15	**Plate Tectonics and the Phenomenon of North American Oil and Gas Shales** Frank R. Ettensohn (University of Kentucky, USA)
12.30	**Deep Seismic data from the North Carnarvon Basin, North Western Australia, exposes ancient in-place oceanic lithosphere** Paul Bellingham (ION Geophysical)
12.45	**Discussion**
13.00	**Lunch and Posters (Lower Library & Main Library/Fellows room)**
	Session 10: Session Chair: Mary Fowler (University of Cambridge, UK)
14.30	**KEYNOTE: Tectonics beyond Earth: No Plates, Different States** Catherine L. Johnson (University of British Columbia, Canada)
15.00	**The Plate Tectonics of Exoplanets** David Waltham (Royal Holloway University London, UK)
15.15	**Secular geochemistry evolution and the Siderian magmatic shutdown** Hugo Moreira (University of Portsmouth, UK)
15.30	**KEYNOTE: Plate Tectonics and Continental Growth** Chris Hawkesworth (University of Bristol, UK)
16.00	**Discussion**
16.15	**Tea, coffee, refreshments and posters (Lower Library & Main Library/Fellows room)**
	William Smith Lecture
16.45	**Introduction** James Jackson (University of Cambridge, UK)
17.15	**Plate Tectonics at 50** Dan McKenzie (University of Cambridge, UK)
18.15	**Discussion**
18.30	**Close**

POSTER PROGRAMME

1	**Forearc basin structuring and seismicity patterns controlled by a trapped sliver from the Caribbean Large Igneous Province (CLIP): Northern Andes** **C.A Aizprua** (Norwegian University of Science & Technology, Norway and Lille University, France)
2	**Improving plate-reconstruction models using crustal-thickness maps from gravity inversion: examples from the Gulf of Mexico & Indian Ocean** **Andy Alvey** (Badley Geoscience Ltd)
3	**Peri-Gondwana Terranes in Central Brazil** **E.L Dantas** (University of Brasília, Brazil)
4	**Crustal architecture and tectonic evolution of the Antarctic continent in light of recent aerogeophysical exploration** **Fausto Ferraccioli** (British Antarctic Survey (NERC))
5	**Crustal Architecture of the Proto-Caribbean Oceanic Crust** **B.R Frost** (Anadarko Petroleum)
6	**Break-up Processes in the Presence of Plume Magmatism: New Insights into the Tectonostratigraphic Development of the South Atlantic** **Ken G. McDermott** (ION Geophysical)
7	**Carbon from Crust to Core: recording the history of deep carbon science** **Simon Mitton** (University of Cambridge, UK)
8	**Continental Southeast Asia (Sundaland): Continental history of eastern Cimmerian ribbon continent and its component block movements** **Michael F Ridd** (Formerly BP)
9	**The South China Craton – one plate or two?** **Steven Robinson** (University College London, UK)
10	**Oman's two ophiolites: Subduction related Semail and Mid ocean ridge Masirah** **Hugh Rollinson** (University of Derby, UK)
11	**Kinematics of the East Pacific Rise predicted from Pacific and Nazca/Farallon Subduction-Related Torques: Support for significant deep mantle buoyancy controlling EPR spreading** **David Rowley** (The University of Chicago, USA)
12	**Long-Term Sea Level on a Dynamic Earth** **David Rowley** (The University of Chicago, USA)
13	**Assessing the nature of crust in the central Red Sea using potential field methods** **Wen Shi** (University of Manchester, UK)
14	**Early Carboniferous extension in Eastern Avalonia: 350 My record of lithospheric memory** **Jeroen Smit** (Utrecht University, Netherlands)
15	**Plate Kinematic Model of the Northwest Indian Ocean and Application to Paleostress Modelling**

	Amy Tuck-Martin (Royal Holloway University of London, UK)
16	**Reconstructing first-order changes in sea level during the Phanerozoic and Neoproterozoic using strontium isotopes** **Douwe G. van der Meer (**Utrecht University, Netherlands & Nexen Petroleum UK Ltd)
17	**A Global Geological Framework: putting Plate Tectonics in its place** **Benjamin van Wyk de Vries** (University of Clermont Auvergn, France)

ORAL ABSTRACTS
(in programme order)

Morgan's and McKenzie's discovery of plate tectonics

Hank Frankel
University of Missouri, USA

In early spring 1967, Jason Morgan discovered the theory of plate tectonics. This monumental discovery turned seafloor spreading and continental drift into a more powerful theory. He essentially took Wilson's ideas of transform fault and rigid blocks and applied them to a sphere. This allowed him to describe their relative motion in terms of Euler's Point Theorem. Morgan first presented his theory at the spring 1967 AGU meeting where few understood or appreciated what Morgan had done. In fall 1967, McKenzie, not knowing of Morgan's work, discovered plate tectonics on his own while at Scripps. His paper, co-authored with Parker, appeared in December 1967. McKenzie recognized that slip directions can be used to test plate tectonics and to determine them correctly from first motion studies. Nonetheless, Morgan, as acknowledged by McKenzie and Parker, has priority for discovering plate tectonics. In 1969, McKenzie and Morgan explained the evolution of triple junctions, points where three plate meet. They provided a formal procedure for determining the stability of triple junctions and their work was crucial for applying plate tectonics to past relative motions between plates. Their monumental discovery geometrized geology. By dividing Earth's outer surface into plates, most comprising both oceanic and continental lithosphere, and of sufficient rigidity to apply Euler Point Theorem, they could explain the movements of Earth's outer surface in terms of relative rotational velocities, why almost all earthquakes occur in typically long and narrow seismic zones, why most earthquakes in the same type of seismic zones have the same mechanism, and why slip directions of earthquakes along the common boundary of two plates are roughly parallel to each other. Plate tectonics remains, after 50 years remains the unifying theory of Earth science.

Both characterized plate tectonics as a kinematic, not a dynamic theory. It is ironic that it did not provide a cause of plate movements but was immediately accepted by most Earth scientists who understood it, given that the major difficulty raised against continental drift was that its proponents offered no viable mechanism.

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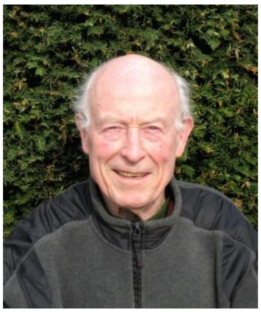
Why Wegener missed plate tectonics



Wolfgang Jacoby
Geowissenschaften, Johannes Gutenberg-Universität Mainz, Germany; jacoby@uni-mainz.de

Wegener was close. He reasonably reconstructed the shifting of continental sheets of "lithosphere", and he anticipated the role of mid-ocean ridges as kind of seafloor spreading (1912) and was probably aware of *Ampferer's* (1906) and *Schwinner's* "(1920) subfluence" of Pacific floor below the Andes. However, he had no rigid oceanic lithosphere capable of transmitting stress over large distances. For him the ocean was underlain by SIMA without an asthenosphere. Increasing temperature with depth suggested viscosity or ductility to gradually decrease. Moreover, published petrological data (Dölter, 1906) suggested continental „lithosphere", SIAL, to be harder than SIMA at 100 km depth. Seismicity below the oceans was poorly known. Thus, *Wegener* imagined the "***continental*** lithospheric sheets" to drift in the SIMA mantle. Although he thoroughly meditated rheology of rock, he had incorrect ideas about crust and mantle rheological structure. – I cannot prove my speculations but believe they are plausible and I present the evidence in Wegener's own writing. He was aware of the deficiencies, and when considering convection in 1929 he wrote: "If the theoretical foundations prove reliable …, which is not yet clear, convection will have to be taken into account as an agent shaping Earth's surface."

NOTES

Rigidity and Plate Tectonics

Xavier Le Pichon
Collège de France, Aix en Provence

The existence of a Plate Tectonic Revolution is due to the extraordinary success of Plate Kinematics. And this success resulted from the fact that plates behave in an essentially rigid way. In this presentation I will first reflect on the discovery of this rigidity of the plates, and more particularly the way I treated it in my paper “Sea Floor Spreading and Continental Drift” which began: “*It has long been recognized that if continents are being displaced on the surface of the Earth, these displacements should not in general involve large scale distortions, except along localized belts of deformation.*” Thus from the start, the concept of rigidity was central in my paper. Reading the extended outline of the Jason Morgan April 19 1967 presentation at the AGU, I immediately realized that demonstrating the rigidity of plates was the key to a quantification of the motions of what would later be called plates. I made this demonstration in three steps. First I verified the rigidity of the main five oceanic openings, using in particular the Mercator test that had been suggested to me by Jim Heirtzler. This was done by the end of July. Then I worked on the second and what I considered to be the most important step: the closure of plate circuits at the global level, using six plates. This was done by the end of September. Finally, I worked on finite plate reconstructions obtained by matching magnetic anomaly isochrons. This was done in October. The success of these three steps convinced me that we had entered into a new era of the Earth Sciences. Since that time, the concept of the rigidity of plates has been tested in many ways. But to me, one of the most fascinating developments has been the progressive realization that plate kinematics could be deciphered in 4D (3D plus time) in quite a few places, in particular because of the persistence of the thermal identity of the slabs within the mantle. I will take as an example the Eastern Mediterranean area and will use recent developments in the seismological study of the Hellenic slab to develop a 4D kinematic evaluation of the area since 16 Ma.

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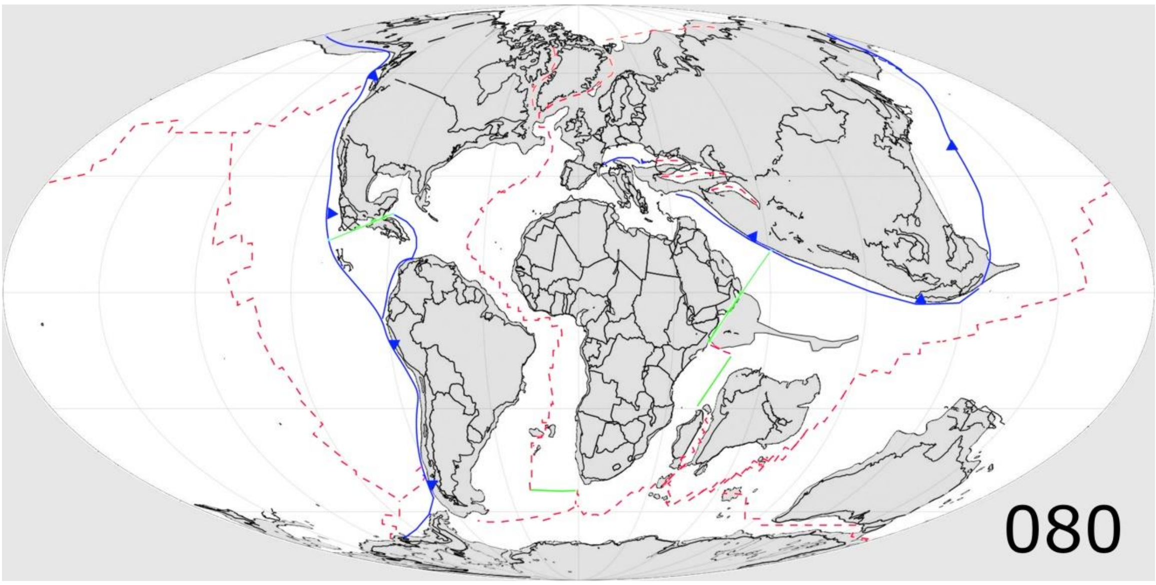
Plate Tectonic Evolution during the Last 1.3 Billion Years: The Movie

Christopher R. Scotese and Reece Elling

Department of Earth and Planetary Sciences, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208; cscotese@gmail.com



This computer animation illustrates the plate tectonic development of the continents and ocean basins during the past 1.3 billion years. The GPlates program (https://www.earthbyte.org/gplates-2-0-software-and-data-sets/) was used both to build the plate tectonic model and to produce the animation. The animation shows the evolution of the plates using the continuously closing plate boundary (CCP) technique (Gurnis et al., 2012) that accurately renders the complex, changing topologies along intersecting plate boundaries.

The latitudinal orientation of the continents was derived largely from paleomagnetic data (Van der Voo, 1993; Pisarevsky, 2005; Veikkolainen et al., 2014). Hot spot tracks and seafloor spreading isochrons (Seton et al., 2012; Matthews et al., 2016) were used to constrain the longitudinal positions of the continents back to ~200 million years. Plate tectonic reconstructions older than 200 million years are necessarily more speculative and were derived by combining diverse lines of evidence: the tectonic history of the continents (i.e, the timing of continent-continent collisions or the ages of rifting), the distribution of paleoclimatic indicators (i.e., bauxites, coals, tillites, and salt deposits; Boucot et al., 2013), and in some cases the biogeographic affinities of fossil faunas and floras (Lees et al., 2002; Cocks and Fortey, 2003; Torsvik and Cocks, 2017).

Though a diverse data set has been used to produce these reconstructions, this data, in itself, was not enough to do the job. So much time has passed, and so little direct evidence of past plate interactions remains, that guidance must also be sought from the "Rules of Plate Tectonics" (Scotese, 2014).

The rules of plate tectonics are largely intuitive. They state that the Earth's tectonic plates do not move randomly, but rather evolve in a manner that is consistent with the forces that drive them. The principal forces are slab pull, ridge push, and trench roll-back. Understanding how these forces work provides important insights into how plate boundaries will evolve through time. Simply said, plates move only if they are pulled back into the mantle by a subducting slab or pushed laterally by a mature mid-ocean ridge system. In this animation, the evolving plate boundaries have been drawn to follow this maxim.

It is also important to note that plate tectonics is a “catastrophic” system. Though “slow and steady” is the general rule, a major plate tectonic reorganization takes place every 50 – 100 million years. These “plate tectonic catastrophes” most often occur when mid-ocean ridges are subducted or when major continents collide. Plate tectonic reorganizations have played an important role in shaping the rock record and providing the evolving context for climate change, the changing distribution of land and sea, and the evolution of distribution of life on Earth.

A preliminary version of the animation can be viewed at: https://www.youtube.com/watch?v=LWIHV4TLQa0.

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True Polar Wander and The Origin of the Hawaiian-Emperor Bend: New Evidence

Richard G. Gordon, Daniel Woodworth, Lily Seidman, and Lin Zheng
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We present an updated apparent polar wander (APW) path for the Pacific plate constructed from paleomagnetic poles determined from the skewness of marine magnetic anomalies, from equatorial sediment facies, and from paleocolatitudes of vertical cores of igneous rock. While paleocolatitude data provide some constraints, their usefulness is limited because they only limit the pole position in one direction, and the uncertainty in that direction is large because of the challenges of averaging secular variation. In contrast, secular variation contributes negligibly to the poles from skewness data, which give compact confidence limits for a well-defined interval of time. We review, update, or present six useful poles available for chrons 12r, 20r, 25r, 26r, 27r-31, and 32, corresponding respectively to 32 Ma, 44 Ma, 58 Ma, 60 Ma, 65 Ma, and 72 Ma.

An APW path for Pacific hotspots can be obtained by moving each Pacific plate paleomagnetic pole with the Pacific plate relative to the hotspots to a reconstruction that corresponds to the age of the pole. This path has a stillstand from 44 Ma to 12 Ma at a location (P1) about 3° from the present spin axis and a second stillstand from 81 Ma to 58 Ma at a location (P2) about 11° from the present spin axis. We hypothesize that the shift from P2 to P1 records an episode of true polar wander sometime between 58 and 44 Ma and that the shift from P1 to the present spin axis records another episode of true polar that has occurred since 12 Ma and may continue today. We test these hypotheses by comparing the APW path of Pacific hotspots with the APW path of Indo-Atlantic hotspots and find them in agreement. Our results imply that global hotspots have moved in unison with respect to the spin axis and that the Hawaiian-Emperor Bend (HEB) does not record a change in motion through the mantle of the Hawaiian plume. Instead the HEB records a change in Pacific plate motion over a stationary plume as originally proposed by W. J. Morgan.

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The Development of a Deformable Plate Model: A Fundamental Requirement for the Reconstruction of Extensional and Compressional Tectonic Environments and for Data Constrained, Global, Palaeogeographic Mapping

John Watson, Simone Agostini, Jim Harris, Alexandra Ashley and Simon Otto
CGG Robertson, Llandudno, North Wales LL30 1SA, UK

Plate geometries are controlled by the combined extensional, compressional and magmatic history of plate tectonic interaction so that the reconstruction of rigid plate configurations creates overlap (in extensional/stretching) and under-fit (in convergent/shortening) environments. Time slice specific data points that provide lithological and palaeoenvironmental (tectonic and depositional) constraints for palaeogeographic mapping are intersected with plate configurations and rotated in palaeospace according to the available plate reconstruction; however in exclusively rigid plate models, under-fit and overlap means that the crucial spatial relationships of palaeogeographic data points is lost. To address this problem a combined rigid and deformable plate model has been constructed.

Three different plate types have been defined:

- 'Continental / Arc', comprising continental and volcanic arc material (obducted ophiolites are also included in this category due to their continental position)
- 'Oceanic plateau', created by Large Igneous Province and plume volcanism and
- 'Ocean crust', formed by seafloor spreading

Plate boundaries and Continent-Ocean Boundaries have been identified through the integration of in-house and published data that includes: free air gravity, Bouguer anomaly, residual Bouguer anomaly and magnetic anomaly grids. These geophysical data are used in conjunction with structural data, field data, borehole logs, seismic lines, and scientific literature to further refine these boundaries. Oceanic isochron data from the Jurassic to the present has been used to drive the plate rotations that underpin the model. In the absence of older ocean-floor, to model pre-Jurassic plate motions, rotation parameters, Euler poles have been calculated from palaeomagnetic data and relative path modelling. The integration of these parameters allows the global model to be defined into the Late Neo-Proterozoic (550 to 0 Ma).

To build a deformable plate model, extension and compression is restored by adding deformation parameters to the rigid model through an in-house tool for ESRI ArcMap. Since its inception (2016) deformation has been modelled in phases for all Atlantic conjugate margins, Baffin Bay, Labrador Sea, the Central and East African Rift Systems, East Africa Margins, East Antarctica margin, India margins, Mascarene Basin, Iran and the Himalayan belt and is now being used in a new model for the Caribbean, Gulf of Mexico and the Pacific (Figure 1). The deformation tool has been designed to allow a time-dependent modelling of the geometry of each deformable plate with a time resolution of 1 Ma. The absence of a thickness parameter in the plate model means that uniform pure shear deformation is assumed. The amount of deformation is defined by the rigid overlap and under-fit between continental blocks and is restored through the deformation tool (Figure 2).

Base maps for palaeogeographic mapping are made using the deformable plate model to reconstruct and retain the spatial relationships of mapping control data points in palaeospace (Figure 3). Mapping palaeoenvironments and tectonics provides an important feedback mechanism that is used to further refine the plate model; illustrated here by reference to regional models and a Global Phanerozoic map series.

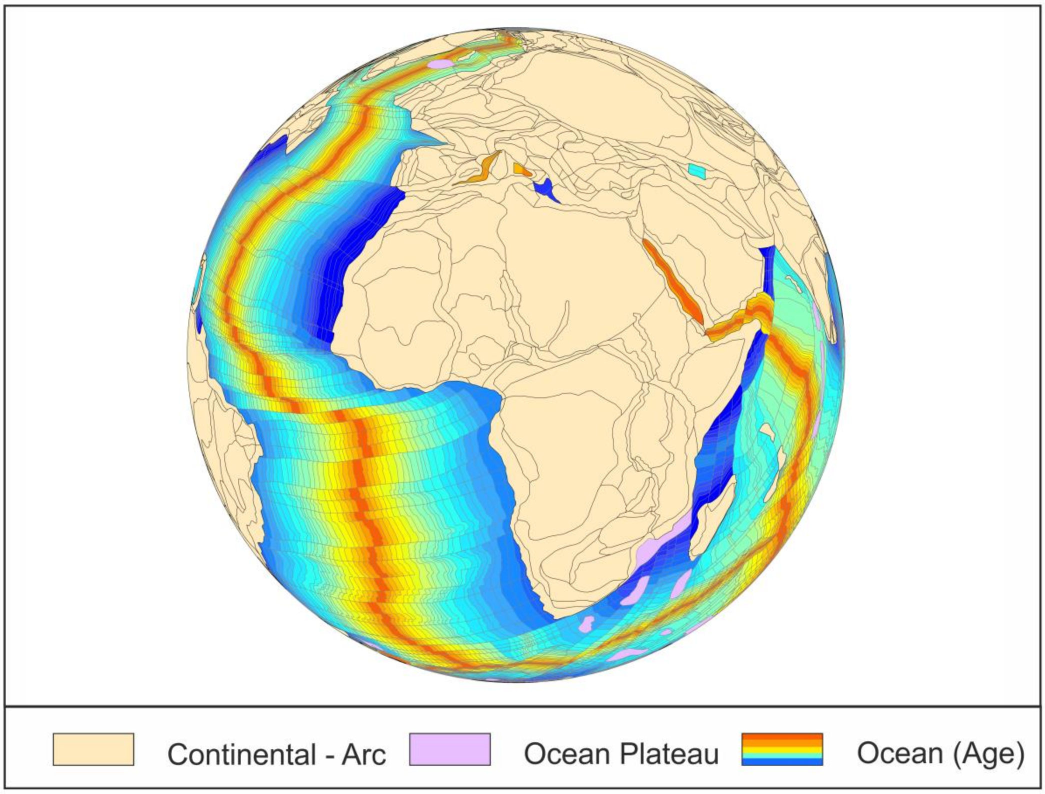

Fig 1 Present Day Plate Wizard Model

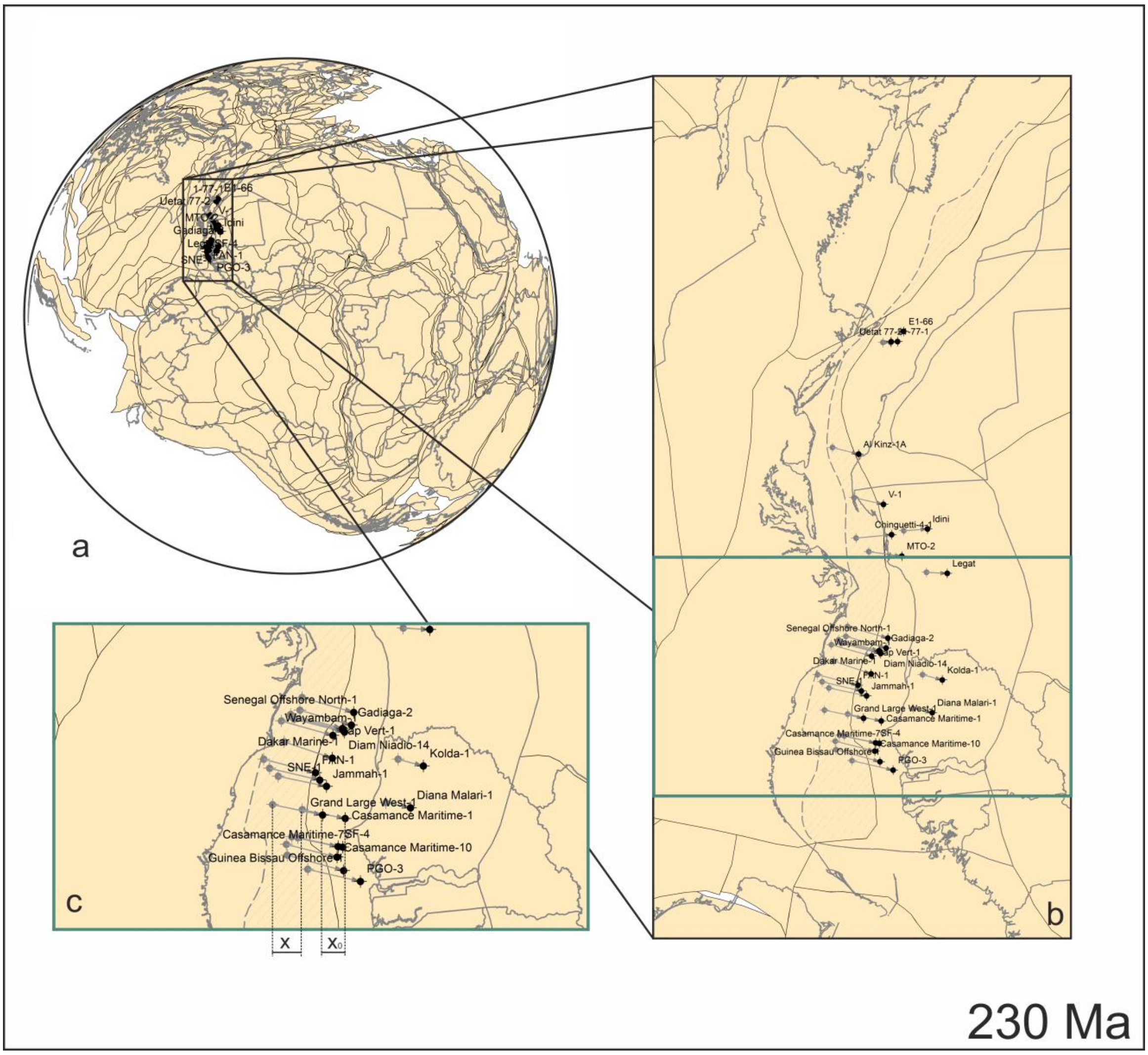

Figure 2 Reconstruction of wells from the West African Margin at 230 Ma: a) global reconstruction showing the palaeo-location within Pangea; b) comparison between rigid (grey dots) and deformable (black dots) reconstructions. The dashed grey area represents the present day extent of the West African Margin restored through the deformation; c) the distance between two wells is restored from x (present day) to x_0 due to internal deformation within the block.

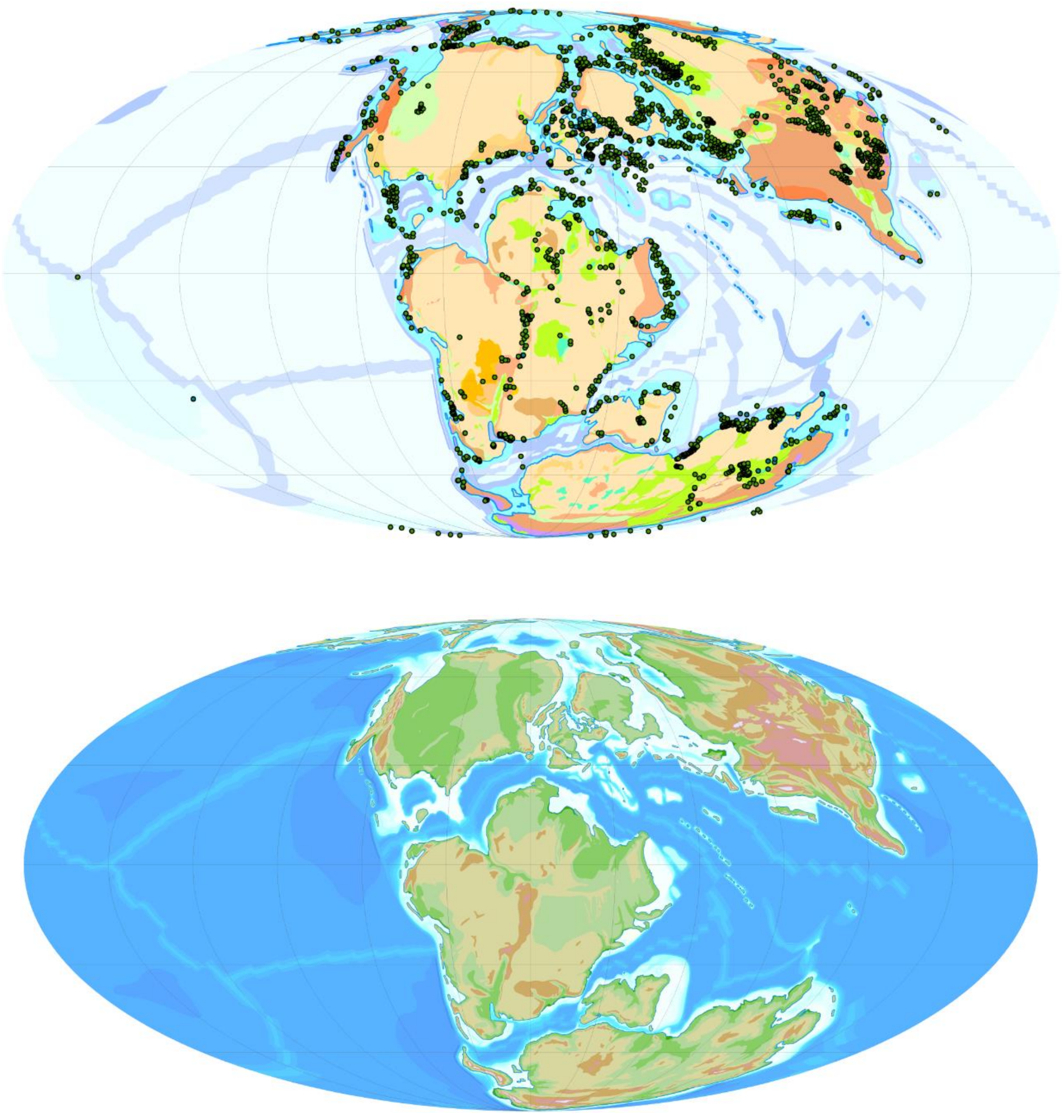

Figure 3.

A. Early Cretaceous, Valanginian GDE with the distribution of mapping control data points positioned in palaeospace using the deformable plate model.

Valanginian topography and bathymetry, the boundary conditions for palaeo-Earth systems modelling

NOTES

Role of the Equatorial Atlantic reconstruction in deducing palaeogeographic and continental margin evolution in the Gulf of Mexico and Caribbean

Jim Pindell[1,2], John Dewey[3], Walter Pitman[4], Kyle Reuber[1], Rod Graham[1], and Brian Horn[1]

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3, University College, Oxford, UK

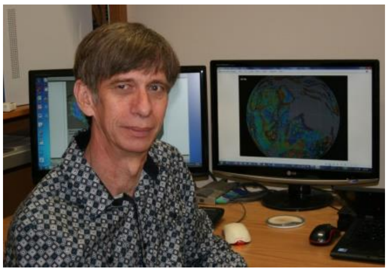
4, Lamont-Doherty Earth Observatory, Palisades, NY, USA

When the classic Bullard Atlantic fit arrived on the scene (1965) and changed geology forever, no one realised it was up to 400km too loose in the Equatorial Atlantic. This is because the entire Amazon shelf was included as "crust", such that Africa and South America could therefore be treated, misleadingly, as rigid plates. Bullard's Equatorial fit went unquestioned until it was recognised that the Amazon shelf's total sediment isopach reached 10 km (Kumar et al. 1979). Removal of the sediment and restoration of apparent crustal extension: 1, allowed great improvement in the Equatorial fit itself (Pindell, 1985); 2, highlighted the significance of and quantified the earlier suggestion that Africa had behaved as two plates in the Early Cretaceous (Burke & Dewey 1974); 3, tightened the initial fit between North and South America by 700 km, thereby satisfying Permian palaeomagnetic data (Van der Voo et al. 1976) and calling for a strongly rotational model for the opening of the Gulf of Mexico (Pindell & Dewey 1982) that remained unverified by potential field data for 30 years until the publication of Sandwell et al. (2014) and Pindell et al. (2016); and 4, greatly increased the likelihood that the Caribbean Plate was of Pacific origin. By 1983-1984, GEOSAT mapping of Equatorial Atlantic fracture zones affirmed the tighter fit and all the associated geological corollaries.

Refined plate reconstructions now may be integrated with modern commercial deep seismic reflection and refraction data to expand the evolutionary understanding into a third dimension - depth. In the Equatorial Atlantic, we see transtensional and transpressional segments along three early pull-apart basins that coalesced as extension continued to form an ocean with highly oblique margins. On the Demerara Rise, we see magmatic addition in the form of SDRs over 20 km thick whose removal facilitates reconstruction with the Bahamian conjugate margin. In the Gulf of Mexico, we can recognise rift-related processes pointing to asymmetrical breakup, with the US and Yucatan margins serving as the lower and upper plates, respectively. Further, these data suggest a mechanism of lower crustal extension that may pertain to models of crustal hyper-extension in general. The data have also highlighted an unresolved dilemma of primary significance to basin analysis: How does the planar (unfaulted) base-salt ("break-up") unconformity subside to depths greater than the oceanic crust at margins? A possible solution is that the margins tilt strongly basinward after crustal rifting and while the continents continue to slough off the rising mantle between them, but further work and dynamic modelling are required to test and quantify this process.

NOTES

Reconstructing Phanerozoic and Proterozoic Earth Evolution: building on pre-existing efforts and data



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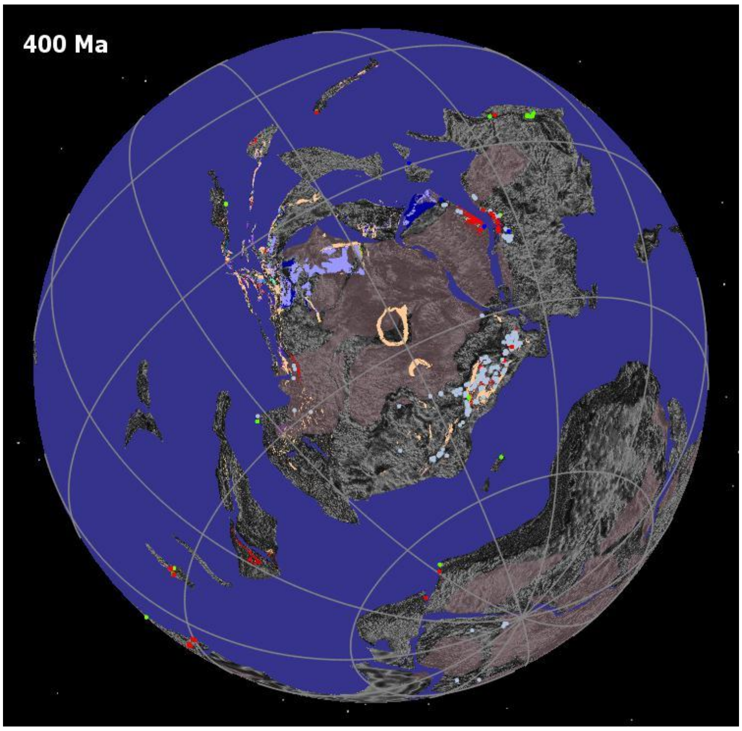
Tremendous strides have been achieved since the first development of modern plate tectonic concepts 50 years ago. Many of these concepts were encapsulated in ground-breaking plate reconstruction models, often aided by advances in computing and software technology. As models become increasingly complex to more exactly reproduce knowledge of the Earth's evolution, new data compilations provide additional information which, when visualized, aid the model development.

We are now at the stage that it is possible to visualize and assess geology, geochronology, palaeomagnetics, lithochemistry, palaeontological, isotope geochemical, climate sensitive and other 4D data back to at least 1800 Ma in an internally consistent model. Combination of multiple data sets, all with time and space control provide opportunities to assess the interplay of many aspects of Earth evolution in ways not previously quantifiable. The holistic picture with evolving time provides valuable constraints which should be included in model development. Many other geological constraints also need to be considered. For instance, various ore deposits types form in distinctive geodynamic settings; arc and other magmatic settings often display distinctive signatures and active magmatism, especially in arc settings, mostly occurs in upper plate settings. Together, these and other data sets can better constrain models.

One of the challenges going forward is to compile regional and global data in ways that better facilitate their direct use in reconstruction models. Modern models need to consider continually evolving reconstructions so as to avoid incompatibilities introduced by a series of independent 'snap-shots'. It is no longer acceptable to create qualitative 'conceptual' diagrams when the tools and data are available to create more quantitative versions, nor can one continue to ignore plate reconstruction blocks just because palaeomagnetic data don't exist for the specific time of interest.



Reconstruction at 400 Ma, illustrating combination of grey-scale gravity image, location of major Archaean cratons (dark pink), depositional setting for sediments (blues = marine, greens and yellows = terrestrial, peach = undifferentiated), igneous rocks (red = plutonic, purple = volcanic), geochronology (red dots = plutonic, green = volcanic, blue = metamorphic and grey = cooling). Lithostratigraphic data from various regional geological maps with attribute information from the StratDB database. Geochronology from the DateView database. Plate model is the PalaeoPlates model and reconstruction performed using the GPlates software.

More effective compilation of data would be aided by improved understanding by both scientists and journal editors of the need to present data in formats that facilitate rather than hinder data mining. Multiple independent data tables do not make a database and certainly don't provide one which can be effectively interrogated. Where possible, compatibility of design needs to be built in to data systems. Geological maps need to become more freely available in vector format, not just in image form as is currently the norm.

As we look back on 50 years of plate tectonic understanding, it is important to acknowledge that our current successes in modelling and visualizing Earth evolution are only possible because of the ground-breaking work of many other earth scientists.

NOTES

Rifting and the Wilson Cycle: New Plate Tectonic Perspectives from Africa and N. America

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J. Tuzo Wilson's concept of alternating convergence and divergence for continental tectonism provided a context for the accretion and modification of Earth's continents, and stability of cratons. The model has two major components, each with distinctive observable characteristics. Initial subduction of ocean lithosphere collides continents across a closing ocean basin, creating a mountain range; rifting then initiates within the collisional orogeny and progresses to create oceanic spreading, which separates the former mountain range across a new ocean basin. Subduction eventually initiates near the old, cold, and heavily sedimented continental margin, and the cycle is repeated. By inference, continental interiors would be stable, and strain is localized to the broad orogenic belts that evolve to rifts and ocean basins. This model is largely kinematic in nature, and predictive in application. We re-evaluate the rift initiation to ocean basin components of the Wilson Cycle in light of perspectives afforded by surface to mantle results from active and ancient rift zones in Africa and North America. Our process-oriented approach addresses 1) the localization of extensional strain and magmatism and 2) stability of continental plate interiors.

Localization of Strain and Magmatism

In both Africa and N. America, geophysical imaging and xenolith studies reveal that thick, buoyant, and chemically distinct Archaean cratons have deep roots that may deflect mantle flow, and localize magmatism and strain. Recent studies of the Colorado Plateau and East African rift zones reveal widespread mantle metasomatism, and high levels of magma degassing along fault zones and at active volcanoes. The volcanoes and magmatic systems, in turn, show a strong dependence on pre-existing lateral heterogeneities in the plate, with strain accommodated by magmatism and consequent heating and volatile transfer leading to further strength reductions. Syntheses of the EarthScope program in N. America show that lateral density contrasts and migration of volatiles that accumulated during subduction could effectively refertilize mantle lithosphere, and allow new tectonic cycles. Post-orogenic gravitational collapse may occur far inboard of the site of collision. In other words, plate interaction with continental mantle can lead to deformation outside the classic Wilson Cycle. For example, the passive margin of eastern N. America shows tectonic activity, uplift, and magmatism long after the onset of seafloor spreading, demonstrating the dynamic nature of coupling between the lithosphere, asthenosphere, and deeper mantle.

Stability of Continental Plate Interiors

As demonstrated by the East African Rift, the Mid-Continent Rift, and other active and ancient rift zones, the interiors of continents, including thick, cold Archaean cratons are not immune to tectonism. The eventual higher-strain zones that are the sites of potential breakup appear to develop anywhere within a tectonic plate, including near but not limited to former collisional suture zones. Recent studies in N. America and Africa reveal >1000 km-wide zones of dynamic uplift, low upper mantle velocities, and broadly distributed strain. The distribution of magmatism and volatile release, in combination with geophysical signals, indicates a potentially convective origin for widespread intraplate earthquakes and magmatism, across areas broader than the surface expression of rifting. Integrated geophysical, geological and geochemical studies reveal large volumes and rates of magmatism at rift zones, provoking re-evaluation of crustal accretion and global carbon and water cycles, as well as consequent earthquake and volcanic hazards.

NOTES

Active tectonics in Turkmenistan and the South Caspian region

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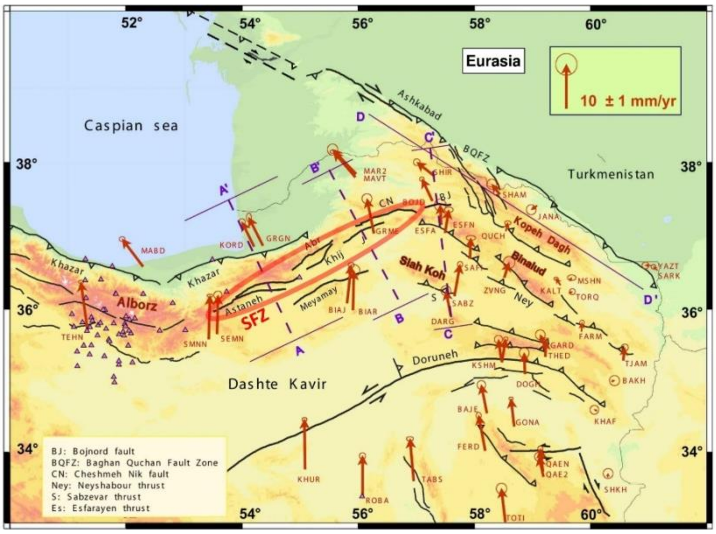
Shortening related to this continental collision extends throughout NE Iran and the Kopeh Dagh mountains, and extending across the border into Turkmenistan. Further to the west, however, the active faults are also influenced by proximity to the South Caspian basin (SCB), which moves independently of its surroundings, but with a direction and rate that are not well resolved. Much of the basin is under water, which has prevented detailed field investigation and direct measurement. Instead, we must infer its motions from observations at its boundaries.



Active fault map and GPS velocity field for the South Caspian region, represented with respect to the Eurasian plate (from Mousavi et al., 2013). The South Caspian motion is accommodated on major faults in Iran (the Shahroud fault zone –SFZ), and Turkmenistan (the Ashkabad, or Main Kopeh Dagh, fault)

Determining the motion of the South Caspian is important for studies of global tectonics, but also for hazard (as the active faults produce earthquakes), and economic geology (as the South Caspian is an important oil and gas basin). The relative motion between the SCB and surrounding parts of Iran and Turkmenistan are accommodated by the Shahroud left-lateral fault system in Iran, and the Main Kopeh Dagh fault, sometimes known as the Ashkabad fault, in Turkmenistan. Determining the rates and directions of slip on these two faults is key for determining the motion of the SCB, and yet there are relatively few estimates at present, such that several different tectonic models exist.

Satellite RADAR measurements of strain accumulation across the Shahroud fault system show 5-6 mm/yr of left-lateral motion being stored across the fault (Mousavi et a., 2015). This amount is consistent with GPS measurements of strain accumulation if the pole of rotation of the SCB is sited far from it. Satellite RADAR measurements of strain accumulation across the Main Kopeh Dagh fault, however, have large uncertainties such that the rate of strain accumulation is anywhere in the range 5-12 mm/yr (Walters et al., 2011). Existing GPS measurements in Iran suggest that the slip rate on the Kopeh Dagh fault is up to 7.5 mm/yr right-lateral, though as the GPS stations are sited far from the fault, it is unclear how solid this estimate is (Mousavi et al., 2013).

The Kopeh Dagh strike-slip fault. In this view a series of streams are displaced right-laterally by ~60 m. Displacements of several hundred metres are also common.

Here, we present the findings from a period of preliminary fieldwork in Turkmenistan with the dual aims of (1) Providing estimates of the long-term slip-rate on the Main Kopeh Dagh fault, and (2) To provide initial estimates of its past earthquake activity. We show that the fault retains surface evidence for a large magnitude earthquake that is not known in the historical record. Through the dating of sediment samples from alluvial fans displaced across the fault we provide a direct estimate on the fault slip-rate, and hence refine estimates of the relative motion of the South Caspian.

Mousavi, Z. et al., 2013, Global Positioning System constraints on the active tectonics of NE Iran and the South Caspian region, EPSL, Vol. 377–378, pp 287–298.

Mousavi, Z., et al., 2015. Interseismic deformation of the Shahroud fault system (NE Iran) from space-borne radar interferometry measurements. Geophysical Research Letters, 42(14), 5753-5761.

Walters R. J., et al., 2013, Rapid strain accumulation on the Ashkabad fault (Turkmenistan) from atmosphere-corrected InSAR, Journal of Geophysical Research, 118(7), 3674-3690.

NOTES

How do the continents deform?

Wright, Tim J (1); Biggs, Juliet (2); Elliott, Austin (3); Elliott, John (1); Ebmeier, Susi (1); Gaddes, Matt (1); Gonzalez, Pablo (4); Hatton, Emma (1); Hooper, Andy (1); Hussain, Ekbal (1); Ingleby, Tom (1); McDougall, Alistair (1); Parsons, Barry (3); Qiang, Qiu (1); Spaans, Karsten (1); Walker, Richard (3); Walters, Richard (5); Weiss, Jonathan (1)

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On the fiftieth anniversary of plate tectonics, we are now able to use high-resolution satellite data to make direct measurements of how the continents deform. We will show new observations from the Alpine-Himalayan tectonic belt, stretching from Spain to China, where the collision of Africa, Arabia, and India with Eurasia is causing deformation and seismicity in a wide zone, up to 2000 km from the nominal plate boundaries (Figure 1).

Satellite geodetic methods have developed at a remarkable pace over the past 25 years. Two technologies in particular have transformed our ability to measure continental deformation: GNSS and InSAR. Global Navigation Satellite Systems (GNSS), such as the US Global Positioning System (GPS), can be used to track the 3D motions of individual sites with an accuracy that is now better than 1 mm/yr. The 3D velocities of around 20,000 GPS have now been measured globally. Synthetic Aperture Radar Interferometry (InSAR) tracks changes in the distance between the satellite and the ground using radar images. This technique works without any instruments on the ground and gives measurements of motion every few tens of metres, with an accuracy that is now approaching 1 mm/yr. The EU Copernicus Sentinel-1 constellation is now acquiring between 2 and 8 images every 24 days for the entire continental land mass; we are processing these routinely within COMET and making the results available to the community (http://comet.nerc.ac.uk).

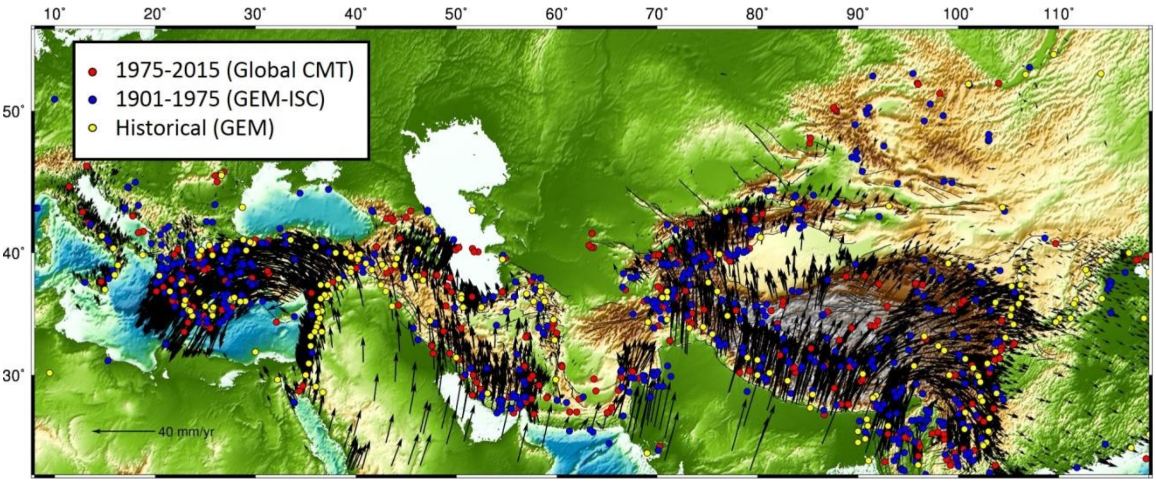

Figure 1: Distribution of earthquakes and GNSS velocities in the continents. Background colours show the topography from the Shuttle Radar Topography Mission. Each circle is an earthquake with M ≥ 6; colour denotes time of occurrence and source catalogue. GNSS velocities, plotted relative to the Eurasian plate, were compiled by Kreemer et al. (2014) for version 2 of the Global Strain Rate Model. The collision of Africa, Arabia, and India with Eurasia has created a wide deforming zone of thickened crust, high seismicity, and high strain rates that stretches for up to 2000 km from the foothills of the Himalayas to the distant steppes of Mongolia.

We will present our latest maps of deformation of the Alpine-Himalayan tectonic belt derived by combining GNSS and InSAR data. The results show that strain is not uniformly distributed in the continents. There are large, undeforming regions, including the Indian and Arabian plate on a large scale, and the Tarim and Sichuan basins on a smaller scale. Some major faults, such as the North Anatolian Fault, Himalayan Frontal Thrust, Altyn Tagh Fault, and Kunlun Fault show high concentrations of tectonic strain in ~50-km-wide regions centred on the faults. In general, these strain zones do not surround isolated micro-plates. Other large regions, such as Western Tibet, appear to show diffuse deformation. Although the large scale deformation appears to be relatively constant in time, we also observe transient deformation in fault zones, during and after earthquakes.

We will discuss the implications of these observations for the rheology of continental lithosphere, models of continental tectonics, and the distribution of seismic hazard.

NOTES

The Spreading Plate Boundary across Iceland: Rifting and Volcanism

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The mantle plume beneath Iceland pushes the Mid-Atlantic Ridge above sea level, making it an ideal natural laboratory in which to study rifting and volcanism at a spreading plate boundary. Over the past 25 years we have operated a large seismometer array and run a series of seismic experiments across Iceland in conjunction with geodetic and petrologic constraints to study the dynamics of plate spreading and volcanism. Icelandic crustal structure constrained by wide-angle seismic refraction, by receiver functions, by ambient noise analysis and by local earthquake tomography shows the influence of the underlying mantle plume in generating additional large volumes of melt at the spreading centre.

The plates in Iceland are spreading at a full rate of 20 mm/a. In central Iceland the spreading direction is about 10 degrees oblique to the fabric of the volcanic rift zones. This is sufficient for the tectonic motion in the brittle layer to be accommodated almost entirely by conjugate strike-slip faults rather than by the expected normal faults. In a well documented example, we have mapped two crossing conjugate faults moving simultaneously using hundreds of small earthquakes.

We have captured in unprecedented detail three dyke injection episodes and the largest volcanic eruption for 250 years as well as long-term pockets of seismicity in the lower and middle crust caused by melt rising from its source in the mantle. The 2014-15 Bárðarbunga dyke propagated horizontally for almost 50 km at a depth of 7 km before erupting for 6 months in the Holuhraun lava field. We have mapped the two-week dyke propagation by locating the hypocentres of more than 31,000 microearthquakes generated at the cracking front of the dyke. Moment tensor solutions enable us to constrain the strain field at the dyke tip. Concurrent seismic activity in Bárðarbunga, beneath which lies the melt reservoir which fed the eruption, constrains the subsidence of the caldera as magma emptied along the dyke, as well as the post-eruption adjustments.

Tomographic studies and repeating pockets of deep crustal seismicity show that melt is stored at a variety of depths in the crust, and that melt may be fed long distances laterally from central sources. This is consistent with petrological geobarometers which suggest that there are multiple sills within the crust through which the mantle-derived melt passes, or often freezes in situ.

NOTES

Intra-ocean Ridge Jumps, Oceanic Plateaus & Upper Mantle Inheritance

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Ridge jumps within oceanic lithosphere, often associated with enhanced magmatism and the formation of oceanic plateaus, are common and appear to be a fundamental geodynamic process adding complexity to plate tectonics and ocean basin development. Numerous examples globally. The Indian Ocean shows multiple ridge jumps including those between the Conrad Rise, Crozet Plateau and the Madagascar Plateau, between Seychelles and India, and between Kerguelen Plateau and Broken Ridge. The South Atlantic shows examples associated with the separation of Southern Brazil and Namibia leading to the formation separation of the Rio Grande High and Walvis Ridge.

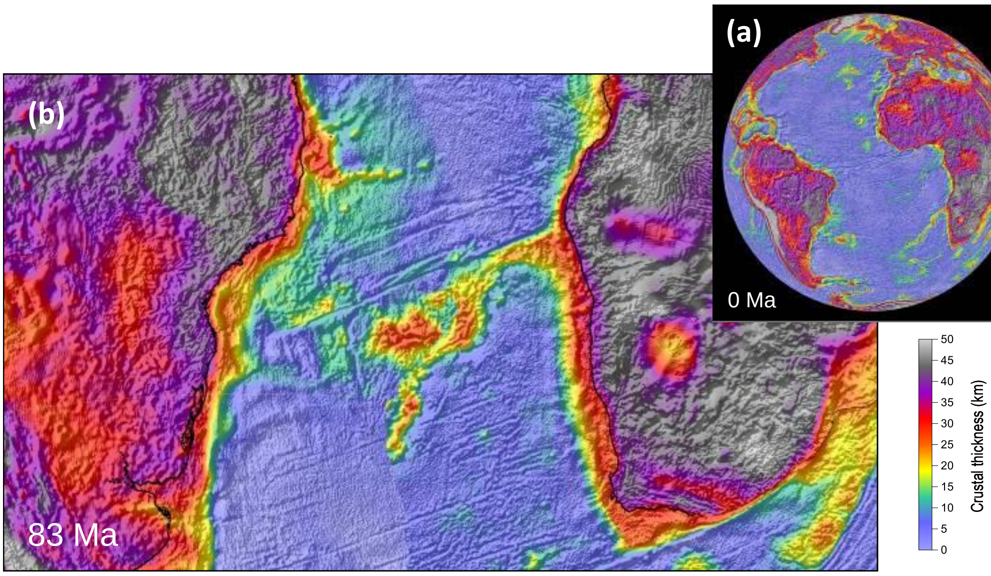

Figure 1 (a) Present day crustal thickness from gravity inversion for the Atlantic Ocean. (b) Crustal thickness restored to 83 Ma using GPlates 1.5*.*

Gravity anomaly inversion of satellite derived free-air gravity incorporating a lithosphere thermal gravity anomaly correction data now provides a useful and reliable methodology for the global mapping of oceanic crustal thickness. The resulting maps of crustal thickness may be used to determine the distribution of oceanic lithosphere, micro-continents and oceanic plateaus. Using crustal thickness and continental lithosphere thinning factor maps with superimposed shaded-relief free-air gravity anomaly, we can improve the determination of pre-breakup rifted margin conjugacy and sea-floor spreading trajectory during ocean basin formation. This mapping shows micro-continents, oceanic plateaus and ridge jumps consistent with a complex evolution of ocean basin development.
Examples include:
Rio Grande Rise and Walvis Ridge. Their evolution shows multiple ocean ridge jumps into pre-existing oceanic lithosphere with hot spot magmatism generating 30 km thick oceanic crust. Recent sampling has shown that the Rio Grande Rise contains some continental material of Proterozoic age. Plate restoration to 83 Ma of crustal thickness derived from gravity inversion for the S Atlantic shows the Rio Grande Rise and Walvis Ridge forming a single feature analogous to Iceland (Fig. 1).
Conrad Rise, Crozet Plateau, Madagascar Plateau and SWIR. The evolution of the SW Indian Ocean shows sequential ridge jumps between Antarctica, Conrad Rise, Crozet

Plateau and Madagascar Plateau leading to the present-day South West Indian Ridge. Ocean ridge jumps into pre-existing oceanic lithosphere are magma rich generating oceanic plateaus (Fig. 2).
Mauritius, Nazareth, Mascarene and Chagos Banks. These are underlain by crust rifted and magmatically thickened ahead of propagating sea-floor spreading. Precambrian age zircons have been found on Mauritius.

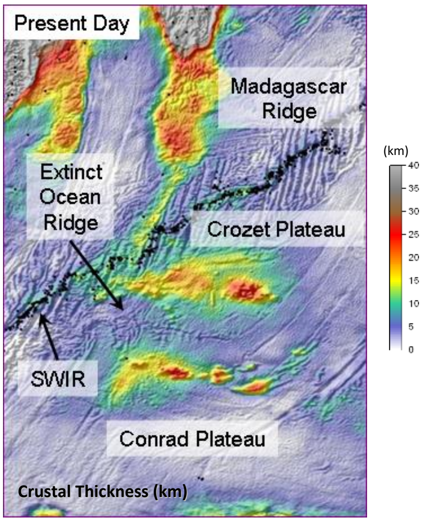

Figure 2 Present day crustal thickness from gravity inversion for the SW Indian Ocean showing magmatically thickened oceanic crust underlying Conrad Rise, Crozet Plateau and Madagascar Ridge. Sea-floor spreading on SWIR developed at ~ 55 Ma. An earlier now-extinct Late Cretaceous oceanic spreading centre can be seen between Conrad Plateau and Crozet Plateau. Early Cretaceous sea-floor spreading was located south of Conrad Rise immediately north of Antarctica.

Canaries and New England Sea Mounts. Plate restoration of the Central Atlantic shows that the intraplate magmatism of the New England Sea Mounts (Late Cretaceous) and the western Canaries (Neogene) align perfectly and also coincide with the northern limit of the West African craton. However this spatial alignment of intraplate magmatism of different ages is not consistent with a mantle plume or hot-spot track source.
Iceland. Crustal thickness mapping shows large crustal thicknesses (> 30 km) under SE Iceland extending offshore to the NE and consistent with SE Iceland being underlain by a southward continuation of the Jan Mayen micro-continent as suggested by geochemical evidence (Fig. 3).

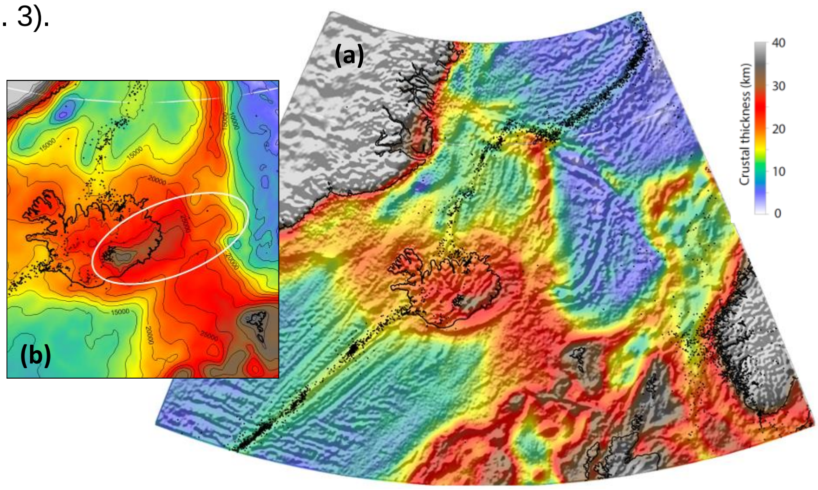

Figure 3 (a) Present day crustal thickness from gravity inversion for the NE Atlantic Ocean. (b) Higher resolution map of crustal thickness for E Iceland.

Important questions include:
(i) Why do some intra-oceanic regions show repeated rift/ridge jumps and hot spot magmatism? Are these plate re-organisations locally or globally driven?
(ii) Are these intra-oceanic regions underlain by lithosphere (or deeper tectosphere) with some continental compositional component?
(iii) Are these intra-ocean ridge jumps attracted by rheological weaknesses controlled by compositional or thermal anomalies (or both)?

(iv) Can these ocean ridge jumps (and hot spots) be explained by upper mantle chemical heterogeneity (water?) and thermal “weather” (+/- a few tens of ^{o}C)?

NOTES

Plate tectonics, mantle convection, and the dynamics of subduction zones.

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With perfect hindsight, it is clear that the basis for our modern ideas of mantle convection were well established by the 1930s, with (among many others) Holmes, Vening Meinesz, Pekeris, Wadati, and Griggs providing a conceptual basis, observational evidence, and a mechanistic basis to allow for a mantle convection explanation for Wegener's observations of continental drift (see e.g., Griggs, American Journal of Science, 1939). After the establishment of plate tectonics, mantle convection computations allowed to provide a quantitative link between the surface plate motions and the dynamic heat loss of the Earth's interior.

A full dynamical explanation of plate tectonics has remained elusive, in large part due to the very different rheological (and perhaps, non-rheological) behavior of the lithosphere. In particular, the processes leading to the initiation of subduction and the establishment of long-lived subduction zones remain poorly understood.

In this presentation, I will provide an application of mantle convection with simulated plates to develop a better understanding of the long-term chemical evolution of the Earth. I will also discuss recent progress in our imaging of the subducted slabs and the role of metamorphic dehydration reactions on the generation of free fluids and intermediate-depth seismicity.

NOTES

Residual Depth Anomalies and the Nature of Mantle Convection

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The success of plate tectonics often conditions the way in which we think about large-scale structure and deformation. For example, the generation of elevated topography is usually linked isostatically to episodes of crustal and lithospheric shortening, which are ultimately controlled by horizontal plate motions. Despite this success, there is excellent evidence that the `tyranny of isostasy' does not always prevail and that some fraction of topography is supported by sub-plate processes. For example, the crustal thickness beneath Northwest Scotland (~25 km) is smaller than that beneath London (~32 km) but the elevation difference suggests the opposite. On a larger scale, the crustal thickness beneath Colorado and Michigan is the same (~40 km) but the elevation difference is ~2 km. In both cases, measurable horizontal shortening is several orders of magnitude smaller than that required to support elevation by crustal or lithospheric isostasy. Convective circulation of the Earth's mantle maintains plate motion. However, we know little about the spatial and temporal details of this circulation. It is reasonable to expect that this circulation pattern generates and maintains dynamic (i.e. transient) topography at the Earth's surface. On the continents, small dynamic topographic signals are difficult to measure because the density structure of the crust and lithosphere is poorly known. More rapid progress can be made by exploiting our quantitative understanding of the thermal evolution of oceanic lithosphere. Newly acquired seismic reflection and legacy seismic wide-angle profiles have been used to measure residual depth anomalies worldwide. Positive and negative deviations from the global age-depth curve are common and have amplitudes of +/- 1 km and wavelengths of 100-10000 km. Spherical harmonic analysis of these observations shows that the results of computational models that calculate dynamic topography from the distribution of mantle mass anomalies are substantially incorrect. However, observed residual depth anomalies are consistent with long-wavelength gravity anomalies and with upper mantle seismic tomographic anomalies. Along the West African margin, a series of broad structural domes straddle the continental shelf. Uplifted marine terraces, offshore stratigraphic geometries, and fluvial drainage networks suggest that these gigantic features mostly grew in Neogene times. Along the northwest shelf of Australia, oceanic depth anomalies show that a broad depression intersects the coastline. Here, we observe rapid post-Miocene subsidence which is recorded by a dramatic switch from aggradation to progradation within a buried coral reef. This switch caused organic-rich source rocks at depth to enter the hydrocarbon window and charge overlying structural traps. In the North Atlantic Ocean, buried ephemeral landscapes have recently been discovered on three-dimensional seismic surveys. Their existence implies that rapid (i.e. ~1 million year) transient uplift events occurred in Cenozoic times. We attribute these vertical movements to periodic fluctuations within the Icelandic plume. In the 1960s, Lester King argued that large-scale warping of the Earth's surface occurred during Late Cenozoic and Quaternary times. His ideas were profoundly influenced by extensive field observations, especially in South Africa where he suspected that young regional uplift was caused by hot `levitated mantle'.

NOTES

Robust measurement of anisotropy in the mechanical strength of oceanic lithosphere

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The mechanical strength of the lithosphere, typically measured by analogue to a purely elastic plate with thickness T_e, is a key geodynamic parameter that modulates, and in turn is modulated by, many key tectonic processes, including rifting, orogeny, and volcanism. The anisotropy inherent in these processes leads to a natural expectation that the resulting material strength of the lithosphere may also be anisotropic, which will in turn influence future deformation and volcanic activity.

Anisotropy in the strength of continental lithosphere has been studied by a range of authors, but anisotropy in oceanic T_e remains nearly unstudied, despite the highly anisotropic nature of its formation at mid-ocean ridges. Here, we extend our robust analysis of anisotropy in continental T_e (Kalnins et al., 2015) to the oceanic domain. We design and develop a robust method optimised for oceanic structure and datasets that consistently identifies and removes spurious measurements of anisotropy, leaving only those directions that are both mathematically and geophysically significant. We compare results from free-air admittance, more commonly used in the oceans, with Bouguer coherence, widely used in the continents, and hence used for previous studies of anisotropy in T_e. We also consider the influence of different available marine datasets, particularly the use of bathymetry datasets that include data estimated from the same sea-surface altimetry data used to determine the free-air gravity anomaly. Using four dataset pairs, we find that robust directions typically are common across all pairs, with initial areas of disagreement generally removed by the robustness testing.

Our first results show a general alignment of strong directions ridge-parallel and weak directions ridge-perpendicular, suggesting widespread anisotropy dominated by formation processes in young oceanic lithosphere. However, few to no robust measurements are recovered near sites of major intraplate volcanism, suggesting that this anisotropy may become less marked as the lithosphere cools and thickens, with the lower lithosphere potentially more mechanically isotropic. Alternatively, the anisotropy might be reset by thermal rejuvenation associated with the volcanism itself. Accurately mapping this anisotropy in the strength of the oceanic lithosphere will develop our understanding how spreading rate, fracture zone dynamics, normal lithosphere maturation, upper mantle flow, and finally plate bending influence the evolving strength profile of the oceanic lithosphere from ridge to trench.

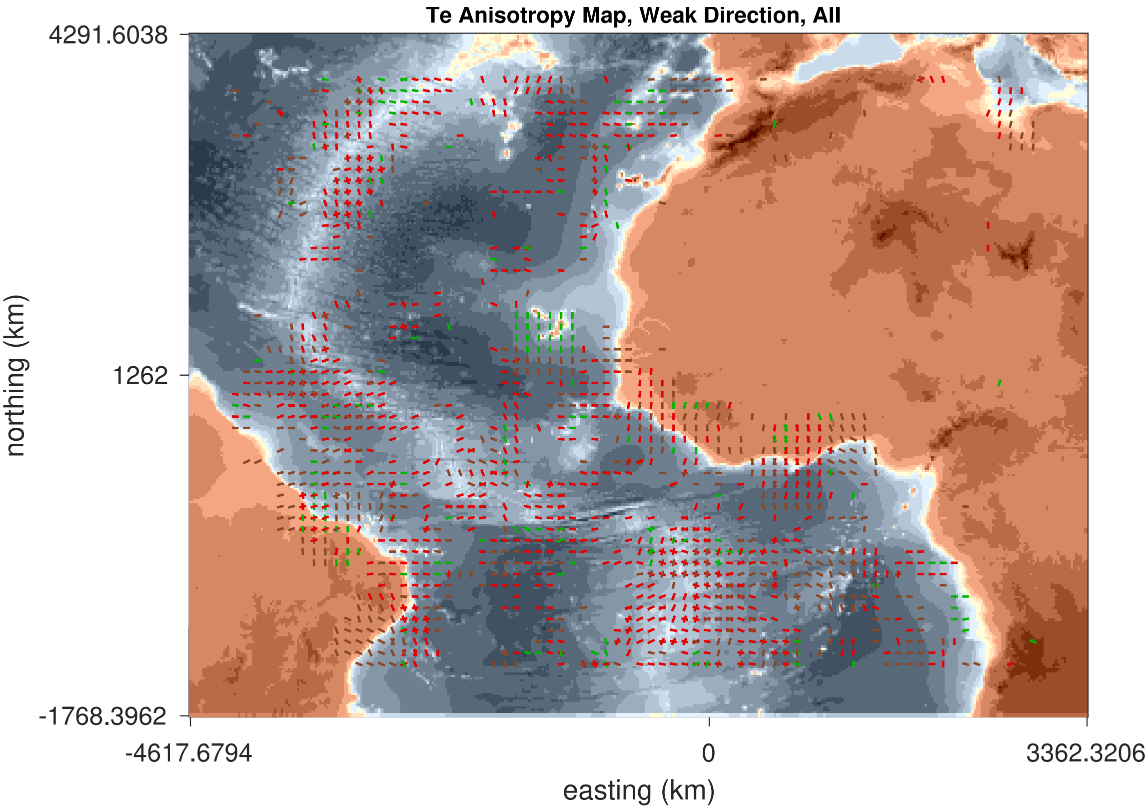

Figure 1: Mathematically and geophysically significant weak directions in T_e over the central Atlantic. Green and brown directions show alignment with anisotropy in the input gravity and bathymetry data, respectively: this data anisotropy may be sufficient to create the measured anisotropy in the coherence, or it may be aligned with true anisotropy in T_e. Red directions are not aligned with any anisotropy in the input data and are fully robust.

NOTES

Depth through time in the South Atlantic

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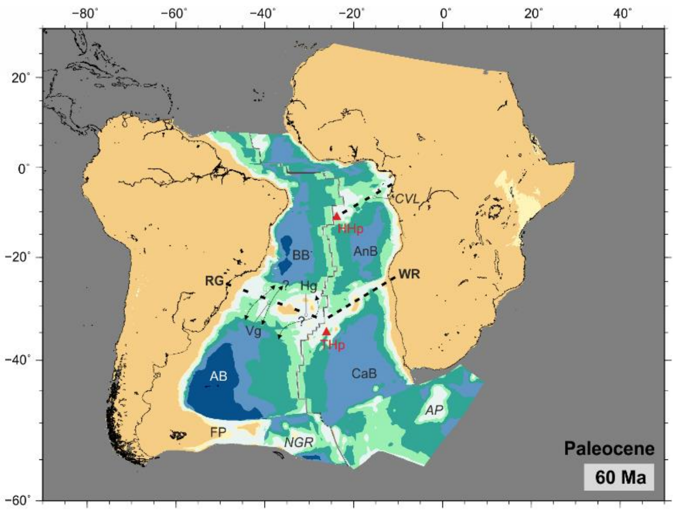
It is no surprise that the opening of the South Atlantic ocean is one of the most extensively researched problems in plate kinematics. After all, it was the similarity of the coastlines of South America and Africa that inspired the basic foundations of plate tectonic theory. An accurate representation of the plate motions that led to the growth of this ocean basin is crucial to understanding the dynamics of its margins, the formation of petroleum systems and the driving mechanisms behind present and past water circulation patterns. General agreement exists about ocean opening being the result of the diachronous separation of two major plates (South American and African), having involved a certain degree of intracontinental deformation. However, for a fuller understanding, the bathymetric evolution also needs to be considered.



Here, we present a series of high resolution paleobathymetric reconstructions (Early Cretaceous to present) for the South Atlantic which represent a big step forward with respect to previous attempts, for three reasons. First, the foundation of our modelling procedure is a robust plate tectonic model based on high-resolution seafloor spreading data. Second, our workflow accounts for a number of processes affecting bathymetry at a variety of temporal and spatial scales (both within the ocean and the extended continental margins), neglected by other paleobathymetries published to date. Lastly, we have thoroughly quantified the uncertainties in our modeling approach, which allows us to provide accuracy estimates for our reconstructions.

Our modelling procedure follows a number of steps. First, we calculate an "idealised" basement surface by applying plate-cooling theory to seafloor ages and integrating the results with COTZ depths as predicted by removing the effects of post-breakup processes on their present-day bathymetry. Then, we refine the depths of this basement surface to account for the effects of sedimentation, variations in crustal thickness and mantle fluctuations.

Most of the paleodepths modelled following our approach are accurate to <1 km, offering a strong quantitative basis for studies of paleocirculation, paleoclimate and paleobiogeography. Circulation in an initially salty and anoxic ocean, restricted by the topography of the Falkland Plateau, Rio Grande Ridge and Walvis Rise, favoured deposition of thick evaporites in shallow water of the Brazilian-Angolan margins. This ceased as seafloor spreading propagated northwards, opening an equatorial gateway to shallow and intermediate circulation. This gateway, together with subsiding volcano-tectonic barriers would have played a key role in Late Cretaceous climate changes. Later deepening and widening of the South Atlantic, together with gateway opening at Drake Passage would lead, by mid-Miocene (~15 Ma) to the establishment of modern-style thermohaline circulation.

NOTES

Large-Slab Obducted Ophiolite Complexes and Their Role in Subduction Inception, Arc Plate Growth and Crustal Evolution.

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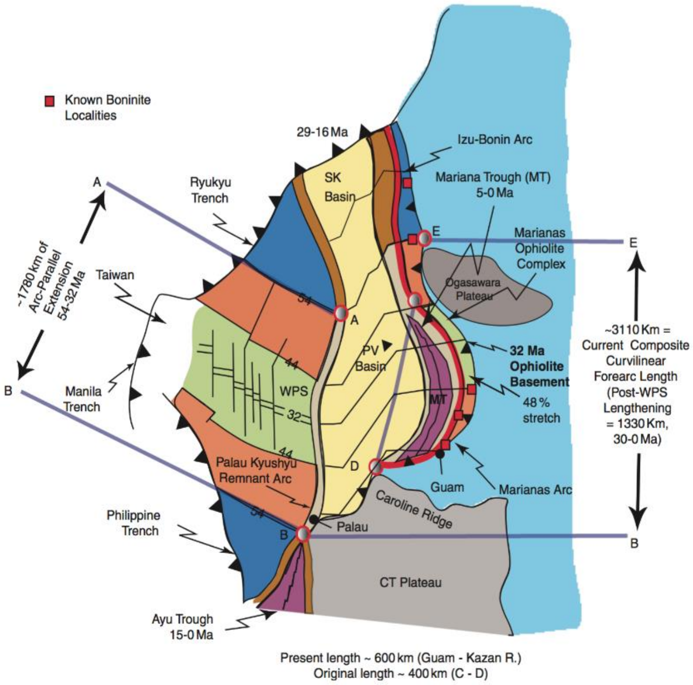
Phanerozoic large-slab ophiolite complexes with relatively complete lithologic sequences typically show remarkable preservation compared to their proposed earlier counterparts and include assemblages of ultramafic residual and plutonic rocks and mafic plutonic, sheeted hypabyssal diabase and submarine volcanic rocks, with minor more evolved plagiogranitic intrusions. Theses ophiolite assemblages commonly preserve a basal dynamothermal metamorphic sole with steep inverted P-T gradients that range from two pyroxene-garnet granulite to lower greenschist facies or anchi-metamorphic melanges interpreted to be material subcreted to the sheared high-temperature mantle detachment above. Mafic and sedimentary protoliths within soles from the downgoing subducted oceanic crust are subcreted in a progressive retrograde fashion. Increasing focus and studies of the petrology and geochemistry of igneous rocks in ophiolite complexes have shown that most large-slab ophiolites have erupted magmas formed in supra-subduction zone settings and show forearc to arc affinities. MORB-like forearc basalts (FAB), arc tholeiites (IAT), boninites (BON) and adakites (AD) are present and are similar to igneous rocks documented within modern forearcs and arcs and within some Archean terranes (TTGs, greenstones, sanukitoids). These rocks reflect partial melting of fertile to ultra-depleted mantle above subduction zones, dehydration and element flux from subducted slabs to mantle wedges, partial melting of the mantle wedges with progressive changes from fertile mantle lherzolites to ultra-refractory harzburgites, and in some cases by direct partial melting of components of the subducted slab (e.g., adakites). Subducted-slab melting and element fluxes within forearcs imply unusually high geothermal gradients and are associated with the absence of preserved subcreted high pressure blueschists. Although such thermal structure of subduction zones is usually considered to reflect subduction of younger lithosphere, ophiolitic metamorphic soles indicate young and hot overlying ophiolite plates likely control the subduction geotherm. Near coincident geochronologic ages for the formation of the ophiolite assemblages and their associated metamorphic soles indicate that both rock associations may be more related to the thermal structure and age of newly accreted lithosphere of upper plate as detachment and subduction below the ophiolite is occurring within the forearc simultaneous with accretion, although the age of the lower plate may contribute. Here we examine modern day analogue tectonic settings (e.g., IBM arc (Fig. 1, Tonga-Kermadec, New Hebrides-Hunter Transform) of supra-subduction zone ophiolite formation at or near R-Tr-Tr or R-Tr-T triple junctions, the nature of the slab and forearc thermal structures expected, numerous modern near-trench supra-subduction zone spreading centers at triple junctions and their eruptive center characteristics, mechanisms of forearc extension and upper plate lithosphere production, and mechanisms of subduction zone lengthening and arc crustal growth.

Figure 1. Summary tectonic map of Philippine Sea Plate.
Palau/Kyushu remnant arc ridge denotes initiation of subduction during spreading along the WPS Spreading Center in the back arc terminating in the IBM forearc RTrTr (orange-green lithosphere). The beginning of back-arc, arc, to forearc splitting (SK and PV Spreading Centers) and triple junction (yellow lithosphere) in the IBM forearc, followed by Mariana spreading center split terminating at a forarc triple junction (purple lithosphere). CT Caroline-Truk Plateau, MT Marianas Trough, PV Parece Vela Basin, SK-, WPS West Philippine Sea (from Dewey and Casey, 2011).



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Insights into subduction zone dynamics from seismic anisotropy

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Subduction zones play a fundamental role in the plate tectonic cycle, hosting the bulk of Earth's earthquakes and abundant volcanism that builds new continental crust. Seismology has made great inroads in understanding the structure of these regions, using patterns of seismicity and tomography, for example. However, these methods provide a static image of slabs. To what degree the plate and asthenosphere couple in these regions and the style of mantle flow, and how these affect volcanism and seismicity, are still debatable. The seminal paper of Hess (1964) showed how directional variations in seismic wave velocities – or seismic anisotropy – reveals the dynamic interaction of the crust and the underlying mantle and led to early support for the concept of oceanic spreading centres. Similarly, observations of seismic anisotropy at subduction zones provide the signature of mantle flow and plate processes in these regions.

The propagation of two independent shear waves (or shear-wave splitting) is the most unambiguous indicator of wave propagation in anisotropic media. The strength of anisotropy is reflected in the travel-time difference between the two shear waves and its symmetry is revealed by the polarization of the shear waves. However, a challenge is to localize where the anisotropy exists and its underlying mechanism. For example, anisotropy due to the preferred alignment of olivine a-axes (A-type olivine) was frozen into subducting lithosphere when it formed at a mid-ocean ridge. In contrast, mantle deformation above and below the slab will also lead to the lattice preferred orientation of olivine and other minerals, providing a signature of the current flow field. The hydration of the mantle wedge above a subduction zone can lead to other mantle fabrics, such as those associated with B-type olivine or serpentinite domains. Furthermore, the presence of aligned pockets, bands or zones of partially melted material is also very effective in generation anisotropy. Finally, the crust can impart a signature of anisotropy due to the alignment of cracks, fractures or faults. Fortunately, domains of anisotropy can be distinguished using seismic sources in the overlying crust and downgoing plate, and using distant teleseismic events that sample the entire region (e.g., SKS phases).

A global survey of shear-wave splitting in subduction zones reveals considerable variation in the style and strength of anisotropy in subduction regions. Mantle circulation associated with 2D poloidal flow seems to be the exception rather than the rule. Here I give a quick overview of some observations. Recent work on the Tonga subduction zone shows anisotropy oriented in the direction of plate convergence beneath the Fiji plateau. The pattern rotates to a trench parallel direction beneath the Lau basin, which is interpreted in terms of slab-perpendicular flow, but also the alignment of melt associated with back-arc spreading in the basin. Shear-wave splitting in the mantle wedge is large, suggesting well developed mantle convection in the region. In contrast, the mantle wedge of the Lesser Antilles appears to be nearly isotropic. However, shear-wave splitting in teleseismic phases recorded at islands along the arc indicate that the sub-slab mantle is significantly anisotropic. Furthermore, gaps or tears in the slab are revealed from abrupt deviations in the pattern of anisotropy. As a final example, strong mantle-wedge anisotropy beneath the Ryukyu forearc suggests well developed convection through the region, which is best explained by the alignment of antigorite. In contrast, the mantle wedge beneath the more northerly Japan trench is effectively isotropic, suggesting that convection here is not well developed. In this talk, I will summarise observations of anisotropy in subduction zones, highlighting the various mechanisms at play and considering the implications for seismicity and volcanism.

NOTES

Subduction-transition zone interaction: a review

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As subducting plates reach the base of the upper mantle, some appear to flatten and stagnate, while others seemingly go through unimpeded. This variable resistance to slab sinking has been proposed to affect long-term thermal and chemical mantle circulation, plate motions through time, plate coupling and upper plate deformation. A review of observational constraints and dynamic models highlights that neither the increase in viscosity between upper and lower mantle (likely by a factor 20-50) nor the coincident endothermic phase transition in the main mantle silicates (with a likely Clapeyron slope of -1 to -2 MPa/K) suffice to stagnate slabs. However, together the two provide enough resistance to temporarily stagnate subducting plates if they subduct accompanied by significant trench retreat. Older, stronger plates are more capable of inducing trench retreat, explaining why back-arc spreading and flat slabs tend to be associated with old-plate subduction. Slab viscosities that are about 2 orders of magnitude higher than background mantle (effective yield stresses of 100-300 MPa) lead to similar styles of deformation as those revealed by seismic tomography and slab earthquakes. None of the current transition-zone slabs seem to have stagnated there more than 60 Myr. Since modelled slab destabilisation takes over 100 Myr, lower mantle entry is apparently usually triggered (e.g. by changes in plate buoyancy). Many of the complex morphologies of lower-mantle slabs can be the result of sinking and subsequent deformation of originally stagnated slabs, which can retain flat morphologies in the top of the lower mantle, fold as they sink deeper and eventually form bulky shapes in the deep mantle.

NOTES

Seismic probe of mantle mixing/unmixing in the Earth's transition zone

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Plate tectonics and subduction operating over much of the Earth's history can induce mantle mixing, chemical heterogeneities and recycle volatiles into the mantle. Some slabs are penetrating into the deep lower mantle, but others are stagnated near the transition zone (TZ). Presumably, the thermochemical state of the TZ is a consequence of delicate balance and feedback between long-term mixing and unmixing.

TZ seismic discontinuities hold the key resolving the mystery of mass and heat transport in the Earth's mantle as well as the composition of the Earth's interior. But deciphering discontinuity properties are not trivial. Data were typically limited to either mantle triplications, converted waves (P-to-S or S-to-P) or mantle reflections (e.g. SS precursors, ScS reverberations). These observations place constraints on the velocity gradient near the discontinuity as well as discontinuity reflectivity, but hardly offer independent information on the density jump or/and density gradient. In few cases where multiple datasets are jointly analyzed to resolve the density jump, the region of sensitivity (or the fresnel zone) of different dataset does not necessarily coincide. Finally, the use of short period (~1 Hz) data (e.g., P'P' precursors) or long period (~> 0.1 Hz) data (e.g., SS precursors) does not allow us to simultaneously address the transition width and the gradient near the discontinuity.

We advocate a simple and effective strategy. Specifically, we involve broadband direct converted waves (e.g., P410s, P660s) and the topside reflections (the multiples, e.g., PpP410s, PpP660s) in the context of P-wave receiver function technique. Such a tactic not only minimizes tradeoffs between velocity and density jumps, but also allows self-consistent estimates of the shear velocity jump, the density jump, the transition width and the velocity/density gradient near the boundary.

We will present the first successful attempt near the region of stagnant slab beneath China. These new observations, along with the thermodynamic framework, HeFESTo, allow us to test and validate hypotheses including the state of mantle mixing, compositional heterogeneities and the degree of hydration in the TZ. Along with other high-resolution regional seismic profiles in the transition zone, we will also show that the presence and absence of localized stratification between basalt and hartzburgite near the 660 are spatially correlated with past subduction history, calling for rheology to allow separation between basaltic and hartzburgitic layers during downwelling.

NOTES

The Atlas of the Underworld: a catalogue of slab remnants in the mantle imaged by seismic tomography and their geological interpretation

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Seismic tomography has caused a breakthrough in the analysis of plate tectonic history by tracing remnants of ancient subduction that appear as positive seismic wave-speed anomalies across the entire mantle. Subduction also leaves a geological record that allows for dating the period of active subduction. Combining these sources of information has led to the identification of many slab remnants and provided novel constraints on absolute plate motions, mantle convection models, volcanic degassing of CO_2 and global sea level through time.

This review paper documents the Atlas of the Underworld, a compilation of 94 subducted slabs and their geological record, comprising subduction systems active in the past ~300 Myr. Initially we identify slabs and their depth extent in the 3-D P-wavespeed model UU-P07 and next check for consistency of detection with independent S-wavespeed models. Our geological interpretations of slabs start with active subduction for which we estimate the onset age of subduction from the geological record. Next, for detached slabs we interpret ages of onset and end of subduction, associating progressively deeper slab remnants with progressively older geological records of subduction. We assume that adjacent slabs did not undergo major horizontal motion relative to each other after detachment.

The Atlas of the Underworld also identifies slabs that affected the shapes of large low shear wave velocity bodies (LLSVP's) in the deep mantle. For the Pacific LLSVP this concerns the Telkhinia slabs, while for the “Perm Anomaly” below Siberia we propound that it was separated from the large African LLSVP by the Balkan slab associated with Permian subduction in the Urals.

This compilation is intended to provide a starting point for systematically linking present-day mantle structure to plate tectonic evolution and is also accessible online at www.atlas-of-the-underworld.org and includes a discussion forum for post-publication peer review and updates.

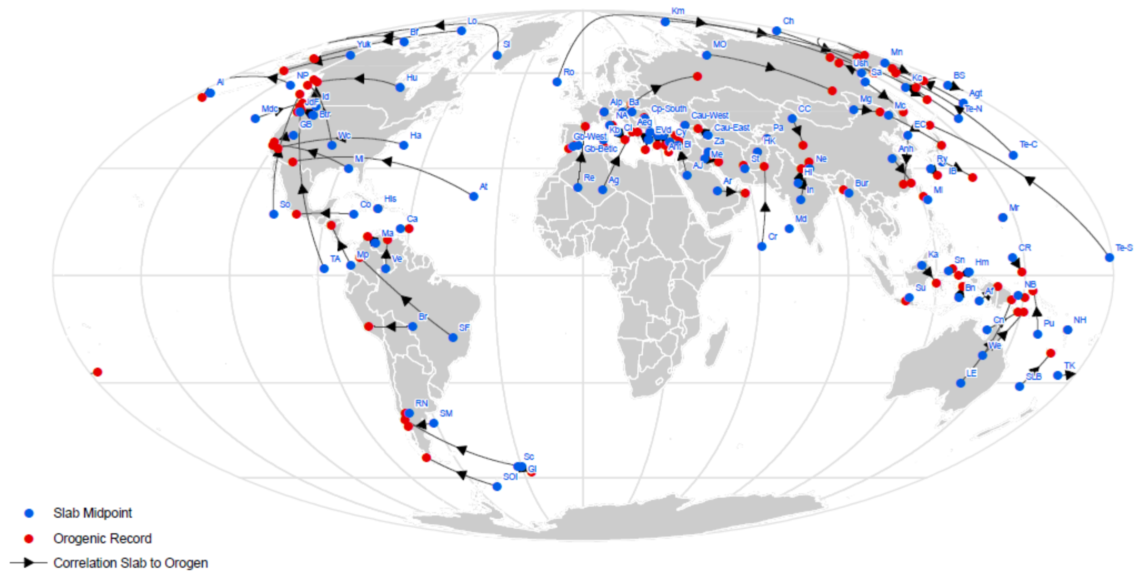

Figure. Map showing the locations of slabs in the Atlas and corresponding geological records.

NOTES

Plate tectonics and the geology of plate boundary zones.

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Since Tuzo Wilson 1965 milestone paper, which introduced and outlined the theory of plate tectonics, an understanding of the relationship of bulk regional rock suites to plate boundary zones has been clear, since when there has been a progressive refinement and the development of numerous qualitative models for extant, Phanerozoic and Late Precambrian orogens. Atwater's (1970) analysis of the relative motion and evolution of the Pacific, Gorda, Farallon, and North American Plates, their boundaries and two key triple junctions, and the geology of western North America provided the first example of relating, quantitatively, the geological evolution of a large region to the relative motion among a plate mosaic that was responsible for that evolution. Similar studies soon followed for the Alpine System, the Caribbean, and Southeast Asia. There is still substantial controversy on when plate tectonics started; my preference is about 2.0 Ga. GPS and seismic moment-derived velocity fields have become a powerful tool in understanding strain, displacement, and partitioning in most modern plate boundary zones, especially the Alpine-Tibetan System, the Andes and New Zealand. Palaeomagnetic studies in New Zealand indicate very large vertical axis rotations, which, in a smooth velocity field, show that strain and displacement occur at a small-scale and that models involving very large blocks or platelets are unlikely to be valid. The Zoback and Zoback global stress maps are also a very useful guide to the deformation of the brittle surface layer. The central problem of tectonics is relating the detailed structural, metamorphic, igneous, and stratigraphical evolution in a plate boundary mosaic to the evolving relative motion of the causal plate mosaic and the evolution of its triple junctions. The complexity of this problem is illustrated by the evolution of several theoretical plate mosaics with and without "non-subductable continents. Using quite simple mosaics on stereographic projections, these show very rapid continuous change in the rate and direction of slip at points along the plate boundaries, rapid successions of tectonic patterns as triple junctions change their form and position, the conversion of ridges and transforms/fracture zones to subduction zones, andthe evolution of finger plates like the Caribbean. If there is a relationship between these models and the resultant evolution of rocks masses , plate evolution is a foundation for understanding their great complexity of geometry and history. A difficulty, however, is the inversion problem. It is easy to use a model to make very detailed predictions but generally almost impossible to develop a unique causal model from real data; Dewey and Casey have attempted to relate the structures in an ophiolite obduction melange to the evolution of its suprajacent ophiolitic forearc before, and during obduction. Some structures, such as high-temperature gneissic flow folds, have their geometry determined by lower crustal flow along gravity gradients. The short-term evolution of continental triple junction can yield complex and unexpected results. The Karliova transform/transform/thrust triple junction in eastern Turkey results from the expulsion of Anatolia from the jaws of the Arabian/European vise and the welding of two half transform walls, which yields a shear zone containing "contradictory" strike-slip shear senses in a shortening zone. At the southwest termination of the East Anatolian Transform, the Adana Basin, characterised by radial stretching, is generated at a transform/transform/transform junction. Where continental transforms have locking and unlocking bends, they develop diachronous transpressional and transtensional zones with vertical axis rotation as rock masses move into the bends then an opposite rotation as they move out of the bends. The immensely-variable rheological layering of the lithosphere yields a further complexity of structural behaviour and evolution in plate boundary zones, from the resistance of hard "knots of Archaean lithosphere to the thin versus thick-skinned thrust styles of the Peruvian and Bolivian Andes, determined by the presence or absence of a ductile layer in the crust.

NOTES

Plate tectonics in the Andes: old paradigms and new insights

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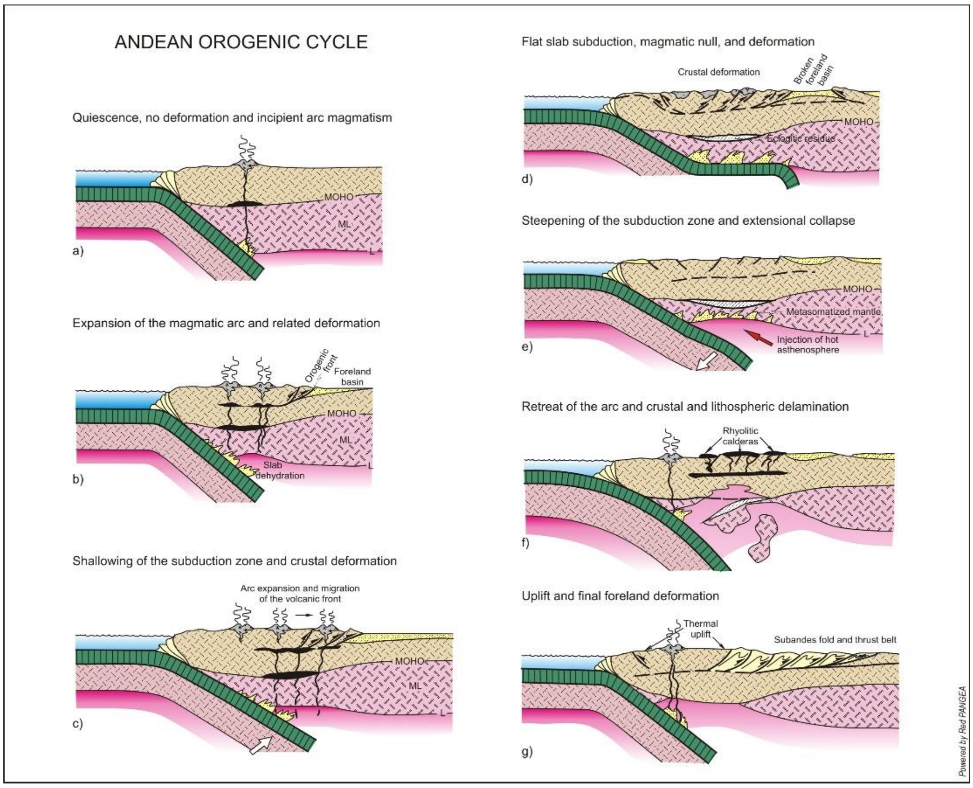
After the pioneering proposal of John Dewey in the late sixties of an Andean-type orogen, numerous studies tried to understand the mechanisms of plate tectonics that operate in the Andes. Despite the strong resistance of some tectonicians expressed in the Geological Society's Andes meeting held in London in 1984, the new ideas were slowly gaining adherents.

These 50 years had important benchmark studies, which contributed to the present knowledge of the Andean tectonics. One of them was the analysis of the different geological processes related to changes in the slab geometry during subduction that led to the present understanding of the Pampean and Peruvian flat-slab subductions. The geological processes associated with the increase of the subduction angle have taken longer to be understood, but have shown the development of important rhyolitic provinces with large calderas or outsized basaltic lavas plateaux, depending on the thickness of the previous continental crust.

These changes in the slab geometry led to the identification of crustal delamination and removal of the lithosphere as common processes during steepening of the subduction angle in late Mesozoic-Cenozoic times. Lately, these processes are being recognized in the late Paleozoic. Thermal uplift of a large high plateau is a consequence of crustal delamination, which favored lower crustal softening and propagation of fold and thrust belts in the foreland.

Striking evidence showed the importance of the climatic control in the tectonic regimes, expressed on both sides of the Andes. This control is observed in the hyperarid forearc of the Central Andes, where tens of kilometers of crustal erosion by subduction took place at the time of localized extension along the Pacific margin, together with important changes in the magmatic arcs. Surprisingly this forearc extension is in stark contrast with coeval compression in the Andean system with fast shortening of the foreland fold- thrust belts. The new techniques in low-temperature thermochronometry constrain the timing of uplift of different segments of the Andes, as well as the climatic influence in the valley incision. Large features as the Patagonian batholith exposures over hundreds of kilometers along the margin are the result of exhumation controlled by the prevailing westerly winds and heavy precipitations, more than simply tectonic uplift.



The Dickinson Andean Orogenic cycle (after Ramos, 2009).

These tectonic processes as a whole define the development of a complete orogenic cycle in the Andes, exclusively associated with the subduction regime, without the participation of any collision. This cycle of mountain formation and its subsequent destruction had already been proposed more than 40 years ago by William Dickinson, and it is presently known as the Dickinson Cycle.

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The Plate Tectonic Approximation: An Update

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The two original tenets of plate tectonics are that the plates are rigid and that the plate boundaries are narrow. It was soon recognized, however, that plate boundaries through continents are in many places diffuse (e.g., Molnar & Tapponnier 1975). It was later recognized that diffuse plate boundaries also occur in many places in the oceans (e.g., Wiens et al. 1985). Particularly large and important are the diffuse plate boundaries in the equatorial Indian Ocean separating the India, Capricorn, and Australia plates. The strain rates in diffuse oceanic plate boundaries are about an order of magnitude lower than in continents. Nevertheless, India and Australia—originally believed to be on the same rigid tectonic plate—approach one another at a rate of ≈15 mm a^{-1}. The integrated rheology of oceanic lithosphere unsurprisingly appears to be different from that of continental lithosphere. Thin viscous sheet models of deforming oceanic lithosphere of the equatorial Indian Ocean indicate a power-law exponent of ≈30, which is much higher than the power-law exponent that best fits most continental deformation (Gordon & Houseman, 2015). Diffuse plate boundaries cover ≈15% of Earth's surface and are an essential part of the global tectonic system.

Given the widespread occurrence of diffuse plate boundaries, plate rigidity remains as *the* central tenet of plate tectonics. But how rigid are the plates and by what processes do they deform? One process causing deformation of plate interiors is the movement of plates over a non-spherical Earth (McKenzie 1972; Turcotte & Oxburgh, 1973). Woodworth & Gordon (2017) find that the current maximum strain rate for each plate ranges from 10^{-9} to 10^{-3} Ma^{-1} (10^{-22} to 10^{-16} s^{-1}), with 80% of Earth's lithosphere deforming at rates between 10^{-7} and10^{-4} Ma^{-1} (between 10^{-20} and 10^{-17} s^{-1}). Higher rates of intraplate deformation are indicated in some places, however, for horizontal thermal contraction of oceanic lithosphere as it cools and subsides (Collette, 1974; Kreemer & Gordon, 2014). Such strain rates are as high as ~10^{-3} Ma^{-1} (~10^{-15} s^{-1}) and integrate to displacement rates across "rigid" plates composed in whole or part of oceanic lithosphere of 1−2 mm a^{-1}, which in a global plate motion circuit may sum to ≈5 mm a^{-1}. With some assumptions, transform faults on shrinking oceanic plates are predicted to differ slightly in azimuth from the direction of relative plate motion with the sign of the predicted difference changing between left-lateral and right-lateral slipping transform faults. Observed azimuths of transform faults are consistent with the predictions of the shrinking-plate hypothesis and are inconsistent with the rigid-plate hypothesis (Mishra & Gordon, 2016).

An outstanding unresolved problem is to understand the cause of the non-closure of the Cocos-Nazca-Pacific plate circuit, which fails closure by 15 ± 5 mm a^{-1} (95% confidence limits; DeMets et al., 2010). Recent work revises this non-closure downward to 12 ± 5 mm a^{-1}, but it remains large and significant and challenging to explain (Zhang et al., 2017).

NOTES

The East African Transform Margin: - a major new interpretation using potential fields geophysics

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The continental margin of East Africa is a result of several superimposed structural events, commencing with episodic extensional rifting during the Permian and early Triassic, followed by rifting and separation of eastern Gondwana in the early Jurassic. As East Gondwana moved south in the later Jurassic and early Cretaceous, a transform margin developed between Madagascar and Tanzania-northern Mozambique bounded by the Davie-Walu fault system with more oblique rifting and oceanic spreading to the north and south. Spreading in the deep water Somalia Basin stopped in the Aptian and the transform margin subsided during the later Cretaceous and early Cenozoic to be buried by thick deltaic to deep marine clastics, interrupted by periods of regional uplift and tilting. During the Neogene and into the Plio-Pleistocene, underlying Jurassic and Permo-Triassic faults of the old transform margin were reactivated to form a wide zone of transpressional to transtensional deformation inboard of the Davie Fracture Zone. The western margin is expressed as a long sigmoidal 4,000km dextral strike slip fault.

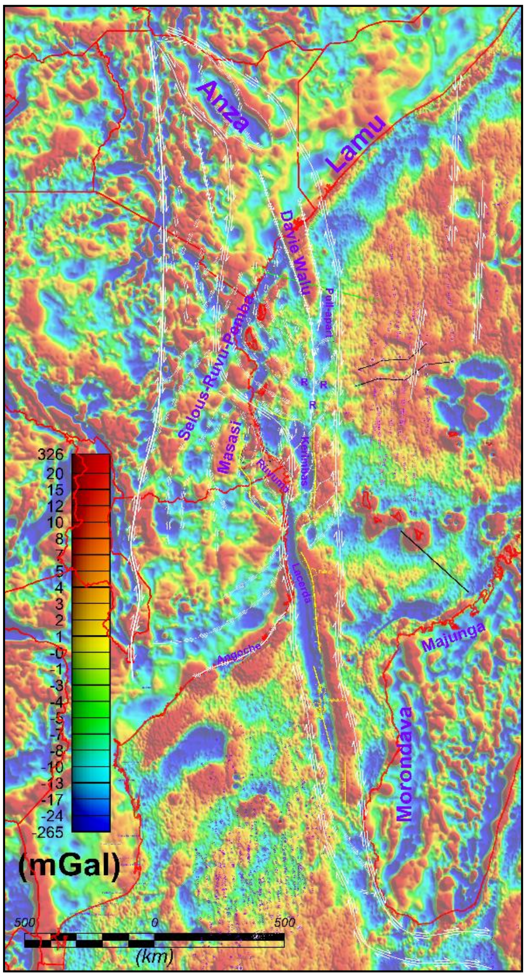
Complete processed derivatives of the latest satellite products of Sandwell's Free Air Gravity (Sandwell et al, 2014, version 23) and the Enhanced Magnetic Model (Chulliat et al, 2015) released in 2015 supported by published seismic and well data provide a robust regionally consistent framework to examine and assess this reactivated transform margin. A re-assessment of earlier views is enabled utilizing isostatic decompensated residual gravity (figure 1) and reduced to pole IGRF corrected residual magnetics (figure 2) from which it is concluded the entire margin represents a broad transform zone bound to the east by a dextral strike slip fault delimiting the Somali Basin spreading centre and oceanic crustal domain.

In the north, we identify Neogene inversion in the Anza Graben as the reactivation of a 4,000 km transform fault that ends in active strike slip south of Madagascar. The strike slip corridor extends over 700km in width westwards to the western arm of the East African Rift System (E.A.R.S.), with distinct deformation provinces developed within the transform zone.

South of Anza, a transpressional horsetail splay of synthetic faults is present, bound by the Davie Walu Ridge in the east, and to the west by a significant strike slip fault initially trending at 135 degrees that bends 100km north of the Rovuma Delta and then strikes south following the coastline and defining the western margin of the present day offshore transform corridor to southern Madagascar. East of Davie Walu Ridge, crustal extension of the offshore Lamu Basin is evident as a transition to a rifted, passive margin to the east of the bounding transform fault

Transpression is replaced eastwards across the Davie Walu axis by extensional deformation evidenced by a pull-apart basin and further south a failed triple 'R' aucolagen. Further south, a 200km wide corridor of duplex fold structures bound by en echelon basement horsts to the east, and a restraining strike slip bend to the west transfers to a narrow transtensional zone, reactivated by Tertiary E.A.R.S., comprising the Karimbas and Lacerda graben systems. South of Angoche the transtensional zone is transferred into another transpressional leg that is defined by a restraining bend west of Madagascar, before the transform margin turns east into a present day active strike slip fault offshore southern Madagascar.

We conclude the East African transform margin was initiated prior to Jurassic rifting forming a continental transform margin that has been reactivated several times through the Cretaceous and Tertiary. Prior to Gondwana breakup in the Jurassic, Madagascar was bound to the west by an early transform margin that facilitated rift and drift from the northern passive margin of the Lamu embayment. Generally, the transform margin structures young south along the length of the present day strike slip zone. The bathymetric expression of the Davie Ridge represents the Tertiary uplift and offshore activation of the eastern arm of EARS, which is bound by the older transtensional structure of the transform margin. With special thanks to David Boote and Nick Cameron for their valuable comments.



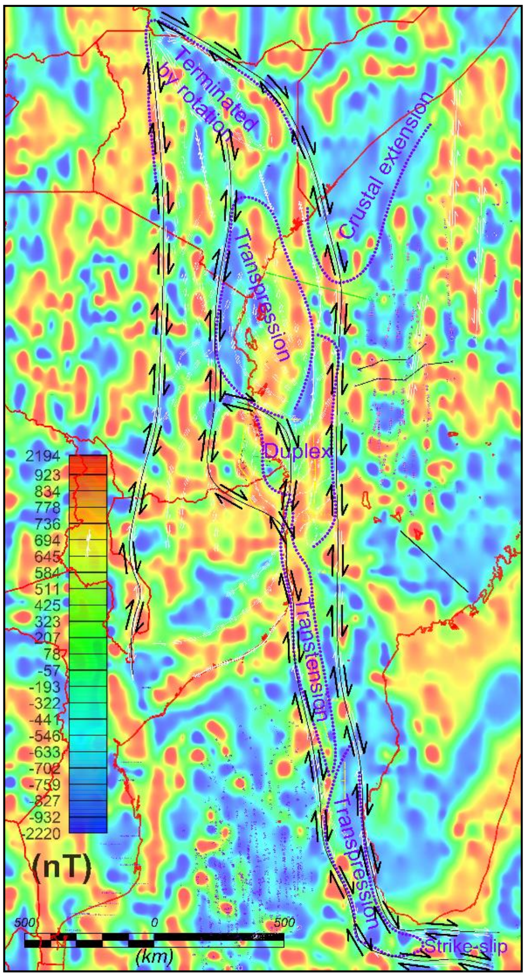


Figure 1(left): Decompensated isostatic residual gravity (derived from Sandwell et al, 2014) with interpreted transform margin structure. Figure 2 (right): Enhanced magnetic model (Chulliat et al 2015), IGRF corrected, reduced to pole and amplitude gain corrected, with interpreted regional structural features.

Selected references:

Chulliat, A., P. Alken, M. Nair, A. Woods, and S. Maus, 2015, The Enhanced Magnetic Model 2015-2020, National Centers for Environmental Information, NOAA. doi: 10.7289/V56971HV [10th May 2015]

Sandwell, D. T. et al, 2014, New global marine gravity model from CryoSat-2 and Jason-1 reveals buried tectonic structure, Science, Vol. 346, no. 6205, pp. 65-67, doi: 10.1126/science.1258213

NOTES

From inland-sea basins to confined orogens: An example from the Neoproterozoic Araçuaí-West Congo orogen and implications for Plate Tectonics

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Although they are largely surrounded by continental crust, inland-sea basins (e.g., gulfs) can be partially floored by oceanic crust, as well as, they can be tectonically inverted by orogenic processes driven by plate convergence. Since those basins are relatively uncommon and small in modern Earth, preservation of their remains are expected to be rare and/or hard to identify in the geological record, especially in Precambrian orogens. After our papers published from the 1990's, the Araçuaí – West Congo orogen (AWCO, Fig. 1) became an unique example of an orogenic belt formed from the inversion of an inland-sea basin and, also, the birthplace of the confined orogen concept. Here, we present an updated synthesis on that confined orogen, formed after the subduction of oceanic lithosphere within an inland-sea basin.

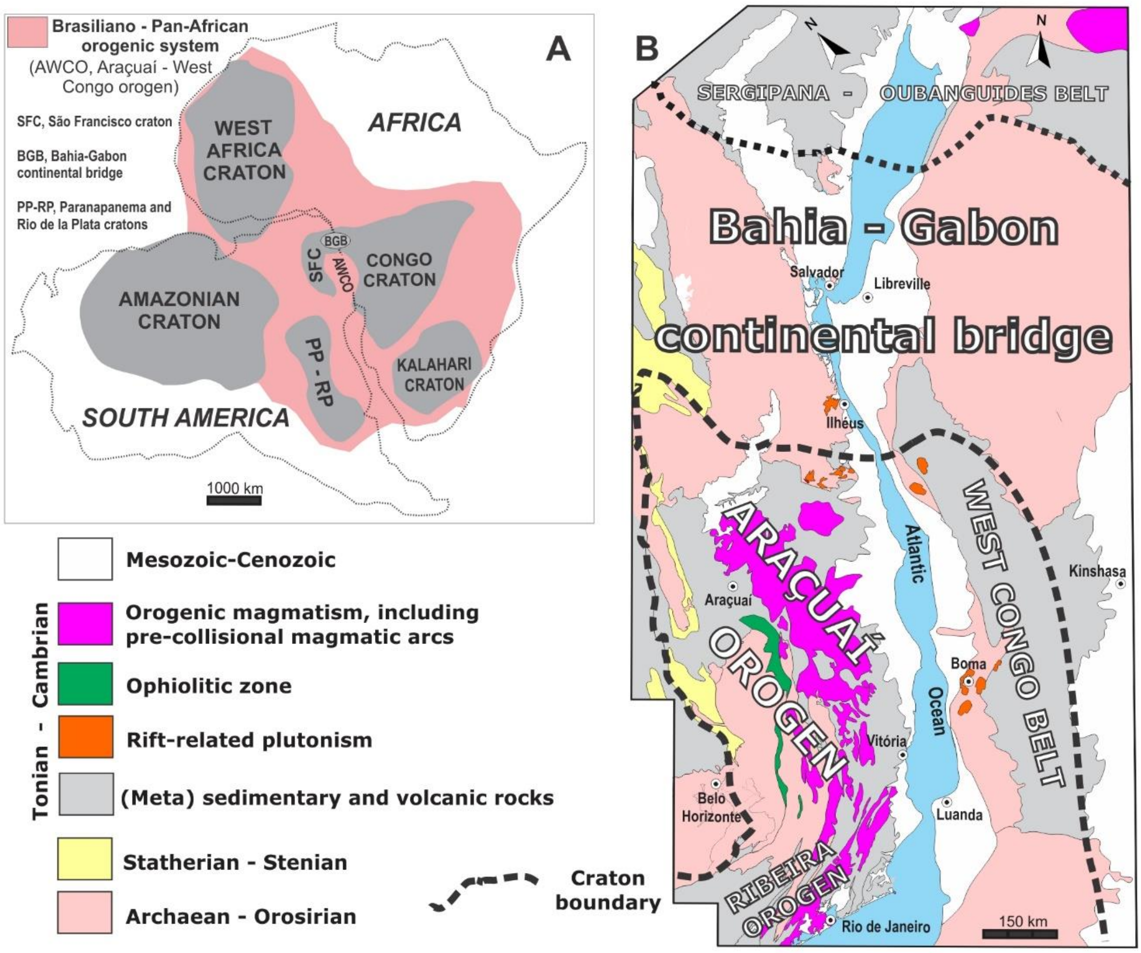

Figure 1. A, the Araçuaí – West Congo orogen (AWCO) in Western Gondwana. B, simplified geological map of the AWCO and Bahia-Gabon continental bridge (BGB), and adjacent regions.

In fact, all palaeotectonic reconstructions for the interval of ca. 2000 – 140 Ma have shown the AWCO surrounded by cratonic land, the Congo – São Francisco (CSF) craton, along three (W, N, E) sides, but connected southwards with the Brasiliano – Pan-African orogenic system developed along SE South America and SW Africa during the Western Gondwana assembly in Late Neoproterozoic time.

From the CSF palaeocontinent amalgamation around 2 Ga to the opening of the South Atlantic Ocean in the Cretaceous, at least six anorogenic magmatic events and rift-related basins (E1, ~1750 Ma; E2, ~1500 Ma; E3, ~1180 Ma; E4, ~1000 Ga; E5, ~930-880 Ga; E6, ~720-670 Ga) record attempts to separate the Congo and São Francisco counterparts along the AWCO site. Although the last continental rifting event (E6) evolved to ocean crust spreading (~ 660 – 600 Ma), it was also unable to break up the Bahia-Gabon continental bridge and only carved an inland-sea basin within the CSF palaeocontinent (Fig. 1). Within this basin, a plate convergence period started around 630 Ma, forming a pre-collisional calc-alkaline magmatic arc to the east of an ophiolitic zone, which locations indicate that the oceanic opening did not reach the northern basin sector. Therefore, this confined orogen shows two very distinct longitudinal segments: i) the northern segment is ensialic and represents the aborted continental rifts; ii) the southern one characterizes the segment where oceanic spreading and subduction of oceanic lithosphere took place. These distinct segments are continuous along the structural trend of the orogen and both show the same collisional features, like the regional deformation and metamorphism, large amounts of peraluminous granites, as well as a number of post-collisional intrusions.

In a scenario for the Western Gondwana assembly, the AWCO represents, after repeated aborted rifts, a relatively weak lithospheric zone within the CSF palaeocontinent, where an oceanic rise, coming from a southern larger ocean (the Adamastor Ocean), faded away toward the stronger and thicker cratonic lithosphere of the Bahia – Gabon continental bridge (Fig. 1).

A mechanism similar to a nutcracker has been suggested to explain the opening and closing processes within the AWCO inland-sea basin, whereas some aulacogens accommodated the related tectonic effects within the CSF craton. If the amount of oceanic lithosphere was not sufficient to promote subduction by itself within the inland-sea basin, the nutcracker model suggests that far distant collisions would have catalysed the subduction process within AWCO inland-sea basin, as it occupies a central region in the scenario of the Western Gondwana assembly (Fig. 1).

Besides representing an intermediate term between the typical plate margin orogens and intra-cratonic inverted aulacogens, confined orogens also require specific precursor basins widely surrounded by continental crust and partially floored by ocean crust.

NOTES

Cenozoic growth of the Tibetan Plateau and its influence on Asian climate: One opinion about 21st century continental tectonics and its role as an environmental agent

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Tibet has grown higher and wider since India collided with southern Eurasia at ~50-40 Ma. At 15-10 Ma, however, crustal thickening ceased (except on the margins), and crustal thinning of the interior of the plateau began. Because of isostasy, the mean elevation of the plateau should have begun to decrease. An extrapolation of the present-day strain rates derived from GPS velocities implies that at 15-10 Ma, Tibet may have stood 1000 m higher than today. Seismological studies suggest thinner crust and missing or thin mantle lithosphere beneath northern Tibet, where volcanism today is most widespread, than beneath southern Tibet. A simple interpretation of this change assigns cause to removal of mantle lithosphere, which added buoyancy and gravitational potential energy to the remaining Tibetan lithosphere. Concurrent with the switch from crustal thickening in Tibet to crustal extension and thinning of Tibet's crust in the high plateau, surrounding areas have grown higher. Not only eastern Tibet, but also the Tien Shan and the high mountains of Mongolia grew high largely since 10-15 Ma, presumably in response to the added force per unit length that Tibet applied to its surroundings.

Topographic changes in these regions apparently contributed to changes in Miocene climate of Asia, but for different reasons in different parts of Asia. For example, loess deposition in China, which began in mid-Cenozoic time, spread over the Loess Plateau at ~10 Ma. Modern dust accumulation results from springtime storms that develop by lee cyclogenesis on the southeast side of the Mongolian Altay. Lower terrain over Mongolia before ~10 Ma may have denied the atmosphere the seed it needed to grow into storms. Concurrently, northwestern India and Pakistan underwent a change from a relatively moist climate to the present-day arid one. Browsing animals that ate leaves from trees gave way to grazing animals that thrive on grass. I associate the aridification of northwestern India and Pakistan with the rise of eastern Tibet and enhanced orographic precipitation there. By analogy with Rodwell and Hoskins's application of the Gill model to lower latitude circulation, latent heating over eastern Tibet induced subsidence over NW India, which led to aridification. Thus, the growth of high terrain in Asia seems to have affected climate in different parts of Asia (loess deposition, aridity over NW India, and maybe also rainfall over East Asia), but the mechanisms by which the high terrain influenced climate differ from region to region.

NOTES

Intraplate orogenesis: Eurekan Orogen

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Plate tectonics has it that major orogens form at plate boundaries, specifically in response to collision of continental lithospheric plates with other continental lithospheric plates or island arc terranes and so on. A multitude of schematic diagrams have been published in the last 50 years showing black-coloured oceanic crust being subducted under white-coloured continents, continental fragments, other pieces of oceanic crust, often with subduction polarity flipped from one panel to another. Lately, abundant evidence, and a theoretical basis for it, has been published showing that many orogenic belts involve extreme shortening of previously severely thinned and often significantly intruded continental lithosphere but, nevertheless, continental lithosphere that was not breached or broken in a plate tectonic sense to produce a new lithospheric plate boundary at which new oceanic lithosphere is accreted. Although there are semantics involved, this cannot count as orogenesis at a plate boundary: it is, accordingly, "intraplate orogenesis". However, besides this mode of "intraplate orogenesis", which is receiving much interest at present, there is another mode of "intraplate orogenesis", one in which significant shortening deformation occurs in an intraplate setting not including the inversion of a predecessor deep marine basin. An example of this is the Eurekan "Orogen" in Canada's high Arctic. The Eurekan "Orogen" involves the further shortening in the Cenozoic of a predecessor Palaeozoic orogenic belt (although there would have been some subsidence and basin formation in the area during the intervening >200 My). Recently, the Ellesmere Lithosphere Teleseismic Experiment (ELLITE) has allowed, for the first time, a model of the crustal structure of the Eurekan Orogeny to be proposed on the basis of well-constrained receiver functions and gravity data. The model crosses the major tectonic/structural domains of Ellesmere Island, running some 460 km NNW-SSE from the vicinity of Yelverton Bay on the Arctic Ocean coast in the north to the vicinity of Bache Peninsula on the Baffin Bay coast in the south. A series of inferences on how this kind of crustal-lithosphere scale intraplate shortening takes place can be drawn from the relationships between the geophysical crustal structure and the exposed geology of Ellesmere Island, including the existence of crustal underthrusting below a large, crustal-scale "pop-up" structure forming the heart of the Eurekan Orogen itself and a Eurekan (Cenozoic-aged) fold-and-thrust belt involving Neoproterozoic and lower Palaeozoic strata.

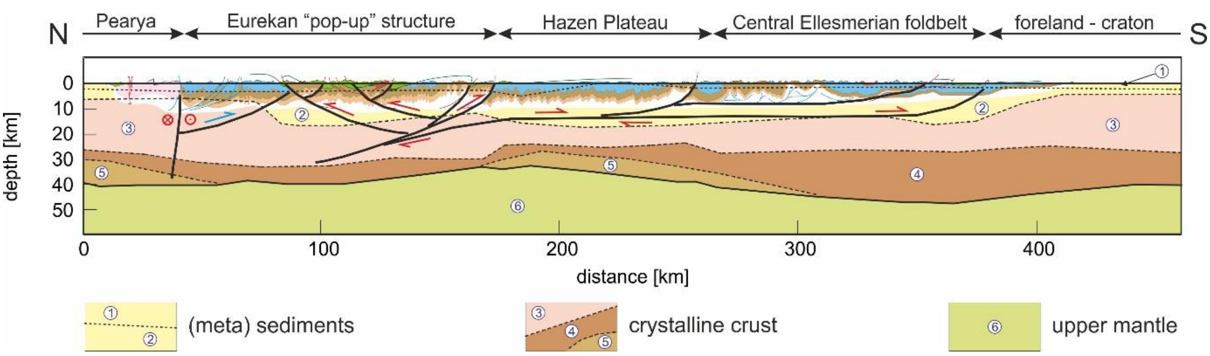

Figure: Model crustal layers are from ELLITE receiver functions, adjusted for observed gravity (Stephenson et al. 2017, GeolSoc SP, doi:10.1144/SP460.12); the superimposed geological transect (depth <10 km) is from Piepjohn et al. 2017, GeolSoc SP, doi:10.1144/SP460.5).

NOTES

Intraplate Mountain Building in Non-Cratonized Continental Interiors: Lessons from Central Asia

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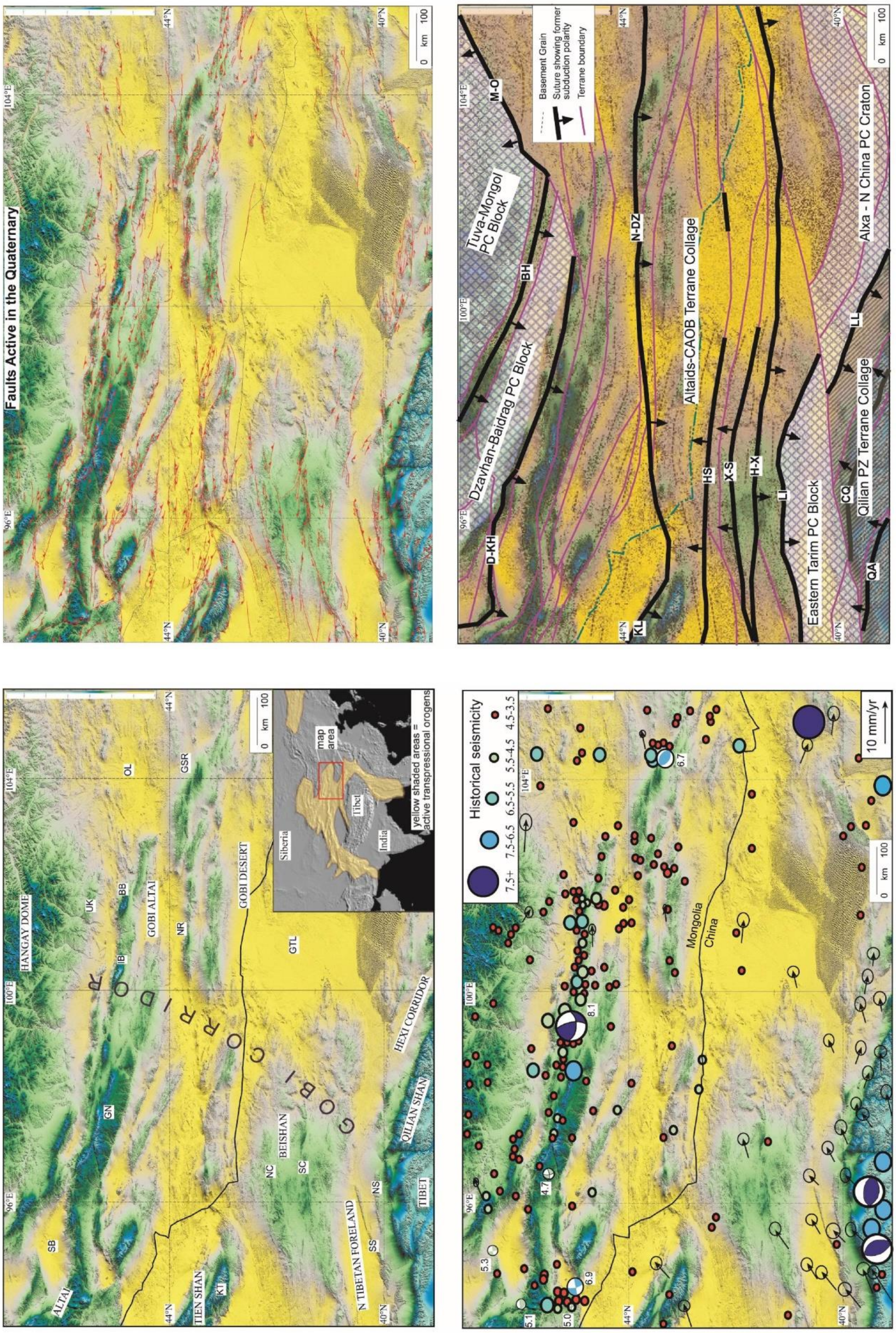
The Gobi Corridor region north of Tibet is arguably the world's finest natural laboratory for documenting lithospheric controls on the distribution and kinematics of intraplate mountain building. Earthquake, geodetic, geomorphic and structural data in the north Tibetan foreland, Beishan, easternmost Tien Shan and Gobi Altai indicate that a diffuse network of Quaternary faults has accommodated sinistral transpressional deformation as a distant response to NE-directed compressional stresses driven by the continued Indo-Eurasia collision, 2000+ kms to the south. Gobi Corridor crust is a Paleozoic terrane collage (Central Asian Orogenic Belt) sandwiched between rigid Precambrian-Archaean cratons that was repeatedly reactivated during the Permo-Triassic, Jurassic, Cretaceous and Neogene. Late Cenozoic reactivation was likely facilitated by thermal weakening of the crust due to Jurassic-Miocene volcanism, and diffuse Cretaceous rifting and crustal thinning. Active faults north of Tibet terminally accommodate intraplate strain in oblique deformation belts dominated by restraining bends, horsetail splay thrust ridges, and individual thrust ranges that collectively define a transpressional basin and range physiographic province. Although terrane boundaries and other faults are reactivated in many areas, thrust and oblique-slip reactivation of WNW striking shallowly dipping sedimentary bedding and metamorphic fabrics is equally important. Conversely, modern E-W trending strike-slip faults typically crosscut older basement trends. In the Altai and Gobi Altai, the Late Cenozoic fault array is best described as a transpressional duplex. Coalescence of separate ranges into topographically continuous mountain belts in the Altai, Gobi Altai and eastern Tien Shan is an important mechanism of mountain building not predicted by classical plate tectonic models. Throughout the Gobi Corridor, tectonic loading is shared amongst a diffuse fault network challenging assumptions about earthquake recurrence intervals and seismic hazard forecasting.

The Neogene-Recent deformation of the Gobi Corridor region reminds us that the complete life cycle of an orogenic belt may also include one or more later phases of intracontinental, intraplate reactivation, not predicted by plate tectonic theory. Similar crustal reactivation events within older orogenic belts may be more difficult to recognize in the rock record because intracontinental, intraplate orogens like the Gobi Altai or easternmost Tien Shan may involve less than 5 kms of rock uplift and similar amounts of erosional denudation and landscape lowering. The mountains may also be eroded flat and no longer expressed in the landscape after a geologically short period of time, depending on ambient erosion rates. Magmatic and metamorphic effects are likely to be non-existent or undetectable at surface exposure levels. Thus the signature of an ancient intracontinental, intraplate orogen may be subtle and elusive, and perhaps only detectable by low-temperature thermochronometers, preserved orogen-derived sedimentary sequences, fault zone evidence for younger brittle reactivation, and recognition of a younger class of cross-cutting tectonic structures. Thus the Late Cenozoic deformation of the Gobi Corridor region provides a sobering message to continental tectonicists, that important intracontinental orogenic events in Earth history may have gone un-noticed until now, and still await discovery.


Faults Active in the Quaternary
HANGAY DOME
GOBI ALTAI
GOBI DESERT
GOBI CORRIDOR
ALTAI
TIEN SHAN
BEISHAN
N TIBETAN FORELAND
HEXI CORRIDOR
QILIAN SHAN
TIBET
Siberia
Tibet
India
map area
yellow shaded areas = active transpressional orogens
Historical seismicity
7.5+
7.5-6.5
6.5-5.5
5.5-4.5
4.5-3.5
10 mm/yr
Mongolia
China
Tuva-Mongol PC Block
Dzavhan-Baidrag PC Block
Altaids-CAOB Terrane Collage
Eastern Tarim PC Block
Qilian PZ Terrane Collage
Alxa - N China PC Craton
Basement Grain
Suture showing former subduction polarity
Terrane boundary
0 km 100

NOTES

Revolution in the Earth Sciences: An African plate perspective

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The Plate Tectonics revolution was accomplished around 50 years ago, over a period of about 5 years [1963-1967], during which time the qualitative concept of Continental Drift was transformed by a new paradigm of quasi-rigid lithospheric blocks, consisting of continental and oceanic crust overlying a strong layer of upper mantle, moving coherently over a weak asthenospheric layer of lower effective viscosity. Complete quantitative integration of the Nubia and Somalia components of the African plate (McKenzie et al., 1970) into the current global plate model (DeMets et al., 2010) took a further 40 years. It required the co-evolution of satellite and computer technology, the development of Space Geodesy, its application to global tectonics (e.g., Gordon & Stein, 1992), and the integration of these new methods with seismotectonic data provided by slip-vector directions derived from earthquake focal-mechanism solutions (e.g., Calais et al., 2006). The outcome is a multi-plate model, where the larger African "composite plate" remains a single mechanical entity, despite the resolvable relative motions of its constituent or "component plates". A strong dynamic coupling is maintained across their boundaries, especially in the southern sector, where the pole of relative rotation between the major Nubian and Somalian plates lies close to or within the extent of an intervening, oceanic Lwandle plate (Hartnady, 2002). Here there is a transition from extensional to compressional horizontal-stress regimes, giving rise to the second-largest "vertical integrated stress anomaly" on the planet (Bird et al., 2008). In terms of seismic hazard analysis, the estimation of earthquake size-frequency distributions, and the probability of great (magnitude > 8) events along certain boundary segments, the seismotectonic implications of the new African plate-kinematic and –dynamic regime are profound. Further elaboration of kinematics along the ultra-slow (<5 mm/yr) extensional elements of the plate-boundary system, and mapping of stress regimes within African intraplate regions, promises further important insights for the understanding of seismic hazard on the continent (Meghraoui et al., 2016).

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NOTES

Tectonic roles of South America Tectonostratigraphic Terranes in the Brasiliano Collage

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The Brazilian structural provinces were consolidated in several stages during the Neoproterozoic and Cambrian (ca. 800 Ma, ca. 750 Ma, 640-610 Ma, 590-560 Ma, 540-480 Ma). Distinct time intervals are recorded in the different provinces. In all the provinces, participation of pre-Brasiliano basement inliers (Archaean, Paleoproterozoic, Mesoproterozoic and Early Neoproterozoic in age) is remarkable. Simple plate interaction models are unable to explain the structure of the distinct fold belts. The tectonic organization of the provinces is generally complex, mosaic-like, where basement inliers interference was very important. Participation of these older “terranes”/”massifs” (as they are usually labelled) in the tectonic evolution of the Neoproterozoic orogens is outstanding.

Pre-800 Ma paleogeographic reconstruction is possible, and involves precursor oceanic domains and interacting continental blocks. Among the latter are the major continental plates (Amazonian, São Luís-West Africa, Parnaíba, São Francisco-Congo, Paranapanema, Luís Alves, Rio de La Plata), representing the sin-Brasiliano cratons. In addition, there are a number of smaller continental blocks, usually labelled as “massifs” and/or “terranes”, the origin of which is varied. Although these smaller blocks where variably reworked during the Brasiliano collage orogenic processes it is possible to recognize their role during the Neoproterozoic orogenic events.

In the three largest Brasiliano structural provinces, the northeastern Borborema Province, the southeastern Mantiqueira Province, and the central-western Tocantins Province, the identified “massifs”/”terranes” bear diverse tectonic histories. A look at the geologic maps of these provinces reveals an elevated number of actors in the process of tectogenesis, among which, terranes stand out in particular. These terranes have been interpreted as former micro plates, former microcontinents or simple (erosional) exposures of the older sialic basement. Aside from these cases, some basement inliers could just be thermo-tectonically reworked marginal parts of former major plates. Some other basement inliers were former antiformal cores or alike, developed during post-orogenic exhumation. In the latter case, the “massifs” expose Archaean and/or Paleoproterozoic basement cores surrounded by Neoproterozoic metavolcanic-sedimentary belts.

Diversity of the significance and of exposure of the basement inliers is remarkable in Neoproteorozoic belts of South America, and not too frequently found in usual models proposed for Precambrian mobile belts. In our view, using the “meta-craton” term is inadequate, and not advisable for several reasons of concept, semantics and the tectonic histories of these pre-Brasiliano segments.

NOTES

Sedimentation and tectonics in the plate tectonic era

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The plate tectonic revolution provided an explanation for the long-recognized geological similarities between formerly contiguous continents, and challenged the generally descriptive, static view of sedimentary history in which sedimentation was seen as alternating with orogenesis for no apparent reason, and stratigraphic elements in close proximity today were with few exceptions viewed as having been deposited that way. The volcanic-bearing eugeosynclines and volcanic-free miogeosynclines of Hans Stille and Marshall Kay, for example, were regarded in the 1940s and '50s as parallel divisions of mobile belts formed *in situ*, and not as disparate rock suites brought together by subduction and mountain building (the contemporary view). The work of John Crowell on the strike-slip tectonics of California, beginning with his 1947 PhD dissertation on Ridge basin, is notable for recognizing the significance of large-scale displacements along faults of the San Andreas system before such mobility was more generally appreciated.

Plate tectonics supplied a new spatial, kinematic, and genetic context for interpreting sedimentary basins of identifiably different character, and for more clearly differentiating mechanisms of subsidence: lithospheric thinning and rifting; thermal subsidence; crustal thickening and loading; in-plane force changes; strike-slip deformation; deep-mantle phenomena; compaction and sediment loading; salt and shale tectonics. Qualitative conceptual models were swiftly improved with reference to fault mechanics, geophysical forward models, and 'backstripping' – an attempt to use the stratigraphic record to determine how a given site of sedimentation or 2D profile had subsided as a function of time, and according to specific mechanisms of tectonic or driving subsidence.

An important innovation in both the petroleum industry and academic oceanographic institutions, beginning in the 1950s, was the development of geophysical tools, particularly seismic reflection profiling, permitting subsurface stratigraphic and structural geometry to be imaged and interpreted in three dimensions. An unexpected byproduct of so-called seismic and sequence stratigraphy in the late 1970s and '80s was to recognize just how discontinuous sedimentation is, with the cyclic development of prograding wedges and regional onlap against unconformities. Following the work of Peter Vail and colleagues at Exxon, such patterns were generally ascribed to cycles of sea-level change, a view that remains popular though increasingly challenged.

The frontiers today in sedimentation and tectonics are at two different scales. At large scale, questions relate for example to how lithospheric extension is partitioned between the brittle upper crust (sedimentary basins) and the deeper lithosphere, including the weakening role of magmatism; and the mechanisms by which continents break apart to form ocean basins. The significance of mechanically problematic low-angle normal faults in both continental and oceanic crust, and the development of hyperextended continental margins have yet to be fully resolved, though substantial progress has been made. At small scale, questions relate primarily to the origin of sedimentary cyclicity, and particularly to the varied roles of tectonic processes. In a recently published high-resolution sequence stratigraphic study of the Cozzette Sandstone (Campanian) of western Colorado, we showed how cyclicity relates in 3D not to sea-level change but to the subtle tilting of fault blocks beneath the late Cretaceous foreland basin. Work is currently under way to investigate the trade-off between

eustasy and crustal deformation in late Oligocene to middle Miocene synrift deposits of the Gulf of Suez, Egypt.

NOTES

Kilometre-scale burial and exhumation of passive margins and continental interiors: an overlooked consequence of plate tectonics?

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For many years, the notion of continental drift was regarded as unrealistic by many geologists, due (at least in part) to the lack of a mechanism by which continents could move across the surface of the Earth. This situation changed with the development of plate tectonic theory, and a wide variety of geological processes can now be explained within this concept. In particular, plate tectonics can explain how horizontal stresses can lead to vertical displacements, namely subsidence in extensional settings and mountain building in collisional settings. However, some geological observations remain as yet unexplained, and are controversial due to the lack of an accepted mechanism.

Here we are concerned with positive and negative vertical movements of rock at “passive” continental margins and cratonic interiors, revealed using paleo-thermal (low temperature thermochronology, vitrinite reflectance) and/or paleo-burial (sonic velocities) methods. These events involve deposition and subsequent removal of km-scale thicknesses of section on a typical timescale of 10s of Myr (Japsen et al., 2012; Green et al., 2013). Examples have been reported from many parts of the globe, notably from the continental margins of Greenland, Norway, southern Africa, Brazil and southeast Australia (Green et al., 2013) and the cratonic interiors of North America (Flowers and Kelley, 2011) and Scandinavia (Figure 1; Japsen et al., 2016). But despite extensive documentation the nature of the controlling processes are unknown. Geodynamic models of passive margin development typically relate uplifted margins to processes of rifting and breakup, but fail to acknowledge evidence of km-scale post-breakup subsidence and burial, followed much later by uplift and denudation of similar magnitude. Dynamic topography has been proposed to explain uplift of continental interiors and continental margins but in most models the magnitude of such movements is typically hundreds of metres on a timescale of ~100 Myr, in contrast to observations of km-scale movement over 10s of Myr.

Evidence of these vertical movements (both positive and negative) is often regarded with skepticism, on the basis that no evidence remains of the “missing” section. But a considerable body of evidence now exists to show that many areas have undergone such km-scale positive and negative vertical motions. Some evidence of these vertical movements is hard to deny, such as the presence of post-break up marine sediments at an elevation of ~800m in the Araripe Basin of Brazil.

At present, geodynamic models focus only on the preserved section and ignore “missing section”. Such treatments must therefore only represent partial truths. Recognition of the importance of missing section has major implications for understanding regional geological evolution. In some areas, burial has preserved ancient land surfaces which have more recently been exhumed to the surface. This may give the impression that ancient surfaces have remained at surface levels over long periods, suggesting long-term stability, but application of paleo-thermal methods shows otherwise. And in basin modelling, reconstruction of tectonic subsidence curves conventionally treat unconformities as periods of non-deposition, whereas application of paleo-thermal and paleo-burial methods often reveals that significant section was deposited and removed during these intervals. Understanding the processes that cause these vertical motions has the potential to provide significant new insights in a variety of fields.

Many events show a broad synchronicity in exhumation across continents and in some cases across hemispheres of the globe. This, together with the regional extent of the events (on a scale of 100s of km) suggests that plate motions exert a first order control on these events, but a detailed understanding remains elusive. We suggest that a more complete understanding of the development of both continental margins and cratonic interiors must take into account evidence for section that is no longer present and explain the corresponding km-scale positive and vertical motions. In doing so, further aspects of the plate tectonic paradigm will inevitably emerge.

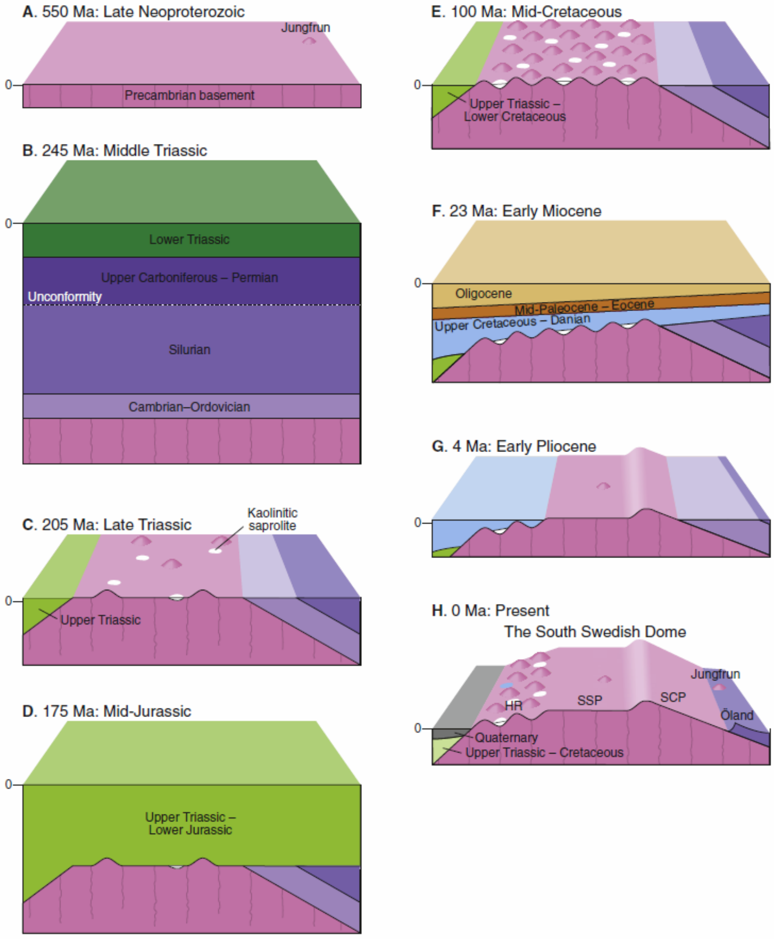

Figure 1: Schematic illustration of the development of southern Sweden based on integration of thermochronological data and stratigraphic landscape analysis (from Japsen et al., 2016).

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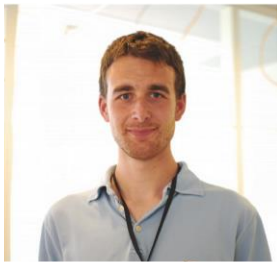

How important are intrabasement structures in controlling the geometry of sedimentary basins? Insights from the Taranaki Basin, offshore New Zealand.

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Intrabasement structures often are envisaged to have acted as a structural template for normal fault growth in the overlying sedimentary cover during rifting (e.g. Barents Sea; Egersund Basin, offshore southern Norway). However, in other settings, the geometry of rift-related faults was apparently unaffected by the pre-existing basement fabric (e.g. Maløy Slope, offshore western Norway). Understanding the nucleation and propagation of normal faults in the presence of basement structures may elucidate how and under what conditions basement fabric can exert an influence on rifting.

This study is based on borehole constrained 3D seismic data from an area of the Taranaki Basin, offshore New Zealand, situated at the boundary between two basement terranes generated during the Mesozoic convergence along the margin of Gondwana. The relatively shallow basement (<3.5 km) is overlain by a late Paleocene to Pleistocene sedimentary cover scarcely affected by the late Miocene inversion and Pliocene rifting, resulting in excellent imaging of basement structures. We mapped the 3D geometry and distribution of throw on the fault planes for clarifying the relationships between basement and cover structures and the kinematic history of the faults.

Our analysis has highlighted two types of intrabasement structures. In the northern part of the survey, a N–S-striking, west-dipping lineament marks the transition between two basement units, characterized by different seismic facies. This lineament was reactivated during the late Miocene inversion. In addition, a network of arcuate, N–S-elongated, west-dipping high-amplitude reflectors cut through a largely homogenous low-amplitude basement throughout the whole study area and is only partly reactivated during the inversion phase.

Two classes of normal fault segments affected different intervals of the sedimentary cover. The lower fault segments are hard-linked with the intrabasement structures and nucleated within few hundreds of metres from the basement-cover interface. They are blind and swing from NW-SE to NNE-SSW trends. We document different styles of interaction between them and the overlying faults. The segments diverging from the regional NNE-SSW trend are confined in the lower 500 m of the sedimentary succession, whilst the aligned ones are connected with the upper segments.

The upper fault segments mostly strike according to the regional NNE-SSW trend; they nucleated within the late Miocene strata and were active during the Pliocene. Above the N–S-striking basement lineament, the upper fault segments strike parallel to it and are systematically hard-linked with the lower ones, generating a single fault zone affecting the whole sedimentary cover. Conversely, away from this lineament, deep and shallow fault planes are only occasionally linked, with some shallow faults totally lacking any connection to basement features.

Our study suggests that basement fabric can effectively constrain the geometry of later normal faults in the proximity of the top basement and at the transition between basement units, whilst elsewhere the deformation seems to respond to the regional stress field. The interplay between intrabasement structures and regional stress generates complex geometric relationships between structures at different levels of the sedimentary cover.

NOTES

Tectonic causes of Cenozoic thin-skin deformation in the Gulf of Mexico

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Two periods of Cenozoic thin-skinned gravity sliding/spreading in the Gulf of Mexico have caused the formation of the Peridido, Atwater and Mexican Ridges fold belts. Early gravity spreading has been associated with the Laramide orogeny. A second thin-skin phase of near-shore extension balanced by offshore contraction has been active throughout the Neogene-Quaternary Period. This deformation has important implications for the recent evolution of the margin, but there has been a lack of consensus regarding the tectonic driving mechanism. The gravitational potential required to initiate these gravity-driven systems appears to be from the complex westward movement history of the North American plate over the subducting Farallon plate.

Water-loaded oceanic residual depths in the GoM reveal present-day anomalous drawdown of the oceanic floor by up to 2 km in the west reducing to 0.5 km in the east. This region of the North American Plate is located directly above the presently subducting Cocos plate – a remnant continuation of the Farallon slab mapped using P and S wave tomography models. We suggest that this drawdown of the North American Plate is a direct result of downwards flow of the mantle driven by the down-going Farallon slab.

Immediately onshore to the northwest of the GoM, the geology is characterised by a present-day angular unconformity cutting down into the south-eastwards tilted Cretaceous and Cenozoic strata. Simple estimates of denudation indicate up to 2 km of missing section has been eroded.

Further west, Palaeogene uplift has been linked to contraction and basement inversion caused by subduction of the young Farallon slab and the resulting isostatic thickening during the Laramide orogeny. Later Neogene uplift and extension of the Basin and Range has been superimposed in both the USA and Mexico. Inversion of river profiles draining western USA indicate regional uplift of up to 2.5 km since 30 Ma. Tomography models and volcanism reveal a region of hot upwelling mantle centered beneath the Colorado Plateau west of the Farallon slab. The initiation of this second phase of uplift is linked to the North American Plate overriding the western edge of the Farallon slab and the palaeo-spreading centre between the Farallon Plate and Pacific Plate.

Combining surface and deep observations suggests that the regional topographic slope from the onshore of the USA and Mexico to the Gulf of Mexico is controlled initially by convergence between two lithospheric plates and later by mantle upwelling processes in the West and mantle drawdown in the East. Formation of this gradient has led to the initiation of thin-skinned gravity spreading observed in the Gulf of Mexico during the Cenozoic Era.

Uplift in the onshore of the Southern GoM currently drives gravity sliding in the Campeche salt region and is associated with the shallow dip of the subducting Cocos plate.

NOTES

The Aleutian Trench, a study of sediment sourcing and delivery that emphasizes the cyclic nature of plate tectonic processes

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The Aleutian Arc, which at 2200km in length is one of the largest and most varied plate tectonic systems in the world, is flanked to the east by an active transform margin that juxtaposes the Alaskan terranes against the arc system. The Pacific-Kula plate subducts northwards in the east, but becomes increasingly oblique towards the west creating a variety of arc environments from compressional to tensional such that the arc is segmented into partially rotated blocks bound by transverse strike-slip faults. Arc inception occurred 56Ma, but fragmentation was due to a reorganisation of the north Pacific plates 43Ma ago. In the context of arc systems worldwide the sediment supply to the Aleutian trench and thus to the accretionary prism may be unique. The high latitude location resulting in active glaciers across the Alaskan peninsula and the immediate access to the trench has meant that intermittently over 4.5Ma glacial sediment, in the form of rock flour, has generated massive turbidity flows into the trench both directly and indirectly by way of abyssal plain channels such as the Surveyor. Thus today the Aleutian trench contains vast volumes of clastic sediment sourced mainly from the glacial erosion of Alaska and controlled by allocyclic influences. GLORIA and multi-channel seismic surveys conducted by the USGS revealed details of both the geometry and distribution of the trench sediments and their associated supply systems. Milankovitch-induced climatic cycles cause the episodic release of sediment transported as both unconfined and confined turbid flows, the latter routed along submarine channels that cross the abyssal plain of the Gulf of Alaska and discharge into the trench. Small volumes of sediment enter the trench directly from glacier snouts at the transform trough-end of the trench and from the Chugach Mountains to the north by supplying Susitna river-sourced sediment firstly to the accretionary prism basins and subsequently by slumping the trench. A major channel system extends along the trench axis and reworks and redistributes the supplied material. Subduction of seamount chains coupled with the westward-increasing obliquity of plate collision and accretionary prism-sourced slumps compartmentalize the trench environment dividing the axial channel system into discrete flow patterns and separate sediment systems. This tectonic controlled regime, when seen against the primary supply mechanisms and when coupled with the effect of compartmentalization, creates distinctive segments of fill. The Alaskan source landscape that consists of accreted terranes formed predominantly of ancient island arcs emphasizes the cyclic nature of earth processes imposed by plate tectonics.

NOTES

Plate tectonics and the petroleum industry – a 50 year symbiosis

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The plate tectonic revolution of the 1960s, driven by the theories of Tuzo Wilson and the revelations from geophysical surveys in ocean basins, took place against a backdrop of accelerated petroleum industry expansion into offshore exploration. Particularly significant were the first North Sea wells, proving commercial gas in the early 1960s and the first commercial oil later in the decade. Seismic coverage and drilling in the newly discovered North Sea rift system provided critical insights into the way continents break apart and, together with work on other extensional regimes, led directly to the lithospheric stretching models that transformed basin analysis in the 1970s.

Thus, from the beginning, the industry and those developing and refining plate tectonic models enjoyed a fruitful symbiosis that has continued to the present day. Using the combined experience of two careers that have more or less spanned this whole history, with seismic sections, plate tectonic reconstructions and animations, we will trace the genealogy of plate tectonic thought and its interplay with commercial drivers. The move towards ultradeep water on continental margins, driven by the promise of new rich petroleum systems and by diminishing easy opportunities onshore and in shallow water, has provided a rich data source for academic study. This is particularly true in the case of passive and transform margins. Long offset, deep seismic profiles, spanning entire margins from inboard abandoned rifts, via hyperextended rifts, to the transition to oceanic crust have now been acquired on most margins. Remarkable images have substantially improved the architectural constraints of continental margins, in turn feeding into research efforts on continental break-up processes. The high cost of exploration in these settings promotes sophisticated integrated studies, including 3D seismic surveys and potential field data, all of which provide unexpected details and constraints for the refinement of plate tectonic theory. Conversely, plate tectonic research provides structural understanding and improved conjugate margin palaeogeographies, guiding play evaluation, acreage acquisition and other exploration choices that are critical to exploration companies working in this high-cost environment.

We will highlight some of the current questions and controversies on continental break-up that are being addressed through industry-academia cooperation, including the role of plate motion, extension rate, strike slip, mantle temperature and dynamics. While these recent contributions tend to yield increasingly more refined second order advances, we will suggest through examples that fundamental issues, such as the plate driving force, are still not fully resolved; the new, increasingly numerical generation of geoscientists still has work to do. We will also speculate on potential future research directions where this collaboration may prove effective. Among these, we expect long overdue advances in understanding the fundamental dynamic controls on cratonic basins where paradoxically, there is much less deep crustal data than in their deep water counterparts. They are arguably just as much a part of the supercontinent cycle as continental margins, and will become increasingly important as the fossil fuel end-game moves back into mature basins in continental interiors.

NOTES

Plate tectonics in hydrocarbon exploration – From time-animated 2D maps to data-rich Paleo-Earth models for next generation spatio-temporal exploration.

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When plate tectonic theory as scientific framework was adopted quickly by hydrocarbon exploration companies and actively integrated into their workflows covering aspects from regional exploration, paleogeography, basin modelling as well as for play development and de-risking. The extreme data-rich environments of globally operating companies fostered the generation of early sets of paleogeographic frameworks in the late 1980's and early 90's such as the maps of Shell's Peter Ziegler in NW Europe, BP's Paleo-Shoreline compilations or Exxon and Mobil's efforts supporting the first incarnation of interactive workstation-based "PLATES" software and project at UT Austin.

At present, plate tectonic concepts and resulting implications for basin formation and -evolution scenarios are deeply embedded into academic research and any play-based exploration projects across industry. The concept has provided the base of successful developments such as the conjugate South Atlantic pre-salt play and has hence direct impact on exploration success. However, over the past decades a relatively static view on plate tectonic modelling became established – illustrating the difficulties of connecting plate-to-play scales, a lack of computing power and tools to generate, visualise and analyse such multi-scale data-rich models, possibly compounded by a fragmentation across the individual disciplines such as basin modelling, tectonics, and stratigraphy. With computing power, -storage and availability having grown near exponentially over the past decade and developments such as the Internet, high-level programming languages, semantic frameworks, and growth of collaborative open-source software development communities, the technical landscape now offers radically new prospects for utilising the plate tectonic paradigm in exploration. Historically accumulated knowledge and rich data environments can now be fused and quantitatively integrated into 4D exploration frameworks that not only take vertical motions and temporal evolution into account but also allow to cover plate-to-play scales.

We will present examples from Shell's recent exploration efforts where integrated plate tectonic modelling was used by exploration teams to evaluate risk and helped polarising views on basin prospectivity with examples from the Gulf of Mexico and the South Atlantic. In both cases plate kinematic models were used as screening tool for regional evaluation and framework building. In the South Atlantic case, we have used the models as foundation to iteratively refine our understanding of the evolution of the South Atlantic rift system offshore Gabon, at the tectonically complex juncture of the main South Atlantic and the aborted Brazilian Reconcavo rift systems. Here, plate tectonic modelling has provided critical insights to understanding the development of Lower Aptian/Barremian sediment fairways, structuration and localisation of deformation mainly as spatio-temporal integration platform/framework for various interdisciplinary data sets.

Lastly, we will illustrate recent efforts on utilising global-scale data sets to build a new generation of Paleo-Earth models that integrate lithospheric deformation and vertical motions, moving towards a data-driven, quantitative view on hydrocarbon prospectivity that is utilising the paradigm of plate tectonics as 4D framework as screening and de-risking tool.

NOTES

Plumetectonics nature forming geological structure of Kazakhstan with large deposits and basins

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According to the seismic tomography, the lithosphere formation of Kazakhstan has a plume origin. In the Paleozoic Kazakhstan was a separate continent, and it consisted of three concentric rings of bounded geometry sutures. The rings made vertical movement under the active influence of mantle plume and their axes made horizontal movement. The development of variously oriented lineaments led to the formation of clumpy-block structure. The modern structure of Kazakhstan formed during the interaction with Europe, Siberia and southern continents during the Paleozoic-Cenozoic.
The proposed geodynamic model of the Kazakhstan development explains the features of the localization of active zones of sedimentation, intrusions and effusive magmatism and metamorphism of the geological formations, ophiolitic zones, availability and promising metallogenic zones and areas with large and unique mineral deposits, oil and gas fields.

According to various estimations, between half and three quarters of the modern continental crust of Kazakhstan formed in the Early Precambrian to the beginning of the late Proterozoic as continent «Qazaqia». As a result of atrophy and the closure of the Early Proterozoic deep basin, this crust in the Early Riphean was shrunk into a single supercontinent called Pangaea I or Megageya, unlike Late Paleozoic-Earlymesozoic Pangaea II (firstly isolated by A. Wegener). On the supercontinent, the paleomagnetic data indicated that the similarity of the curves of apparent migration of the magnetic poles that define different continents. With the beginning of Proto-Tethys mobile belt, Pangaea I was split into two parts, original part (Rodinia) in the north and Gondwana in the south. Already in the Neoproterozoic Kazakhstan began to exist independently.

Assigned by modern geophysical data that the introduction of the plume and the picked materials from the mantle and the asthenosphere into the lithosphere led to local rising and the formation of a fixed nuclei in the form of ring structure (the prototype of the Qazaqia continent). The nuclei-ring structure diameters were approximately 2.5-3.0 km.
Ring structures of Kazakhstan also reflected in the physical fields, particularly in the gravitational field. Moreover, a clear display of the current block structure of the crust of Kazakhstan discovered. Extended, linearly elongated strips of contiguous are anomal (large gradients) of the field Δg allocate deep zone: the faults separating the crust into a number of Kazakhstan megablocks and blocks. The most significant of them, according to geophysical data, cut the crust for all its power, and penetrate into the upper mantle (Daukeev et al. 2004).

Such structures formed in the early stages of development of the territory and acquired a modern appearance in the form of Ural-Mongolian belt in the Mesozoic-Cenozoic. In the Cenozoic, the lineaments and partially dissecting ring structure zone formed.
The proposed new model of geodynamic evolution of the territory of Kazakhstan can serve as a theoretical basis for the forecast of mineral deposits perspective oil and gas sedimentary basins.

NOTES

Plate Tectonics and the Phenomenon of North American Oil and Gas Shales

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In about 2010, the "shale-gas revolution" began in the United States and has since morphed into a "shale-oil revolution" that has pitted the United States against OPEC. This revolution has changed the nature of global diplomatic relations and encouraged other countries to seek their own shale revolutions. In fact, the EIA developed estimates of possible shale-gas reserves for countries across the world, again spawning hopes for "revolutions," energy independence, and the use of cleaner fuels. A closer look at the situation, however, suggests that the U.S. shale revolution was not really a revolution at all, and that abundant shale gas and oil may largely be a North American phenomenon related to geology and promotional factors. Promotional factors have to do with culture, economics, and the continuous characterization of shale source beds since the Arab oil embargo of the mid-1970s; we will not deal with these factors here.

On the other hand, geological factors, mainly plate tectonics, have been critical to the development of basins and their filling with organic-rich shales that today are the sources of North America's unconventional oil and gas. Geologically, North American has more than 30 recognized shale-gas basins, and formation of so many basins probably reflects large size and stability of the continent through nearly 500 Ma since the Laurentian breakout from Rodinia at 760–680 Ma. Continental deformation, when it did occur, only occupied continental margins, and in the process, generated many largely undeformed, lithologically and structurally uniform foreland, intracratonic and yoked basins that served as repositories for the organic-rich sediments generated during basin formation. Orogenies on the Appalachian (four orogenies), Ouachita, and Cordilleran (four orogenies) margins generated multiple foreland basins through flexural loading, a process that in nearly every case generated dark, organic-rich shales as part of a normal stratigraphic loading sequence. Moreover, continued loading in any given orogeny invariably led to the yoking of foreland and intracratonic basins such that the depositional setting for basinal black shales migrated into adjacent basins. In other cases, overlapping foreland basins have led to stacked plays, which are especially economic. Moreover, during Paleozoic and Mesozoic time, when most organic-rich sediments were accumulating, critical parts of North American were situated in the tropics or subtropics, where the generation of organic matter was enhanced during both greenhouse and icehouse climates. After the Triassic and Jurassic breakup of Pangea, even more repositories were generated in the form of rift and rift-margin basins along the eastern and southern continental margins of Laurentia. Along the western margin in California, deformed Mesozoic forearc basins also accumulated dark, organic-rich shales.

Clearly, the size, position, and tectonic history of North America during Paleozoic and Mesozoic time were critical in the generation of so many oil and gas shale basins. Whether or not the same alignment of geologic factors that has occurred in North America can happen elsewhere, I am doubtful. Hence, similar "revolutions" in other parts of the world are unlikely.

NOTES

Deep Seismic data from the North Carnarvon Basin, North Western Australia, exposes ancient in-place oceanic lithosphere

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Deep reflection seismic data from the North West Shelf of Australia demonstrate the likely presence of in-place Permo-Carboniferous oceanic crust beneath parts of the North Carnarvon Basin and require a new model for the tectonic development of the area. It is generally considered that the oldest in-place oceanic crust and lithosphere on the planet is of Jurassic age in the western Pacific Ocean, with potentially older examples in the Eastern Mediterranean (Müller et al 2008; Granot 2016). Here, through integration of deep reflection seismic data, wide angle seismic study results, gravity and isostatic modelling together with other regional geological data, we demonstrate the likely presence of deeply buried, Paleozoic oceanic crust. The new consistent model fits all available datasets, highlights inconsistencies in existing models for the area and proposes an in-place oceanic crust which is at least 75 Million years older than the current oldest recognized oceanic crust buried by, up to 20km of sedimentary section.

The geological history of the Australian North West Shelf has been dominated by two tectonic events; one of Permo-Carboniferous age which created the major depocentres of the present-day margin, and a younger Jurassic event which continued until the eventual development of Lower Cretaceous oceanic spreading in the South Indian Ocean. Previous models for the area have often focused on the importance of this later Jurassic event and have considered the underlying crust to be stretched continental material leading to eventual Cretaceous break-up. This focus is understandable given its intimate relationship to the present day Indian Ocean, its extensive and highly prospective structuration and the fact the event is observable and mappable on available existing industry seismic data. Here, we demonstrate that the earlier Permo-Carboniferous event was in fact the dominant event in the history of the basin and lead to the development of a small oceanic basin which has been filled by the significant sediment influx through Permian and Triassic times including the thick Mungaroo delta. We show that the later Jurassic event was, at a crustal scale, quite localized and minor in comparison.

These results require a re-evaluation of the plate models for the break-up of Gondwanaland and will also have implications for the expected heat-flow history of the basin which may impact models for hydrocarbon generation in the area.

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NOTES

Tectonics beyond Earth: No Plates, Different States

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The discovery and understanding of plate tectonics on Earth has been enabled in large part by diverse geophysical data sets. Satellite, land and marine gravity, magnetic, electromagnetic, heat flow, topographic, and seismic data have elucidated plate motions over time as well as the geometry and structure of plate boundaries. Satellite-based Synthetic Aperture Radar Interferometry (InSAR), and Global Positioning Survey (GPS) data have provided insights into the present-day dynamics of plate boundaries and crustal deformation. Current and past plate motions, together with knowledge of the planet's internal structure, in turn constrain the history of mantle dynamics and the interior evolution of Earth.

Beyond Earth, data sets acquired for planets and moons enable investigations of tectonics, but they are more limited in type and in spatial and vertical resolution. Common data sets acquired at other inner Solar System planets and at the Moon include satellite gravity, magnetic fields, topography, spectroscopy, and imagery (one or more of visible, near infra-red, and radar). Collectively, these enable identification of tectonic structures that are larger in spatial scale than the resolution inherent in the data sets, via the planform expression and topographic relief of such features. Major challenges to tectonic studies of other planets include characterizing subsurface structure and establishing the timing of interior and surface processes. For subsurface structure, gravity and topographic data provide indirect (if non-unique) insight on the thickness and bulk density of the crust and the elastic lithosphere — which can in turn provide estimates for lithospheric thermal gradients and heat flow. Besides Earth, seismic data have been collected only for the Moon, although such data will be acquired by the InSight mission to be launched Mars in 2018. Further constraints on mantle and crustal composition are limited to inferences from spectroscopic observations (for Mercury, Mars, the Moon), meteorites (Mars, the Moon and Vesta), *in-situ* sample analyses (Venus and Mars), and returned samples (the Moon). Limited chronological information is provided by the abundance and degradation states of impact craters across a planet's surface; superposition relations give relative timings of geological processes and events. Here we summarize a few key aspects of the tectonics on the Moon, Venus, Mars, and Mercury, noting that observations from flybys of rocky and icy bodies in the outer solar system also indicate surfaces that often exhibit evidence for tectonism.

The extensive exploration of Earth's Moon during the Apollo era, and more recently with a series of international satellite missions, has paved the way for our understanding of terrestrial planets in general. Key aspects of lunar evolution, tectonism, and interior structure include the recognition of a primordial flotation crust (the product of early differentiation), the near-side/far-side dichotomy in crustal structure, impact history, and volcanism, basin-focused tectonism and volcanism, and the surprising discovery of deep, tidally-driven seismicity.

Venus, despite being Earth's "sister" planet in terms of mass and size, has had a very different atmospheric and geodynamic history. It shows evidence for hot-spot and plate boundary-like features on its surface, such as mountain belts, rifts, and deep troughs that are morphologically similar to terrestrial subduction zones. However, Venusian faults are stronger than their terrestrial counterparts because they are dry relative to faults on Earth and, additionally, the lithosphere is more positively buoyant compared to even continental plates on Earth. This prevents ocean-plate-like subduction but may permit continental-plate-like underthrusting and/or delamination, for which there is evidence in Venus mission data. In the absence of plate tectonics, a major open question then is how Venus loses its heat, although enigmatic volcanotectonic landforms termed coronae have likely played a leading role in the planet's thermal evolution.

Mars, like the Moon, exhibits a hemispherical dichotomy in crustal structure that formed very early in its history and shows no evidence of plate boundary-like sutures. Tectonism on Mars has likely been dominated by loading from the Tharsis volcanic province and the accompanying global distribution of membrane stresses. Mars is probably cooling via conduction and/or stagnant lid convection today.

Mercury also exhibits no evidence for either present or past plate tectonics; its tectonic landforms are dominated by long, often high relief, thrust-fault-related folds, first imaged in one hemisphere of Mercury by the Mariner 10 spacecraft during three flybys of the planet in the 1970s. MESSENGER observations taken in orbit about Mercury from 2011–2015 have allowed a full characterization of the distribution and morphology of these shortening structures. Their morphology, occurrence in both Mercury's ancient intercrater plains and the younger smooth plains, and the predictions of thermal models together indicate that Mercury has shrunk in radius by as much as 7 km in diameter since ~ 4 Gyr ago. As for the Moon and Mars, modeling of Mercury's thrust-fault-related folds provides information on the geometry of the underlying faults, including their burial depth, dip, and maximum penetration depth. This approach is among several that can be used to explore the subsurface of planetary bodies without direct seismic or other in-situ measurements. Just as remanent magnetization played a pivotal role in developing the plate tectonics hypothesis, remanent magnetization recently discovered in Mercury's crust may also provide fundamental information, but in this case to the understanding of Mercury's thermal evolution.

NOTES

The Plate Tectonics of Exoplanets

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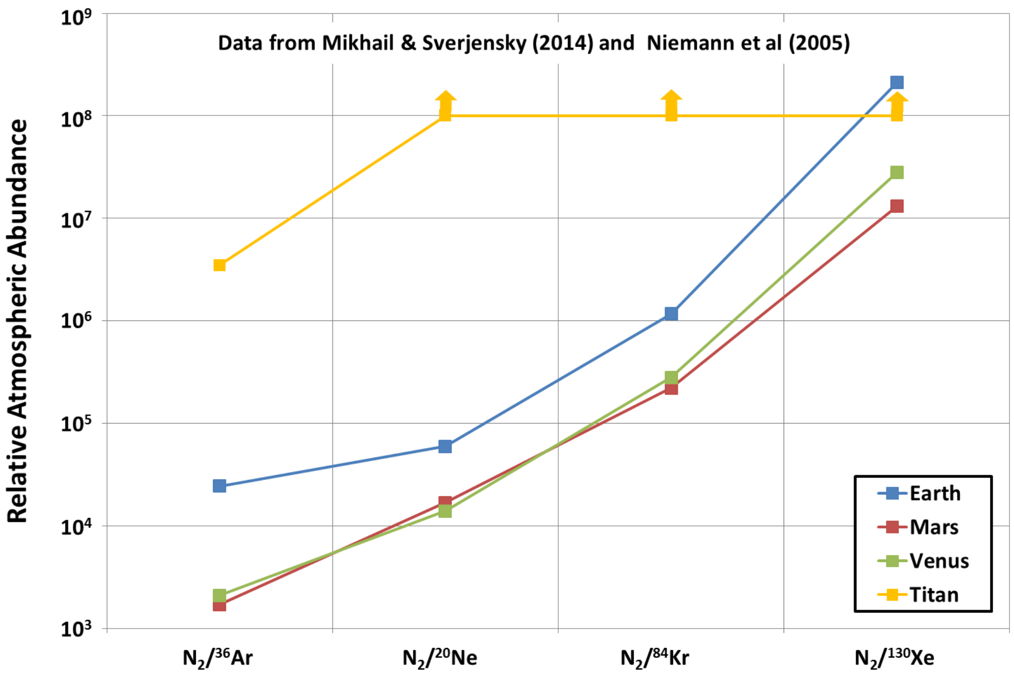
Is Earth unusual in having plate tectonics? We cannot claim deep understanding of our world if we do not know whether this fundamental driver of geology is a typical property of rocky planets or a rare peculiarity. Current theories suggest plate tectonics should be common on damp, rocky worlds of sufficient size but, on the other hand, it has also been argued that plate tectonics is necessary for complex life and that we see it on Earth as a consequence of observational bias (i.e. geologists only arise on planets with plates even if such worlds are rare).

Observational testing of these opposing hypotheses requires a sample of rocky worlds spanning a range of sizes and compositions. Unfortunately, the Solar System does not provide a sufficiently large and diverse array of planets and the only way forward is to look for plate tectonics on exoplanets—planets orbiting other stars. But, is it possible to detect the continental drift of such distant worlds?

Exoplanet characterization (as opposed to exoplanet discovery) is in its infancy but a few planets have already had their atmospheres analyzed. In addition, techniques are under development to generate crude maps of exoplanet temperature-variations, surface reflectivity and clouds. The key to exoplanet characterization is measurement of wavelength-dependent brightness variations during exoplanet transits (passage of planets in front of their host stars) and eclipses (passage of planets behind their stars). Space based telescopes are planned, for the near future, that will make the necessary observations across a wide variety of planets (e.g. ESA's ARIEL project, short-listed for launch in 2026 and the JWST due for launch next year).

There is therefore a need to develop indicators of plate-tectonics that could be found using these techniques. Subduction is the crucial factor. In its absence, volatile transport is largely one-way—i.e. from a planetary interior to its surface via volcanism. But when subduction is present, two-way cycling between surface and interior becomes possible and this fundamentally alters volatile budgets. For example, atmospheric nitrogen is enhanced relative to noble gases—on Earth compared to Mars or Venus (see figure)—and this has been attributed to subduction of wet-plates changing mantle oxidation and allowing easier N_2 outgassing. However, applying such ideas to exoplanets will not be straight forward as demonstrated by the N_2 to noble gas ratios of Titan which are even higher than those for Earth. Furthermore, there will be great difficulty with determining trace-gas concentrations using the low-resolution, low-SNR spectra that ARIEL and other missions will produce.



This presentation will: (i) Discuss models of exoplanet plate tectonics; (ii) Explain why plate-tectonics may be rare; (iii) Describe techniques and up-coming space-missions to characterize exoplanets; (iv) Suggest signatures of plate-tectonics that these missions could detect; (v) Discuss problems with these suggestions. However, the main purpose is to bring the problem of plate-tectonic remote-detection to the attention of Earth-scientists able to criticize these ideas and propose better alternatives. The 2017 William Smith Meeting is the perfect opportunity and, furthermore, a discussion of exoplanets is a good way to celebrate the first fifty years of plate tectonics by looking towards the next fifty.

NOTES

Secular geochemistry evolution and the Siderian magmatic shutdown

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Major and trace elements of both whole-rock and accessory phases have become an important tool in understanding the evolution of the continental crust and plate tectonics. Past and recent research converges on a view in which: 1) most of the crust (c.70%) has been produced by the end of the Archean and 2) subduction-driven plate tectonics is a gradual and evolving mechanism, which is likely to have started at ca. 3.0 Ga and evolved to a modern style at ca. 2.5 Ga (e.g. Dhuime et al, 2012; Hawkesworth et al., 2016). A secular geochemical transition in arc-related magmas is broadly accepted to reflect the second observation, where the opening of the mantle wedge, after a period of shallower subduction, promoted interaction between the metasomatised mantle and crustal-derived magmas (Martin et al., 2010). Globally, this tectonic change is linked to a geochemical revolution, with Tonalite-Trondhjemite-Granodiorite (TTG) magmas dominantly being produced during the Palaeoarchaean and gradually evolving between ca. 3.0 and 2.5 Ga towards calc-alkaline magmas. Sanukitoids (high Ba-Sr) fit temporally in this transition and can also be accompanied by emplacement of hybrid granitoids (Laurent et al., 2014). This change in magmatic composition has been inferred as representing the onset of modern-style subduction in plate tectonics (Martin and Moyen, 2002). The Mineiro Belt, in SE Brazil, comprises distinct granitoids emplaced between ca. 2470 – 2100 Ma during the Transamazonian orogeny. Geochemical data from the plutonic rocks indicate a continuous trend of being more evolved with time, and also represents a secular TTG – sanukitoid transition. In contrast to most of the similar occurrences elsewhere on the planet, where this transition took place at the end of the Archean, the Mineiro Belt potentially represents a unique, later episode of this evolution during the Palaeoproterozoic. Significantly, this later geochemical evolution starts with TTG magma production at around 2350 Ma, within the Siderian Quiet Interval when few juvenile magmas were added to the continental crust (Pehrsson et al., 2014). The magmas evolve to a 2130 Ma sanukitoid I-type suite. Zircon and titanite analysed in this study range in age from 2350 to 2050 Ma and 2160 to 2050 Ma, respectively. The absence of Archaean contribution in the dated samples corroborates the juvenile nature of the belt and its tectonic setting as island arcs converging to a collisional stage against the cratonic area. Additionally, zircon rims and titanite ages overlap within error and suggest a tectonothermal overprint during the collisional arc events. The geochemical signature of coeval plutons is suggested to represent possible contamination of various degrees of crustal/sediment assimilation.

* H. Moreira acknowledges CNPq scholarship (234610/2014-0)

NOTES

Plate Tectonics and Continental Growth

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There is much discussion of the timing of the onset of plate tectonics, yet there is increasing evidence that magma types similar to those from recent within plate and subduction related settings were generated in different areas at broadly similar times in the early Archaean. Preferred global models for the growth of continental crust indicate a reduction in the rates of crustal growth at ~3 Ga, which has been attributed to when the continental crust was primarily generated at subduction related tectonic settings. In this contribution we contrast the results of regional and more global approaches in the context of the development of plate tectonics.

Regional studies indicate differences between Early Archaean and younger tectonic environments and magmatic environments. Various deep seismic techniques allow increasingly detailed mapping of the lithosphere, and indicate the degree of seismic anisotropy to be different in different Archaean terranes. Outcropping structural styles of Archaean terranes are known to vary. Regionally developed dome and basin geometries, believed to reflect dominantly vertical tectonics, characterise the Australia Pilbara and southern Africa cratons. These terranes appear to coincide with areas of relatively isotropic lithosphere. In contrast, long, linear, Archaean orogenic belts with regional deformation fabrics appear to be characterised by lithosphere of greater seismic anisotropy, as in North America. These two distinct terrane geometries tend to be characterized by inferred within-plate and subduction-related magmatism respectively. However, in some areas, terrains with stronger regional fabrics may be younger than those in which such fabrics are less well developed. Perhaps implicit in this distinction is the dominant tectonic driving mechanism being vertical and diapiric or horizontal and related to plate collision.

A number of global models, using different approaches, suggest that at 3 Ga the volume of continental crust was ~70% of its present day volume, and that this may be a minimum value. Juvenile continental crust before 3 Ga was more mafic, and probably thinner, than that generated subsequently. 3 Ga marks the onset of the occurrence of eclogite inclusions in diamond, and a reduction in average growth rates of continental crust from ~3.0 $km^3.yr^{-1}$ to ~0.8 $km^3.yr^{-1}$. This is attributed to an increase in the rates at which continental crust is recycled into the mantle, rather than a reduction in the rates at which continental crust was generated. Simple box models indicate that there was a marked increase in the rates at which crust was destroyed between 3 Ga and 2 Ga, and that this subsequently decreased as the crust became more intermediate in composition. The models indicate that at least 100% of the present volume of the continental crust has been recycled into the mantle over the last 3 Ga. We speculate as to the relationship between the apparently different Archaean tectonic terranes recorded today at surface; seismic properties developed at the cratonic lithospheric scale; and changes in lithospheric growth and destruction through the Archaean to the Present-day.

NOTES

Plate tectonics at 50

Dan McKenzie

50 years ago Jason Morgan and I put together a set of ideas that turned continental drift and sea floor spreading into a coherent theory of the Earth's tectonics. The new theory differed in two important ways from the earlier ideas: it was a kinematic theory which ignored the issue of the driving mechanism, and it quickly became clear that it did not provide an understanding of continental tectonics. An astonishing advance in the period since 1967 has been GPS, which can now measure horizontal velocities to an accuracy of better than 1 mm/yr. The resulting velocity vectors have beautifully confirmed those determined from sea floor spreading and earthquake mechanisms. But in some ways this success has been a disappointment: we have not learned much new.

The two issues, the driving mechanism and continental tectonics, have been the focus of a great deal of research in the 50 years since 1967, and we now have a much better understanding of both. As in the 1960s, this progress has been almost entirely dependent on advances in technology. In the case of the driving mechanism it is our ability to measure gravity to an accuracy of 1 part in 10^$_{6}$, and especially to do so using satellites, that has provided the key. In contrast the key to understanding continental structure and deformation has largely come from seismology, from digital seismograms that are now so easily and widely available. Both advances depend on our ability to handle enormous data sets: in the case of seismology, 10s of terabytes.

The new technologies are now being used to study mantle flow in three dimensions, which is now beginning to provide an understanding of the two important issues that were put aside in 1967.

NOTES

POSTER ABSTRACTS
(in alphabetical order)

Forearc basin structuring and seismicity patterns controlled by a trapped sliver from the Caribbean Large Igneous Province (CLIP): Northern Andes

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The underlying basement of the Northern Andes forearc represents a sliver from the late Cretaceous Caribbean Large Igneous Province (CLIP), accreted to the South American continent during Late Campanian. Although, different studies have documented the main characteristic and affinities of basaltic exposures, to an intra-oceanic arc process, the regional understanding and relationships among exposed crustal blocks remain unclear. Furthermore, their role on the structuring of forearc basins and seismicity patterns observed along the coastal region have not yet been considered. Instead a strong bias has been given to the subduction of the Carnegie ridge as the main responsible for the observed patterns.

Analysis of a recent acquired airborne gravity and magnetic survey along the coastal region of Ecuador have permitted to uncover a ridge like anomaly attributed to a buried arc, possibly the southern prolongation of Tertiary arcs in Colombia. Forward modelling of gravity and magnetic anomalies have revealed a heterogeneous basement, which have been divided into different geophysical domains. Each of these domains have been associated to a specific structural zone within a forearc framework. From this analysis, the following conclusions may be drawn: 1) lateral migration of the late Cretaceous volcanic arc possibly associated to a trench-roll back process, 2) the presence of a backstop may have controlled early structuring of forearc basins and further development of an outer-arc high, 3) same backstop may have controlled deflections on the subducting slab and seismicity patterns.

The data integration approach presented in this study has significant geodynamic implications on our understanding of the early evolution of the Northern Andes and the potential for preservation of intra-oceanic arc tectonic processes buried by younger forearc deposits. Commonly presented as a 2D problem, previous authors have obviated the relationship between the different crustal fragments and their role in the geodynamic context. Therefore, we consider that the presence of the Piñon and Naranjal blocks, acting as a backstop, may have shaped the forearc and outer-arc high since its emplacement. We proposed an alternative model for the seismicity patterns observed along the coastal region, without discarding an interplay among different processes (e.g. subduction of the Carnegie ridge).

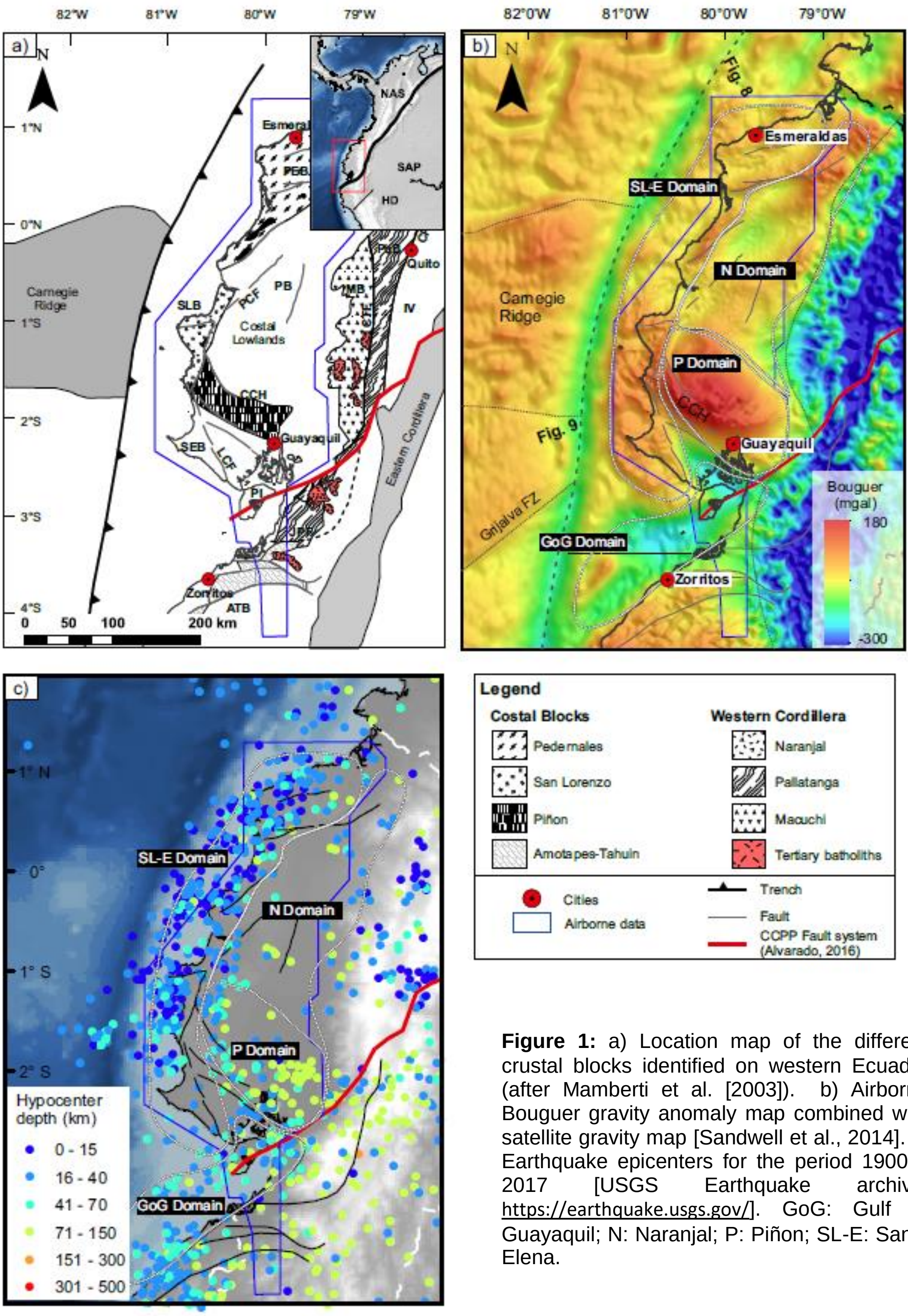

Figure 1: a) Location map of the different crustal blocks identified on western Ecuador (after Mamberti et al. [2003]). b) Airborne Bouguer gravity anomaly map combined with satellite gravity map [Sandwell et al., 2014]. c) Earthquake epicenters for the period 1900 – 2017 [USGS Earthquake archive; https://earthquake.usgs.gov/]. GoG: Gulf of Guayaquil; N: Naranjal; P: Piñon; SL-E: Santa Elena.

Improving plate-reconstruction models using crustal-thickness maps from gravity inversion: examples from the Gulf of Mexico & Indian Ocean

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The Plate Tectonics paradigm was established approximately 50 years ago. Over the subsequent years our understanding of the plate-scale kinematic evolution of continents & oceans has improved considerably. We have seen the relatively simple early reconstruction models updated with models which include deformable plate-boundaries and deformable plate-interiors, as well as the integration of mantle dynamics. Most plate-restoration models, however, still use features such as present-day coastlines, shelf-breaks and bathymetry to guide their final stages back to the time of breakup. These features are ephemeral and not fixed in the geological past; as a consequence they do not usually provide good tests of the final stages of plate restoration, nor do they constrain reliable predictive models. We show how plate restorations can be improved and made more useful by restoring crustal thickness and lithosphere thinning-factor derived from satellite gravity inversion. Maps of crustal thickness and lithosphere thinning-factor help to define the distribution of oceanic crust and constrain the location of the continent-ocean-boundary, independent of ocean isochron data. In addition, the superposition of shaded-relief free-air gravity-anomaly data allows sea-floor-spreading trajectories and conjugate-margin correlation to be tested and re-evaluated. We apply this approach to testing and improving plate-restoration models for the Gulf of Mexico and Indian Ocean.

Crustal thickness mapping using satellite gravity inversion for the Gulf of Mexico (GoM) clearly shows the location of an extinct sea-floor-spreading ridge together with the transform faults which segment and offset the ridge. The transform faults in turn reveal sea-floor-spreading trajectory, providing important constraints on pre-breakup rifted-margin conjugacy and a re-assessment of sea-floor-spreading rotation poles.

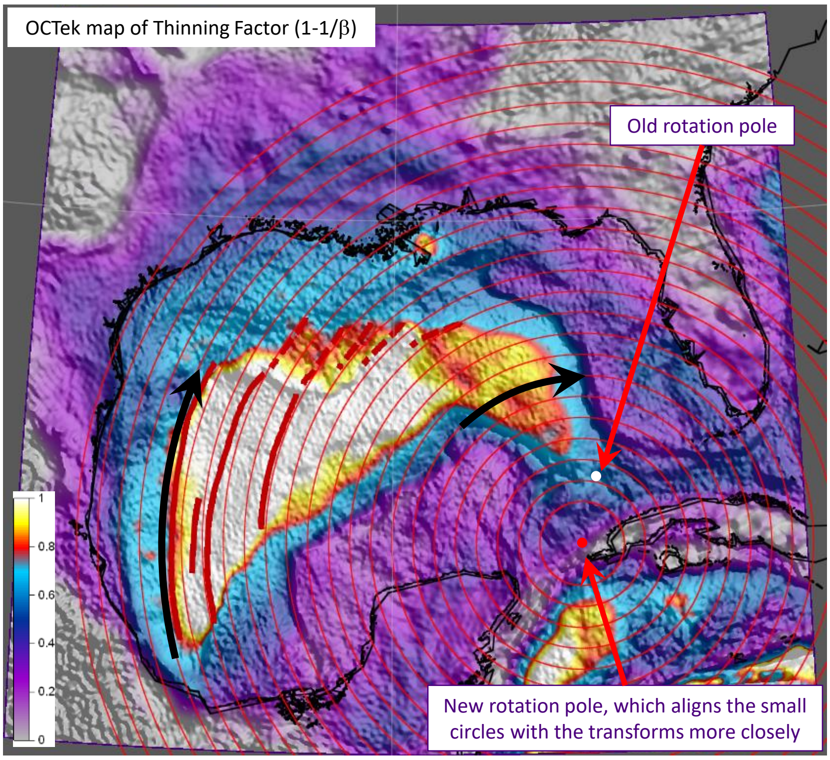

Figure 1: Continental-lithosphere thinning factor from gravity inversion showing the location of arcuate transform faults within the Gulf of Mexico. The small circles which align with these transforms belong to an Euler pole of rotation which is located by the red dot NE of the Yucatan peninsula. The white dot shows the previously-published Euler pole. The two poles are associated with different opening histories for the GoM, discussed in the talk.

Restoring the GoM along the arcuate transform faults suggests that opening occurred in two stages. Initial rifting and breakup occurred in a N-S direction, with the Yucatan block on the southern margin still linked to South America. At this time the West Florida margin (east of the GoM) acted as a transform boundary accommodating the N-S extension. In the second stage, propagation of sea-floor-spreading between Yucatan and South America (south of the GoM) caused the Yucatan block to rotate anti-clockwise away from South America. In this second stage of rotational opening within the GoM the West Florida margin acted as an extensional continental margin. By refining the plate-reconstruction models in this way we also gain a better insight into the linked development of the GoM in the context of the formation of the early Central Atlantic.

While the first-order opening history of the Indian Ocean is already well understood we can improve our understanding of its plate-kinematic evolution by testing and improving existing plate restorations using crustal thickness from gravity inversion. In particular additional information can be gained by mapping the many regions of anomalously thick crust within the Indian Ocean which are resolved by gravity inversion. Some of these areas may be rifted micro-continents, while others are associated with intra-plate volcanism, ocean-ridge jumps and plate re-organisations.

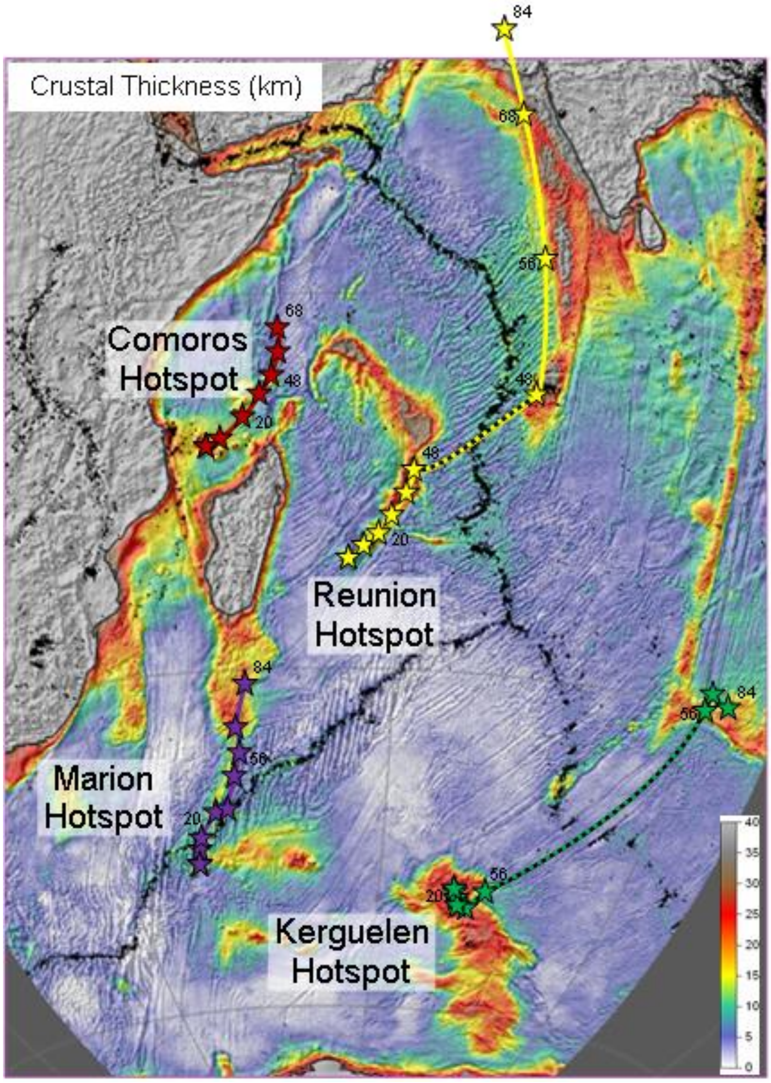

Figure 2: *Crustal thickness map for the Indian Ocean derived by gravity inversion. Regions of anomalously thick crust (in reds and yellows) are numerous throughout the region. Using hot-spot tracks we can explain some of these regions as the product of intra-plate volcanism. The remaining anomalously-thick regions may be micro-continents, a hypothesis which can be tested with plate-reconstruction models.*

Application of these techniques globally provides new insights into the details of continental breakup and ocean-basin development, together with intriguing new information on ocean-ridge jumps and plate re-organisations. This information can be particularly helpful for planning frontier, deepwater hydrocarbon exploration.

Isotopic and Geological Evidence of ca 60 Ma Long Cryogenian to Ediacaran High-K Collisional Magmatism in the Pernambuco - Alagoas Domain, Borborema Province, NE Brazil

Adejardo Francisco da Silva Filho[a]; Ignez de Pinho Guimarães[a]; Lucilene Santos[a]; Richard Armstrong[b]; William Randall Van Schmus[b]; Douglas da Silva Farias[a]; Luan Cavalcanti Dattoli[a] ; Dayse Rosa Lima[a]

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The Pernambuco Alagoas (PEAL) domain shows the major occurrence of granitic batholiths of the Borborema Province, NE Brazil, with Archean to Neoproterozoic range of TDM model ages, giving clues on the role of granites during the Brasiliano Orogeny. SHRIMP U/Pb zircon data for nine granitic intrusions of the PEAL domain, emplaced from early- to post-collision stages, divide the studied granitoids into three groups: 1) granitoids with crystallization ages ca 650-635 Ma (Maravilha, Serra do Catú and other three not yet detailed plutons), 2) granitoids with crystallization ages 610-625 Ma (Curituba, Santana do Ipanema, Água Branca, Mata Grande and Correntes plutons) and 3) granitoids with ages of ca. 590 Ma (Águas Belas, and Cachoeirinha plutons). The intrusions of group 1 and 2, except the Maravilha, Mata Grande and Correntes plutons, show Nd TDM model ages ranging from 1.2 to 1.5 Ga, while the granitoids from group 3, and Maravilha, Mata Grande and Correntes plutons have Nd TDM model ages ranging from 1.7 to 2.2 Ga. The studied granitoids are in part high-K, calc-alkaline, shoshonitic, ultrapotassic and in part transitional high-K calc-alkaline to alkaline. The volcanic arc signatures associated with the Paleoproterozoic TDM model ages are interpreted as inherited from the source rocks. The oldest ages and higher Nd TDM model ages are recorded from granitoids intruded in the southwest part of the PEAL domain, suggesting that these intrusions are associated with slab-tearing during convergence between the PEAL and the Sergipano domains. Zircon oxygen isotopic data in some of the studied plutons, together with the available Nd isotopic data suggest that the Brasiliano orogeny strongly reworked older crust, of either Paleoproterozoic and Tonian ages.
High-K granitoids with crystallization ages older than 630 Ma have not been recorded in the Sergipano and Transversal Zone domains, suggesting differences in the crustal evolution of these two areas during the early stage of the Brasiliano orogeny, when compared to the PEAL domain. The PEAL domain records the Brasiliano orogeny oldest granitic magmatism of the Central and Southern subprovinces.

Peri-Gondwana Terranes in Central Brazil.

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Accretionary terrain amalgamation to the margins of Gondwana is one of the main mechanisms in the formation of this supercontinent. Large magmatic belts, characterized by intense plutonism dated 590-540 Ma, surround old continental blocks. Subduction related arc magmatism is recognized bordering the West African Craton, along the Avalonia and Iberia terranes. We propose that these features extend into Brazil, in South America.

The main exposure of peri-gondawanic terrains in central Brazil is found along the Transbrasiliano Lineament (LTB), an intracontinental strike-slip shear system more than 3,000 km long, which merges with the Kandi Lineament in Africa, in Pangaea reconstructions. We suggest an oblique collision model, in which magmatic arcs interconnected to transform zones systems evolve to accretion of different tectono-stratigraphic terranes during the final stages of Gondwana assembly in the Cambrian. The result of this process is collision of the Amazonian and São Francisco cratons and amalgamation of several crustal fragments and different terranes between them, leading to the final tectonic configuration of this part of West Gondwana.

Arc magmatism with adakitic signature, developed between 590 and 540 Ma, is strong evidence of juvenile crust formation and that the Amazonian and São Francisco cratons had not yet collided at this time, when an ocean basin was being closed at the start of the Cambrian in South America.

Crustal architecture and tectonic evolution of the Antarctic continent in light of recent aerogeophysical exploration

Fausto Ferraccioli
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The Antarctic continent is a cornerstone within the Gondwana, Rodinia and Columbia/Nuna supercontinents; it holds cryptic and yet key records of large scale processes associated with the supercontinent cycle. Despite its importance, our knowledge of the crustal architecture and tectonic evolution in Antarctica is much poorer relative to other continents due to ice sheet cover and its remoteness that makes geophysical exploration both challenging and costly.

Major international airborne geophysics exploration efforts over the last decade are however providing an important tool to peer through the thick ice sheets, and together with recent seismological data compilations and satellite gravity and satellite magnetic studies are unveiling the structure and evolution of the Antarctic continent in an unprecedented way. Here I focus on selected case studies of aerogeophysical exploration performed by the British Antarctic Survey and its UK and international collaborators that are helping reveal the crustal architecture of Antarctica and its links with large-scale tectonic processes.

The first case study focuses on the Gamburtsev Subglacial Mountains in East Antarctica, the least understood intraplate mountain range on Earth, as well as a key site for Antarctic Ice Sheet initiation. Here the combination of airborne gravity and seismological data (An et al., 2015, *JGR*) unveil remarkably thick Precambrian crust (up to 60 km) and lithosphere (>200 km) that define an orogenic Gamburtsev Province inferred here to be linked to global Grenvillian-age (ca 1.1-1.0 Ga) supercontinental assembly of Rodinia, and potentially also to Pan-African age (ca 550 Ma) Gondwana assembly (Ferraccioli et al., 2011, *Nature*). Another finding was the discovery of the Mesozoic East Antarctic Rift System that stretches from India to South Pole. Rifting and intraplate strike-slip faulting likely heralded the breakup of India from East Antarctica and may also have triggered the initial uplift of the Gamburtsev Mountains.

The second case study concerns the Wilkes and Aurora Subglacial Mountains region where airborne geophysics has been successful in peering through major intracrationic basins to unveil the Precambrian basement architecture with significant implications for improving our understanding of the linkages and also previously unrecognized contrasts between Australia and East Antarctica in the supercontinent cycle (Aitken et al., 2014, GRL; Aitken et al., 2016 *Gondwana Res*.).

The third case study focuses on the Weddell Sea Rift region. Here new interpretations of aeromagnetic and airborne gravity data challenge the widely accepted geological and paleomagnetic paradigm predicting that the break of Gondwana was accompanied by a huge amount of Jurassic microplate movement and predict instead more limited and potentially also longer-lived intraplate strike-slip motion and possible orocline bending related to the Gondwanide fold-belt (Jordan et al., 2017, *Gondwana Res*).

Finally, I will showcase the first aerogeophysical views of the South Pole region as part of our current European Space Agency (ESA)-supported project to fill in the polar gap in GOCE satellite gravity data coverage. I will showcase how the new data help unveil one of the least known subglacial basins in East Antarctica, the Pensacola-Pole Subglacial Basin that has remained largely un-explored since its first discovery in late 1970’s (Drewry, 1975, *Nature*). I will present an interpretation of these new data suggesting that the Pensacola-Pole Basin developed in response to Jurassic strike-slip faulting along a former major distributed lithospheric-scale plate boundary between East and West Antarctica.

Crustal Architecture of the Proto-Caribbean Oceanic Crust

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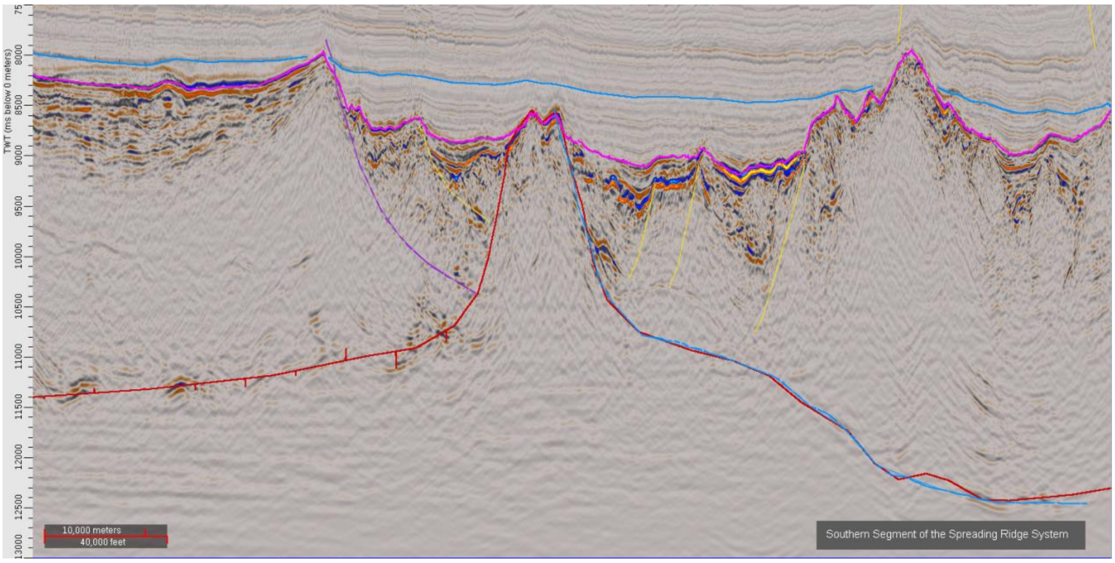
The origin and structure of the Caribbean Plate have remained an enigma since the acceptance of Plate Tectonics as a mechanism to explain continental drift. Unlike other ocean basins, the Caribbean has no easily identifiable and organized system of ridges and fracture zones visible on satellite bathymetry or magnetic data. Only limited research ODP wells and seismic data, and sparse oil industry data have been acquired in the region. The areal extent, structural architecture, and age span of the proto-Caribbean oceanic crust have relied upon model-driven plate reconstructions to explain the space created by the relative motion between North and South American plates.

Our study focuses on this model driven uncertainty, drawing from new long-offset regional 2D and 30,000 km^2 of 3D reflection seismic data acquired in the ultra-deepwater Colombian Basin. The 14 second seismic data record length allows for the identification of a deep reflector interpreted as Moho. The data have been tied into existing well, gravity and magnetic data from a 500,000 km^2 region of the Western Caribbean, which includes the Beata Ridge.

This unique 3D survey defines a relatively undeformed portion of what we interpret as the proto-Caribbean oceanic crust. The 3D seismic data show a 1-2.0 sec TWT thick interval inferred to be a basalt flow layer. Its top surface is characterized by a strong seismic reflector and it was tied into DSDP 153 on regional 2D seismic.

The tectonic boundaries of the ocean crust segment are the Panama accretionary wedge to the southwest, the dextral transpressional Colombian accretionary prism to the southeast, the South Nicaraguan Rise to the northwest, and the North Caribbean Deformed Belt to the north. We focus on the portion underlying the Colombian Basin and Beata Ridge, where its maximum length is 1,000 km and maximum width is 600 km.

The oceanic crust contains a NNE-SSW trending spreading ridge system, which divides the WNW-ESE trending Colombia oceanic fracture zone (70 km wide) into northern (480 km long) and southern (550 km long) segments. Both segments near the fracture zone appear magma-poor. Here, oceanic crust was developed by stretching-dominated mechanisms, cyclically propagating and abandoning shallow-dipping detachment faults. Detachments of the northern segment have their footwalls on the eastern side. The entire footwall side of this segment is characterized by a positive isostatic residual gravity anomaly, and indicates by its reduced burial depth that denser lithospheric mantle rocks ascended higher in the footwall than in the hangingwall. The geometric arrangement of detachments indicates a southward propagation of the northern spreading segment. Across the Colombia oceanic fracture zone, the segments flip polarity; the northern segment has its footwall to the east, whereas the southern segment has its footwall side to the west.



Crust that occurs to the west of the southern segment contains the Esmeralda and Fuerte oceanic fracture zones, which also cut through the entire oceanic corridor. Their seismic expression contains ridges and troughs with bathymetric differences in some cases exceeding 2 sec TWT. They are controlled by steeply-dipping strike-slip faults that cut through the entire crust. The underlying crust is distinctively thinner than the surrounding crustal thickness. Total magnetic intensity images of the zones are typically characterized by negative anomalies, indicating a possible lack of the gabbroic layer, whose magnetic susceptibility character is more important than the basalt flow and sheeted dyke layers.

We interpret this crust to be a product of initial disorganized sea floor spreading. It lacks the characteristic magnetic stripe-anomalies. The free-air Bouguer and isostatic residual gravity anomaly maps do not contain the typical flow-line patterns that are parallel to the spreading vector for any given crustal age. However, 1st order vertical and total horizontal derivatives of the isostatic residual anomaly map show a system of short fracture zones. We interpret these short fracture zones as linked spreading centers that rapidly initialized and subsequently failed. The short fracture zones are no longer than 70-140 km.

The overall Crustal thickness distribution, spanning between 2.4 and 5 sec TWT is variable. It is characterized by abrupt gradients between numerous blocks. The best imaging of crustal inhomogeneity is provided by a 3D seismic surface at the interface between the basalt layer and overlying sedimentary succession. This horizontal time slice shows a crustal architecture characterized by the WNW-ESE trending flow-line pattern of ridges and troughs. It also displays approximately square-shaped blocks of thicker crust in several areas. These flow-lines are parallel to those imaged in the Central Atlantic. This indicates that the studied portion of the proto-Caribbean oceanic crust did not undergo any significant rotation during the subsequent tectonic development of the Caribbean region.

We hope these seismic observations from the new 3D dataset will be useful for refining geologic models for the origin of the Caribbean Plate.

Break-up Processes in the Presence of Plume Magmatism: New Insights into the Tectonostratigraphic Development of the South Atlantic

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The conjugate rifted margins of the austral South Atlantic are classically magma-rich and display extremely well developed examples of all the volcanostratigraphic elements commonly observed on magma-rich margins globally: stretched continental crust, inner and outer SDR (seaward dipping reflector) packages, an outer (volcanic) high, a zone of high-velocity lower crust, and relatively thick early oceanic crust (Planke et al., 2000; Barton & White, 1997).

Rifted continental margins are often considered independently due to a paucity of conjugate high-resolution reflection seismic profiles. Here, newly acquired mega-regional, conjugate seismic datasets are, through palaeogeographic reconstructions, considered as they once were; a single basin with a shared geological history. Observations from these seismic data provide new and important insights into the principle mechanisms involved in highly magmatic continental break-up.

Through a well-correlated stratigraphic and crustal structure interpretation, a new tectonostratigraphic model is presented. This model, describes the development of magma-rich margins influenced by plume magmatism and may have global applications to equivalent margins. The model consists of four distinct crustal domains; continental, magmatic, oceanic and oceanic plateau, and two important crustal boundaries; the limit of continental crust (LoCC), and limit of oceanic crust (Figure 1; McDermott et al., 2015). These crustal domains are delineated with respect to, and reflect the effects of, variable melt volume during continental stretching and break-up.

The tectonostratigraphic model also describes strongly diachronous post-rift and drift phase subsidence and highlights the role the Walvis Ridge – Rio Grande Rise system played in the separation of the central and austral segments of the South Atlantic Ocean. Analysis of subsidence patterns on both conjugates, compared to the drowning of the Walvis – Rio Grande Ridge systems, reveals intriguing correlations between distribution of major source rock intervals and evaporite deposition in the Lower Cretaceous through time and space.

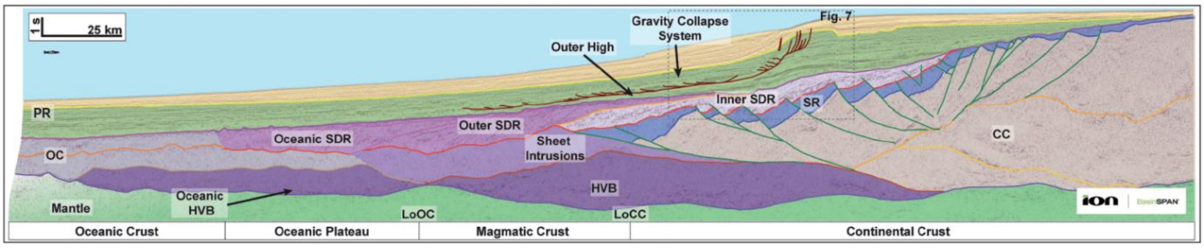

Figure 1 Geoseismic section (McDermott et al., 2015) shown in TWTT details the a typical crustal configuration through the Namibian magma-rich margin. The margin has been CC – continental crust; OC – Oceanic crust; HVB – High-velocity body; SDR – seaward dipping reflectors; SR – syn-rift; PR – Post-rift sediments; LoCC – Limit of Continental Crust; LoOC – Limit of Oceanic Crust.

The observations and processes described here underpin the development of a regional petroleum systems model, allowing prediction of regional heatflow through time as well the likely location of source and reservoir lithologies along the entire austral South Atlantic Basin.

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Carbon from Crust to Core: recording the history of deep carbon science

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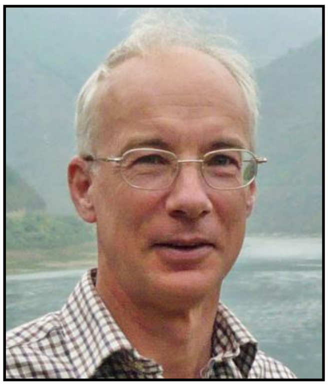
Carbon plays an unparalleled role in our lives: as the element of life, as the basis of most of society's energy, as the backbone of most new materials, and as the central focus in efforts to understand Earth's variable and uncertain climate. Yet in spite of carbon's importance, scientists remain largely ignorant of the physical, chemical, and biological behavior of many of Earth's carbon-bearing systems. The Deep Carbon Observatory (DCO) is a global research program to transform our understanding of carbon in Earth. At its heart, DCO is a community of scientists, from biologists to physicists, geoscientists to chemists, and many others whose work crosses these disciplinary lines, forging a new, integrative field of deep carbon science.

As a historian of science, I specialise in the history of planetary science and astronomy since the beginning of the twentieth century. My current project is directed toward a
greater understanding of the history of the steps on the road to discovering the internal dynamics of our planet. Within a framework that describes the historical background to the new field of Earth System Science, I present the first history of deep carbon science.

This project will identify and document the key discoveries of deep carbon science. It will assess the impact of new knowledge on geochemistry, geodynamics, and geobiology. The project will lead to publication, in book form in 2019, of an illuminating narrative that will highlight the engaging human stories of many remarkable scientists and natural philosophers from whom we have learned about the complexity of Earth's internal world. On this journey of discovery we will encounter not just the pioneering researchers of deep carbon science, but also their institutions, their instrumental inventiveness, and their passion for exploration. The book is organised thematically around the four communities of the Deep Carbon Observatory: Deep Life, Extreme Physics and Chemistry, Reservoirs and Fluxes, and Deep Energy.

This presentation includes a gallery and a provisional list of Deep Carbon Pioneers. As a historian and biographer, I am keenly searching for people who may have been overlooked in the standard accounts of the historical development of geology, geodynamics, and the study of subsurface life. Whom would you choose as pioneers? Can you nominate a colleague, or even add a selfie? Do you have a standout story or personal recollection to enrich my chronicle? I am equipped to do personal oral history interviews: so, what's your story?



The South China Craton – one plate or two?

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China consists of several tectonic blocks, one of which is South China. South China itself is thought to have arisen from the amalgamation of two such units, the Yangtze Block and Cathaysia, around 825 Ma ago. Evidence of their collision is seen in a region-wide angular unconformity caused by uplift (the 'Jiangnan Orogen'), after which sedimentation was controlled by rifting. Most published research takes this scenario for granted. Samples are taken from stratigraphic units commonly identified only at group level on the basis of maps published in the 1980s or earlier, analysed for their geochemistry and discussed in relation to whether the geochemistry supports, for example, an island-arc or a back-arc origin. Group names (e.g. 'Banxi group') are applied to areas 100s of kms across, although stratigraphic continuity is repeatedly disrupted by faults and non-exposure, and groups of approximately the same age are assumed to be equivalent across the entire orogen. Where units are identified down to formation level, zircon dating often proves the mapping to be erroneous, with formations of the same name relating to different time intervals. This situation is less than satisfactory. While 'geochemical data can be used to help constrain tectonic settings... it cannot be used alone to reconstruct ancient tectonic settings' (Condie, 2005). The fundamentals of geological structure need to be established first.

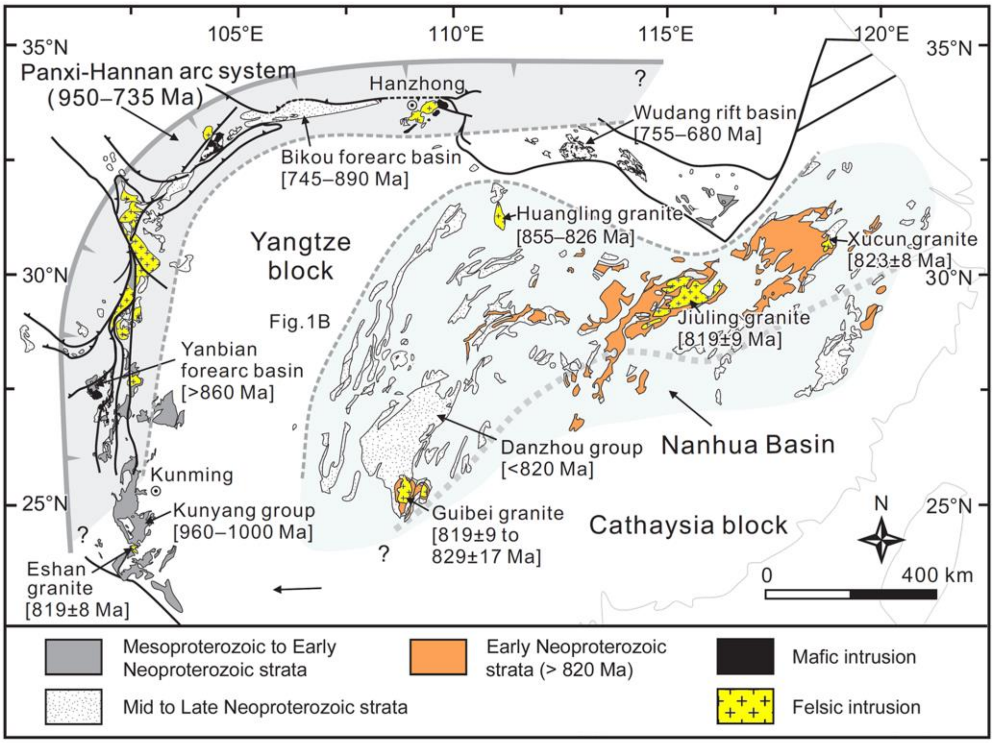

Figure 1. The South China craton/block (after Zhao et al. 2011). The thick dotted line marks the boundary between the Yangtze and Cathaysia blocks as proposed by various authors. The Nanhua Basin consists of a series of rift basins. Granites along the western and northern margins of the craton are associated with subduction. The question is whether those in the Nanhua basin were similarly caused.

There are reasons to question whether the Yangtze Block and Cathaysia were converging at this time. Rifting was occurring well before 825 Ma, when the crust appears to have thinned rather than thickened. The orogen left no mountain roots. Metamorphism was low-grade. Purported ophiolites, poorly dated, are aligned with fault systems (Fig. 2) and appear to be relatively thin slivers of incipient 'ocean' crust that formed in failed rifts and were transported to their present locations by thrusting after 810 Ma, possibly as late as the Phanerozoic. Not being obvious, the location of the suture continues to be debated and, wherever it is placed, pre-825 Ma structures cut across it (Fig. 1). A shared history is also indicated by evidence that both the Yangtze Block and Cathaysia were affected by exceptionally intense granitic magmatism early in the Neoproterozoic. Most outcropping plutons along the Jiangnan Orogen are younger than 840 Ma and developed where the crust was thinnest, within the rift basins. Compositions are ^{18}O-enriched and peraluminous, a consequence of shallow-level melting of sediments in the basins. It has recently been suggested that the unconformity was caused by the ascent of these plutons (Yang et al., 2015), some of them still subsurface. If this is conceded, there cease to be grounds for supposing that the Yangtze Block and Cathaysia were once separated by an ocean, and South China bids fair to join the list of cratons that date back to the Archaean.

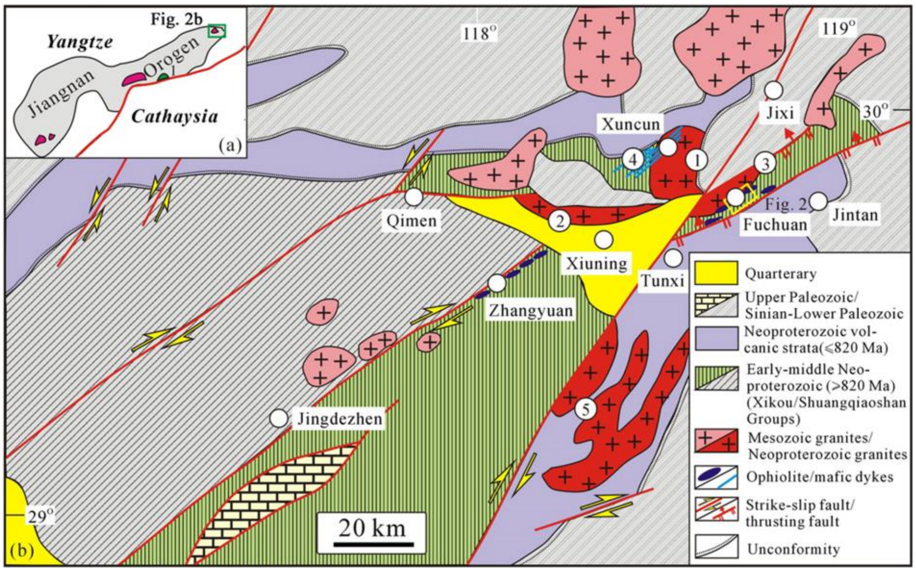

Figure 2. Geological context of the putative ophiolites near Zhangyuan and Fuchuan, Anhui Province, at some distance from the putative suture (from Zhang et al. 2013).

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Kinematics of the East Pacific Rise predicted from Pacific and Nazca/Farallon Subduction-Related Torques: Support for significant deep mantle buoyancy controlling EPR spreading

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Negative buoyancy associated with subduction of cold, dense oceanic lithosphere is generally considered to be the dominant driver of Earth's tectonic plates. In this framework, mid-ocean ridges are viewed as passive plate boundaries whose divergence accommodates flow driven by subduction of oceanic slabs at trenches. Using global plate kinematic reconstructions we show that over the past 80 Myr the East Pacific Rise (EPR), Earth's dominant mid-ocean ridge, has been characterized by limited ridge-perpendicular migration and by persistent, asymmetric ridge accretion that are anomalous relative to other mid-ocean ridges. We reconstruct the subduction-related torques of plates on either side of the EPR since 80 Ma based on published paleo-age grid (Müller et al. 2008) and corresponding plate boundary reconstructions (Gurnis et al. 2012). Slab-pull-related torques retrodict that the EPR should have been characterized by significant (~3800 km) eastward migration in the NNR frame of reference, with ~2000 km in the past 40Ma. In a passive upwelling system there is no reason for systematic asymmetric accretion along the EPR. In contrast to these retrodictions, plate reconstructions retrodict 0 km of eastward migration in that same 40 Myr interval, and an ~60:40% split in accretion to the Nazca/Farallon versus Pacific plate over the past 53 Ma.

We account for these observations of EPR stability using mantle flow calculations based on globally integrated buoyancy distributions derived from jointly inverted seismic velocity, geodynamic and mineral physics data that require core-mantle boundary (CMB) heat flux that may be as high as 20TW. The time-dependent mantle flow predictions, which extend both backwards and forwards in time, yield a long-lived deep-seated upwelling that has its highest radial velocity under the EPR, and is inferred to control its observed kinematics. The mantle-wide upwelling beneath the EPR drives horizontal components of asthenospheric flows beneath the plates that are also asymmetric, but faster than the overlying surface plate motions, thereby contributing to surface plate motions through viscous tractions in the Pacific region.

Long-Term Sea Level on a Dynamic Earth

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Discussions of long-term sea level, that is sea level in the absence of grounded ice, have been predicated on dynamical changes to ocean basin volume. Most often these discussions are phrased in terms of changes in mean age and therefore mean depth of the oceanic lithosphere as a function of time (Pitman, 1978, Kominz, 1984, Müller et al. 2008, van der Meer et al., 2017). A characteristic of these treatments is that changes in the hypsometry of the oceanic lithosphere are treated as entirely independent of the continents, and that age-depth is controlled by a fixed equation specifying both ridge and depth-age relations while the hypsometry of the continental crust is held fixed. Following this recipe the Earth is required to expand and contract with amplitudes of 100's m in direct relation to changes in area of oceanic lithosphere as a function of age over time. These models go completely counter to the general understanding that the Earth's mean radius is effectively unchanging on short time scales (<100-200 Myr) but on time scales of the age of the Earth is shrinking at an exponentially decreasing rate due to loss of heat to space. In this presentation, aspects of changes mean depth of the oceans and changes in fractional area of continental crust are explored within a model that explicitly maintains constant mean radius and hence constant mean elevation of the surface of the Earth by distorting the GIA-corrected global bedrock hypsometry at 1m vertical resolution. Long-term sea level, referred to as the paleo-height of the shoreline, is then computed as the height of the distorted hypsometric surface at which the volume of the ocean basin equals the volume of all ocean water and ice as water, ~1.36×10^9 km^3. The present height of the paleo-shoreline, i.e. sea level as measured on the GIA-corrected hypsometry, is the height of the same 1m bin as the paleo-height of the shoreline. Paleogeographic reconstructions of shorelines as a function of time are used to derived estimates of areal extent of flooding together with estimates of uncertainty provide critical independent constraints on models of dynamic changes in Earth's bedrock hypsometry. The model also incorporates the consequences of changes in fractional area of shallow continental crust on sea level. Combining areal extent of flooding and changes in continental crustal area, based on recently published results of Ingalls et al. (2016), are used to estimate the long term sea level history and associated changes in mean depth of the oceanic lithosphere as a function of age with estimates of uncertainties. Long-term sea level is estimated to have a maximum height of about 100±40 m between about 100 and 80 Ma relative to an ice-free, GIA corrected sea level height of ~40m today. Changes in mean depth of the oceanic lithosphere average about -10m over the past ~165 Ma, with a maximum amplitude of about +8±40m, that given the correlation of changes in mean depth with changes in mean age correspond with decrease in mean age from 63.6Myr today to about 62.8±4.8 Myr between 100 and 80 Ma ago. This contrasts markedly with current published results with the mean age of the oceanic lithosphere of ~41Myr in this same interval (Müller et al., 2008, 2013).

Assessing the nature of crust in the central Red Sea using potential field methods

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The Red Sea is considered an important example of a rifted continental shield proceeding to a seafloor spreading stage of development, and the transition of crustal types there from stretched continental to oceanic should mark the onset of significant mantle melting. However, whether the crust in the central Red Sea is continental or oceanic has been controversial. To contribute to this debate, we assessed the geometry of the basement from potential fields and published seismic reflection data. Prior interpretations of basement in three deep seismic reflection profiles were first verified using Werner deconvolution of marine magnetic data. The seismic depths were then used to reconstruct basement depth corrected for evaporite and other sediment loading. We found that the basement deepening with distance is similar to that of oceanic crust near mantle plumes such as the Reykjanes Ridge. In both cases, the data show a ~80 km wide axial plateau followed by a steep ~0.7 km deepening over ~40 km distance. It has also been suggested that the variability of free-air anomalies observed in lines parallel to the axis is due to crossing oceanic short-offset fracture zones. We assessed this idea by inverting the gravity anomalies for basement relief. Using densities appropriate for oceanic crust and a modified slab formula, we found values for root-mean square (RMS) relief that are comparable to those of weakly sedimented regions of the Mid-Atlantic Ridge. Forward calculations using 2D modelling revealed that the errors in RMS basement relief caused by the slab approximation are ~30%, leaving true RMS basement relief still within the range of values for oceanic crust. While these observations by themselves do not rule out an extremely extended continental crust interpretation, combined with previous analysis of refraction velocities, which are oceanic-like, they are supportive of an oceanic crustal interpretation. Additionally, the RMS values and the cross-axis basement relief both suggest a change in basement rugosity from near the coast to around the axial trough, perhaps supporting a transition in crustal type from stretched continental to predominantly oceanic.

Early Carboniferous extension in Eastern Avalonia: 350 My record of lithospheric memory

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East Avalonia of the British Isles and Ireland is one of the few regions where the initial Mid-Paleozoic basin structure is still recognisable and largely intact despite reactivations during Variscan and Alpine orogenies and the opening of the Northern Atlantic. Unfortunately this is not the case in the southern North Sea, the Netherlands and North Germany where the initial Mid-Paleozoic basin structure and units are obliterated by the thick cover of Late Carboniferous-to-Recent basin fill and by the recurrent fault reactivation. As a consequence, kinematics and dynamics remain largely unknown, in particular in view of the successive Late Paleozoic to recent evolution of the different basins. Consequently, the importance of the mid-Palaeozoic tectonic evolution and structural controls are often overlooked and poorly understood in basin studies.

In this paper, we reassess the importance of Mid-Palaeozoic tectonics on subsequent sedimentary basin evolution of the north-western European East Avalonia microplate. The strong dispersal of available constraints requires a comprehensive study of the East Avalonian microplate from suture to suture. To this end, we analyse the dynamics of early Variscan extension in Avalonia based on the integration and re-evaluation of publicly available geophysical and geological data from lithosphere to basin scales. We complement the map of Early Carboniferous rifting of East Avalonia and propose a new tectonic scenario, linking constraints from the crust and mantle to stratigraphic-sedimentological information.

Reevaluation of deep seismic refraction lines drew our attention to a low P-wave velocity zone (LVZ) in the lower crust that cannot be easily attributed to Avalonia or Baltica plates abutting the TSZ. In general, defining terranes on the basis of seismic velocities alone is not always trivial, as seismic velocity distributions can be affected by tectonic events following their amalgamation. Consequently, it is not always clear in how far current lower crustal velocities still represent a property of the original terranes. In the case of the Thor suture zone (TSZ), however, there is a systematic, consistent, and direct correlation between this structure and a low-velocity zone (LVZ) in the lower crust detected from a set of five parallel deep seismic refraction. We propose that the LVZ corresponds to the existence of a hitherto unrecognized crustal segment that separates Avalonia from Baltica. A comparison with present-day examples of the Kuril and Cascadia subduction zones suggests that the LVZ separating Avalonia from Baltica is composed of remnants of the Caledonian accretionary complex. If so, the present-day geometry probably originates from pre-Variscan extension and eduction during Devonian–Carboniferous backarc extension.

The revised crustal map of the Thor Suture Zone forms the starting point for a new paleo-tectonic reconstruction and tectonic scenario for the Devonian-Carboniferous rifting of East Avalonia from the Atlantic Ocean to the Rheic Suture. Results show that the main basement structuration of northwest Europe was completed before the Variscan orogeny. The structural grain of many crustal fault-dominated sedimentary basin structures such as the North Sea Central Graben can for the first time be placed in a consistent tectonic framework, contributing to fundamental understanding of both crustal structure and basin evolution. Our results indicate that the successive post-Variscan extension and inversion phases reactivated the existing basement structures without creating major new fault groups. Avalonia therefore stands out as a fine example of long lived lithosphere memory, spanning over 350 My of structural control in geodynamic evolution.

Plate Kinematic Model of the Northwest Indian Ocean and Application to Paleostress Modelling

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The structure and evolution of the East African and West Madagascan Margins have been shaped by tectonic processes during the fragmentation of Gondwana since the early Jurassic. We present a new high resolution plate kinematic model of the Northwest Indian Ocean, built using finite rotation poles generated by visual fitting and iterative joint inversion of magnetic isochron and fracture zone data. We identify four phases of tectonic development of the area from 183-177 Ma to present separated by major plate boundary changes, and preceded by the Karoo Rifting Phase (late Carboniferous to late Triassic/Early Jurassic), which culminated in the eruption of the Karoo-Ferrier LIP (183-177 Ma).

A separate period of rifting at the start of Phase 1 (183-177 Ma to 133 Ma) led to successful breakup (~170-165 Ma) between East Gondwana (including Madagascar, India, Antarctica and Australia) and West Gondwana (South America, Africa), and subsequent seafloor spreading in the West Somali and Mozambique basins. At the start of Phase 2 (~133-89 Ma), seafloor spreading in the West Somali basin ceased and the plate boundary relocated to the West Enderby Basin, between Madagascar/India and Antarctica. The initiation of the Mascarene Ridge at the beginning of Phase 3 (89-60 Ma) separated India from Madagascar. By Phase 4 (60 Ma to present) spreading on the Mascarene ridge had almost ceased. The Carlsberg Ridge propagated south to form the Central Indian Ridge, separating India from the Seychelles and the Mascarene Plateau.

The first-order plate-scale tectonic stress field was estimated for different stages of margin development based on the type and geometry of the plate boundaries, and plate motion vectors derived from the plate model. During rifting, the maximum horizontal stress ($S_{H\ max}$) is perpendicular to plate vectors and parallel to the rift axis. After breakup, the orientation of $S_{H\ max}$ changes abruptly with the onset of active seafloor spreading with $S_{H\ max}$ now lying parallel to the plate vector and perpendicular to ridge segments. This method is effective at predicting first-order stress fields but does not take into account lateral variations in topography, lithospheric density and thickness, or the effect of mantle tractions on the base of the lithosphere. To address this, the plate kinematic model was used as input for dynamic stress modelling to calculate the forces acting on the African plate and the resultant stress fields at important tectonic stages. Assuming that the plate is in mechanical equilibrium (i.e. not accelerating or decelerating), the torque arising from mantle tractions must be balanced by the torques arising from edge forces and lithospheric body forces. Edge force torques are generally well constrained by boundary geometry and relative motion derived from our tectonic model, and lithospheric body forces can be estimated from the thickness and density of the lithosphere. These “known” torques provide some constraint on the poorly understood mantle traction torques. We anticipate that the numerous tectonic changes in the NW Indian Ocean described in our plate kinematic model will change the balance of torques acting on the East African margin and thus affect the orientation of the stress field.

Our plate kinematic model provides detailed information about the timing and location of rifting, breakup and seafloor spreading in the Africa/India/Madagascar/Antarctica plate circuit and acts as a foundation for paleostress modelling to highlight the interplay between plate tectonics, plate boundary forces and margin development.

Reconstructing first-order changes in sea level during the Phanerozoic and Neoproterozoic using strontium isotopes

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The eustatic sea-level curves published in the seventies and eighties have supported scientific advances in the Earth Sciences and the emergence of sequence-stratigraphy as an important hydrocarbon exploration tool. However, validity of reconstructions of eustatic sea level based on sequence stratigraphic correlations has remained controversial. Proposed sea level curves differ because of site-to-site changes in local tectonics, depositional rates, and long-wavelength dynamic topography resulting from mantle convection. In particular, the overall amplitude of global Phanerozoic long-term sea level is poorly constrained and has been estimated to vary between ~400mabove present-day sea level to ~50mbelowpresent-day sea level. To improve estimates of past sea level, we explore an alternative methodology to estimate global sea level change. We utilise the Phanerozoic-Neoproterozoic 87Sr/86Sr record, which at first order represents the mix of inputs from continental weathering and from mantle input by volcanism. By compensating for weathering with estimates of runoff from a 3D climate model (GEOCLIMtec), a corrected 87Sr/86Sr record can be obtained that solely reflects the contribution of strontium from mantle sources. At first order, the flux of strontium from the mantle through time is due to increases and decreases in the production of oceanic crust through time. Therefore, the changing levels of mantle-derived strontium can be used as a proxy for the production of oceanic lithosphere. By applying linear oceanic plate age distributions, we compute sea level and continental flooded area curves. We find that our curves are generally within the range of previous curves built on classical approaches. A Phanerozoic first order cyclicity of ~250 Myr is observed that may extend into the Neoproterozoic. The low frequency (i.e., on the order of 10 to 100 My) sea level curve that we propose, while open for improvement, may be used as baseline for refined sequence- stratigraphic studies at a global and basin scale.

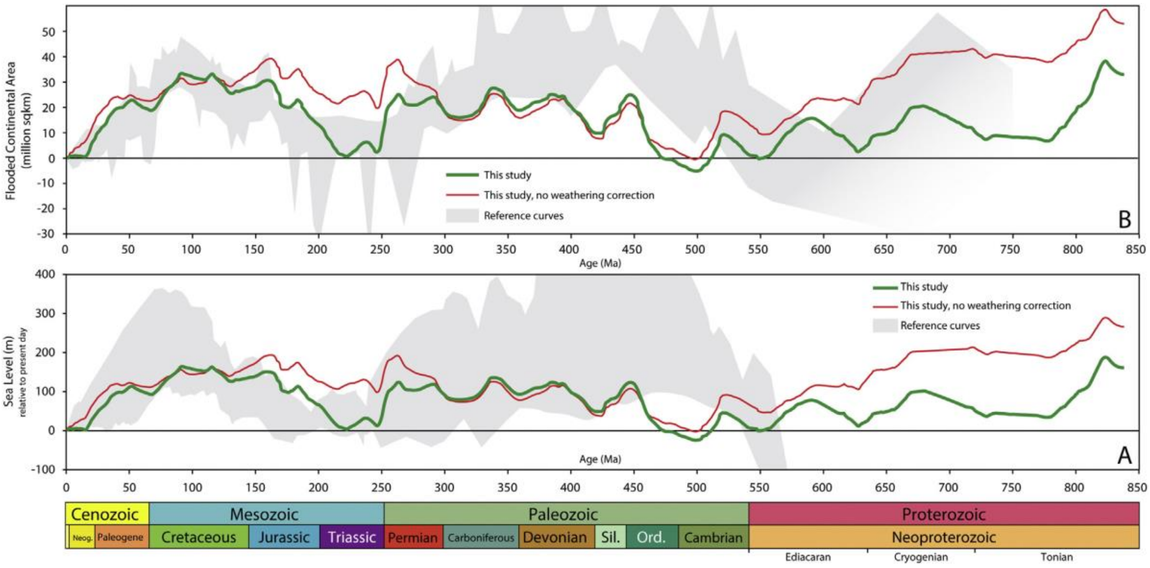

Figure. Here derived sea level curves compared with the reference curves from sequence stratigraphic and plate tectonic methods,

A Global Geological Framework: putting Plate Tectonics in its place

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Plate Tectonics provides a paradigm for the movement of the lithosphere below our feet. It also allows us to connect processes deep in the mantle with processes that impact on the Earth's surface, such as the biosphere and atmosphere. And, importantly, it allows us to build a framework for the whole Earth system. This framework can be used to place our research in a global context, and enables the significance of studies to be communicated to a wide audience, from government to schoolroom. Through such a framework we can appreciate the connections between research in different geological environments and in different fields of study.

I have found that many geoscientists use their own versions of a framework, yet there is no generally used one. This is especially lacking at an international level, where global geosciences needs an overall, simple way to present geoscience research, ideas and policy. At UNESCO, for example, geological World Heritage lacks an overarching scheme. I present a global geological environmental framework, that has been discussed by a broad section of the community, and has been tested outside the community, to assess its usefulness for outreach.

The framework considers core and mantle processes, then the lithosphere and plate tectonics, then the hydrosphere, cryosphere, biosphere (including anthroposphere) and atmosphere, and influences from the solar system and beyond (Figure 1). All Geological Environments can be placed in it and compared with others. To illustrate its use, I take three contrasting rift contexts. 1) The Chaîne des Puys and Limagne fault part of the continental Western European Rift system, probably associated with continental subduction under the Alps. 2) The Dallol mountain and Afar rift are part of the East African Rift system, where continental divergence is being replaced by ocean spreading. 3) Vatnajökull, Iceland is part of the Mid-Atlantic rift and lies over plume, or melting anomaly. To illustrate the different geological environments in Figure 1, I have extracted the most relevant boxes from the framework table in part A. These are shown for each case, with an added block diagram.

In this way, the different plate tectonic contexts are then clearly and simply displayed. The global table allows for further integration of the Earth system, so that for Iceland, for example, the interaction with glaciers and magma can be displayed and developed. For the Afar, the role of evaporites in the volcanoes, and the climatic and tectonic conditions for evaporite formation could be included. For both areas, other surface environment and biosphere elements can be added and their connection to plate tectonics elaborated (e.g. for Iceland from glacial rebound to invasive species). For the Limagne rift, the relationship between Alpine lithosphere sinking and aesthenosphere flow is shown, to explain the origin of the extension (and volcanism). The different boxes extracted from the table can also illustrate how the contrasting rifts evolve differently: the Afar with a sequence of *uplift - volcanism – rifting*, while the Limagne with *rifting – volcanism - uplift*.
The global geological framework is a way of synthesizing the Earth system, and I propose that this is discussed, adapted and then adopted by the major geological science unions and societies as a basis for communication and education of the ongoing importance of plate tectonics.

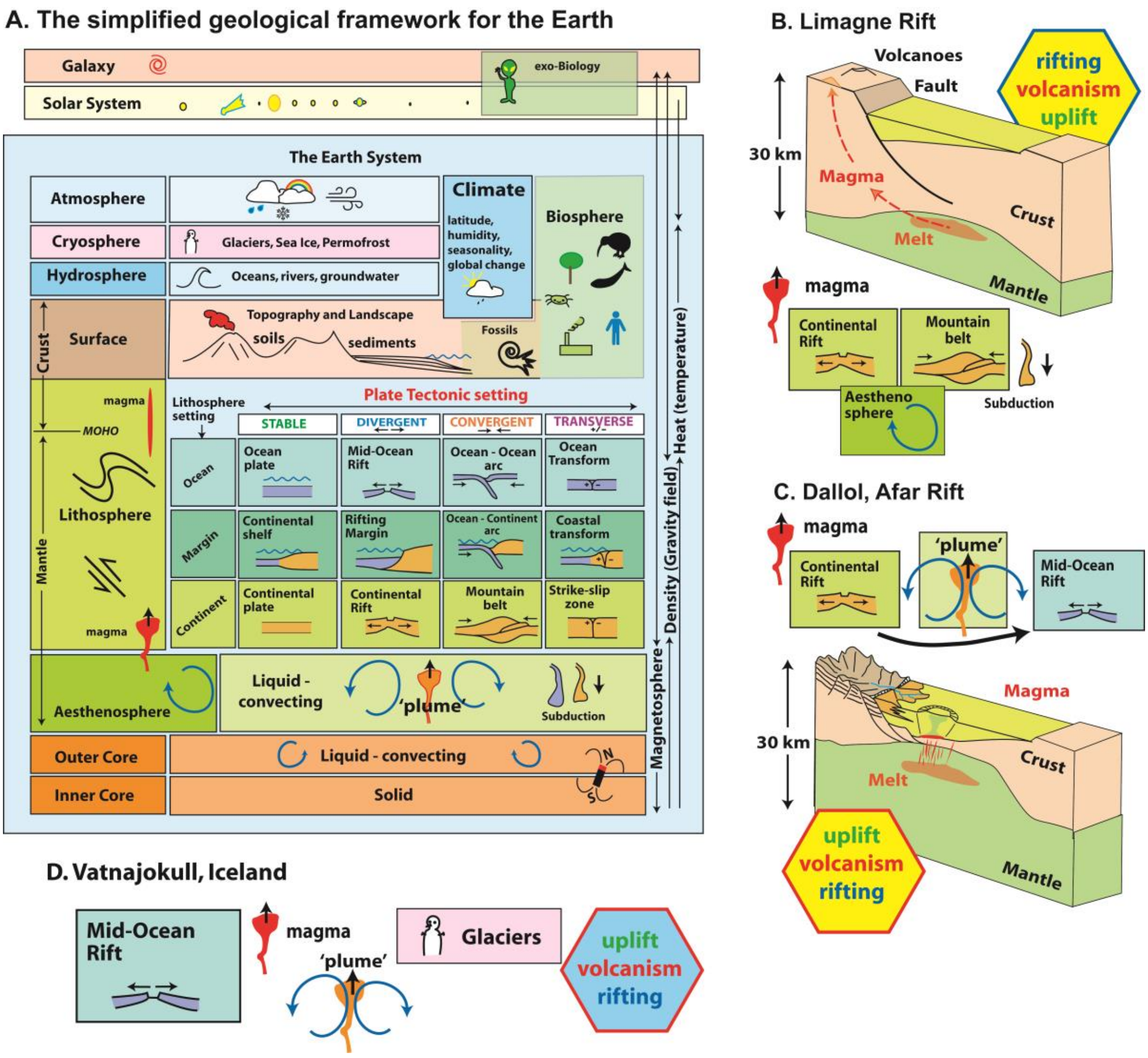

Figure 1. The global geological framework for the Earth. **A**. The framework table going from the core to the galaxy. **B**. The Limagne rift and is extracted context. **C**. Dallol, Afar rift. **D**. Vatnajökull, on the Mid-Atlantic ridge.

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