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Oral Presentation Programme

Monday 23 May 2016	
08.30	**Registration & tea & coffee (Main foyer and Lower Library)**
09.00	**Introduction**
	The Wilson & Supercontinent Cycles
09.10	**KEYNOTE: The Wilson Cycle Of the Opening and the Closing of the Ocean Basins** Kevin Burke (University of Houston, Texas, USA)
09.40	**Geo-Constraints on and confirmation of the operation of the Wilson Cycle since the Neoarchaean** Brian Windley (University of Leicester, UK)
10.00	**Mesoproterozoic terrane collision in the Namaqua belt of south-western Africa - Time for revision of deeply entrenched views?** Steffen Büttner (Rhodes University, South Africa)
10.20	**The Classic Wilson Cycle Revisited** Ian W.D Dalziel (The University of Texas at Austin, Texas, USA)
10.40	**Tea, coffee, refreshments and posters (Lower Library)**
	Record of the Wilson Cycle
11.00	**KEYNOTE: Dyke Swarms of the Canadian Shield: Initial Stages of Precambrian Wilson Cycles?** Henry C. Halls (University of Toronto Mississauga, Canada)
11.30	**A revised 300 Ma geodynamic history for the Iapetian Wilson cycle, based on Hf isotope arrays.** Bill Collins (The University of Newcastle, Australia)
11.50	**Sea level reconstruction from Strontium isotopes; a record of the Wilson Cycle back to the Neoproterozoic** Douwe van der Meer
12.10	**Natural Resource Evaluation within a Global Tectonic Framework: The Past is the Key to the Future** G.R. Nicoll (Halliburton)
12.30	**KEYNOTE: Lithospheric rheology and tectonic style in the Wilson Cycle** John Dewey (University College Oxford, UK)
13.00	**Lunch and posters (Lower Library)**
	Geodynamic Models and Tectonic Reconstructions
14.00	**KEYNOTE: Geodynamic models highlighting the roles of inheritance during a Wilson Cycle** Susanne Buiter (Geological Survey of Norway and University of Oslo, Norway)

14.30	**A Phanerozoic deformable tectonic plate reconstruction model for the Atlantic margins** John Watson
14.50	**Continent-Ocean Boundaries…the end of the line?** Lucia Pérez-Díaz (Royal Holloway University of London, UK)
15.10	**Deformable Plate Reconstructions Provide Insights into the Influence of Structural Inheritance on Continental Breakup and Ocean Formation** Bridget Ady (GeoArctic Ltd)
15.30	**Tea, coffee, refreshments and posters (Lower Library)**
	Basement Inheritance and Reactivation
15.50	**KEYNOTE: Structural inheritance during basin formation and deformation in continents** Mike Daly (University of Oxford, UK)
16.20	**The Sarandí del Yí Shear Zone, Uruguay: crustal reworking of the Río de la Plata Craton margin during Western Gondwana assembly** Sebastián Oriolo (Universität Göttingen, Germany)
16.40	**Late Palaeozoic extensional reactivation across the Rheic-Rhenohercynian suture zone in SW England, the English Channel and Western Approaches** Andrew Alexander (Siccar Point Energy Limited)
17.00	**A half-turn in the Wilson Cycle: the role of inheritance at the Mid-Norwegian margin** Per Terje Osmundsen (Geological Survey of Norway, University Centre in Svalbard and University of Oslo, Norway)
17.20	**Examining the relative roles of basement inheritance, plate boundary forces and intraplate geodynamics: the brittle deformation record of Paleozoic platform rocks of east central North America** Alexander Cruden (Monash University, Melbourne, Australia)
17.40	**KEYNOTE: From orogen to rift: The role of reactivation and reworking.** Haakon Fossen (University of Bergen, Norway)
18.10	**Discussion**
18.30 – 19.30	**Wine reception (Lower Library)**
Tuesday 24 May 2016	
08.30	**Registration and tea & coffee (Main Foyer and Lower Library)**
	Mantle Convection and Plate Movements
09.00	**KEYNOTE: The long-wavelength mantle structure and dynamics and implications for large-scale tectonics and volcanism in the Phanerozoic** Shijie Zhong (University of Colorado, USA)
09.30	**What happens to isotopically distinct mantle during the Wilson cycle?** Tiffany Barry (University of Leicester, UK)
09.50	**Lasting Mantle Scars lead to Perennial Plate Tectonics** Philip J. Heron (University of Toronto, Canada)
10.10	**The Stability of Tibetan Mantle Lithosphere** Gregory Houseman (University of Leeds, UK)
10.30	**Tea, coffee, refreshments and posters (Lower Library)**

	Inheritance and Rheology in Continental Tectonics
11.00	**KEYNOTE: Structural reactivation in plate tectonics: the roles of rheological heterogeneity and anisotropy in the mantle** Andréa Tommasi (Université Montpellier & CNRS, France)
11.30	**Orogenic inheritance and continental breakup: Wilson Cycle-control on rift and passive margin evolution** Christian Schiffer (Aarhus University, Denmark and Durham University, UK)
11.50	**The role of pre-existing rheological heterogeneities during the rifting to drifting process: insights from 3D laboratory experiments** Nicolas Molnar (Monash University, Melbourne, Australia)
12.10	**Controls on strain localisation in natural rifts** Rebecca Bell (Imperial College London, UK)
12.30	**KEYNOTE: Constraints from GPS observations on the balance of forces in the deformation of Anatolia and the Aegean** Philip England (Oxford University, UK)
13.00	**Lunch and Posters (Lower Library)**
	Tectonic Weakening and Localisation
14.00	**What is actually 'breakup'? Can we define a recipe of how to break the lithosphere?** Gwenn Peron-Pinvidic (NGU Geological Survey of Norway, Norway)
14.20	**Possible role of salt accumulations in Wilson cycles** Martin Hovland (Tech Team Solutions)
14.40	**Fault strength and deformation-induced weakening: estimates from India and the northern UK** Alex Copley (University of Cambridge, UK)
15.00	**The role of structural inheritance in controlling the structural evolution and consequences for prospectivity of the Utsira High, Southern Viking Graben** Rachael Hunter (Herriot Watt University, Edinburgh, UK)
15.20	**Reactivation of intrabasement structures during multiphase continental rifting – Implications for the geometry and evolution of rift systems** Thomas Phillips (Imperial College London, UK)
15.40	**Tea, coffee, refreshments and posters (Lower Library)**
	Tectonic Inheritance on Passive Margins
16.00	**KEYNOTE: Unusual examples of continental break-up on the North American margin** Erik Lundin (Statoil Research Centre, Norway)
16.30	**Revisiting the Wilson Cycle in the North Atlantic: The importance of inheritance** Pauline Chenin
16.50	**KEYNOTE: Tectonic inheritance at multiple scales during 2+ Wilson cycles recorded in eastern North America** William A. Thomas (Professor Emeritus, University of Kentucky, USA and Visiting Scientist, Geological Survey of Alabama, USA)

17.20	**SDR dominated rifting in the southern segment of the South Atlantic: a high-strain, narrow rift?** Lidia Lonergan (Imperial College London, UK)
17.40	**Does Crustal Architecture Play a Role in the Location of Continental Break-up?** Alicia Stammer (University of Leeds)
18.00	**KEYNOTE: The Concertina Coast: the role of basement inheritance during repeated reactivation events along Australia's northern margin since the Permian** Myra Keep (The University of Western Australia, Australia)
18.30	**Discussion**
Wednesday 25 May 2016	
08.30	**Registration and tea & coffee (Main Foyer and Lower Library)**
	Arctic
09.00	**KEYNOTE: Evolution of the Arctic fold belts** Sergey Drachev (ArcGeoLink)
09.30	**Basin development in Earth's earliest Rifted Margins: the initial Palaeoproterozoic opening and closure of Baffin Bay, Davis Strait and Labrador Sea** John Grocott (University of Durham, UK)
09.50	**Tectonic inheritance during extension in rifts and passive margins: a Greenland case study** Woody Wilson (BP)
10.10	**Long-lived fault systems and their influence on the rift architecture of the NE Atlantic Margin and Barents Shelf** Stephen Rippington (Astute Geoscience Ltd)
10.30	**Tea, coffee, refreshments and posters (Lower Library)**
	Tethys / Gondwana
10.50	**KEYNOTE: Tectonic Inheritance in the Alps and the Pyrenees: The Role of Post-Hercynian Strike-Slip systems and the Palaeo-Tethys** A. M. Celâl Şengör (Eurasian Institute of Geology)
11.20	**Wilson Cycle: it relevance to S Neotethys in the E Mediterranean region and the role of structural inheritance/ re-activation in the assembly of the Kyrenia lineament, N Cyprus** Alastair Robertson (University of Edinburgh, UK)
11.40	**Continental strike slip fault zones in geologically complex lithosphere: the North Anatolian Fault, Turkey** David Cornwell (University of Aberdeen, UK)
12.00	**The most notable Alpine tectonic phases during Maghrebides orogeny in the Kabylian domain (Centre-East of Northern Algeria)** Sahra Aourari
12.20	**The origin of the Bitlis Massif and its importance for the understanding of the northern convergent plate boundary of the Arabian Plate** Jeremy Goff (BP Exploration)
12.40	**U-Pb zircon geochronology of Daraban Leucogranite, Mawat ophiolite, northeastern Iraq: A record of subduction to collision history for Arabia-Eurasia plates** Yo Mohammad (University of Gothenburg, Sweden)
13.00	**Lunch and Posters (Lower Library)**

	Subduction in the Wilson Cycle
14.00	**KEYNOTE: The Wilson Cycle: the subduction initiation stage** Robert Hall (Royal Holloway University of London, UK)
14.30	**Temporal plume-intracontinent and plume-slab interactions explain tectonic history of East Asia during Cretaceous** Changyeol Lee (Chonnam National University, Republic of Korea)
14.50	**3D Wilson cycle: structural inheritance and subduction polarity reversals** Stephane Beaussier (Geological Institute, Zurich, Switzerland)
15.10	**Subduction initiation in the Appalachian-Caledonide system: Implications for the Wilson Cycle** John Waldron (University of Alberta, Edmonton, Canada)
15.30	**Tea, coffee, refreshments and posters (Lower Library)**
	Understanding Supercontinent cycles
16.00	**Interpretation of Appalachian-Variscan Ophiolite Complexes: A tweeter in woofer's clothing?** J. Brendan Murphy (St. Francis Xavier University, Antigonish, Canada)
16.20	**Tectonic Evolution of the Gulf of Mexico and Caribbean Region: not an open and shut case** Jim Pindell (Rice University)
16.40	**Two many oroclines in Iberia? A Pangea's simple twist of fate** Daniel Pastor- Galán (Utrecht University, The Netherlands)
17.00	**KEYNOTE: Tom Worsley and the origin of The Supercontinent Cycle** R. Damien Nance (Ohio University, Ohio, USA)
17.30	**Discussion**
17.45	**Closing remarks**
17.50	**End**

Oral Presentation Abstracts

The Wilson Cycle Of the Opening and the Closing of the Ocean Basins

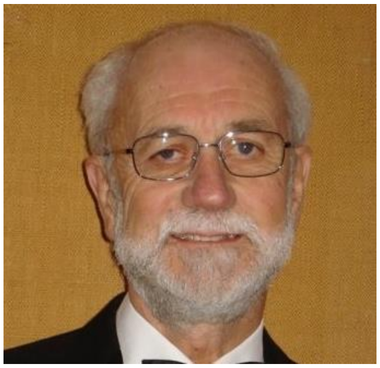
Kevin Burke
University of Houston TX USA

After publishing “Did the Atlantic Close and then Reopen? “(1) Wilson thought about the question: “How can the plate tectonic history of the Earth be deciphered for times earlier than the oldest *in situ* Ocean floor?” His answer (2) was: “In terms of rocks and structures characterizing stages in the Life Cycle of the Ocean Basins “, which soon came to be called “The Wilson Cycle” (3). Only fragments of continents and no *in situ* ocean floor fragments are preserved from pre-oldest Ocean floor times. Suture zones with their related orogenic belts reveal the more ancient record of the life cycle of the ocean basins. Those suture zones locally preserve tectonic slivers of rocks representative of the other stages of the cycle but sutures may also be locally cryptic and represented only by a shear zone juxtaposing the rocks, of two continents (one with reactivated crust) that have collided. Cryptic lengths of suture zones exceed 1500 km. Illustrative suture zones and orogenic belts referred to in this presentation include: The Circum Superior Province suture zone in the Canadian Shield, the Gariep-Beatty-Malawi suture zone of Panafrican age in Southern Africa, the Circum West African craton suture zone of Panafrican age, The Great Indian Proterozoic fold belt (including the Eastern Ghats) and the Caledonides of Scandinavia and the British Isles with their continuation in the Appalachians. Deformed alkaline rocks and Carbonatites complement ophiolitic slivers in marking suture zones. Potential field (gravity,magnetic and heat flow) maps reflect suture zone structure. The Witwatersrand is the oldest preserved foreland basin associated with an ancient orogenic belt. Younger rifts are concentrated on older suture zones (1) so that most orogenic belts are much wider than they were at collision. Wilson’s comprehensive and seminal idea provides the model to be tested in research on ancient orogenic zones. Supercontinents are: ” Assemblies of all the (at the time existing) continental lithosphere in a single continent”(4). Pangea, lacking only N. and S. China was briefly a supercontinent assembled by Wilson cycle processes but all older “Supercontinents”appear to have been incomplete assemblies made by Wilson Cycle processes. Rodinia was incomplete because India, Madagascar and much of East Africa became part of Gondwana only at ~ 500Ma (5).

Succinct Refs.(1) Wilson, NATURE1966 (2) Wilson 1968. See Repro. In Burke AREPS 2012 (3) Dewey and Burke GEOLOGY 1974 (4) Burke 2007 SCIENCE “Dancing continents”(5) Gregory et al.2008 PreC Geology 2008.

NOTES

Geo-Contraints on and Confirmation of the Operation of the Wilson Cycle since the Neoarchaean



Brian Windley[1], Tim Kusky[2]

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The Archaean was dominated by crustal accretion for 1.5 Ga, but by the Neoarchaean small areas were beginning to stabilise to form incipient landmasses that were able to mutually separate and serve as stable platforms for shallow marine shelf sediments against an open ocean followed by subduction and arc volcanism. Further accretion and crustal growth by 2.5 Ga enabled the first modern-style Wilson Cycles to develop with intrusion of trans-continental dyke swarms, continental rifting, the opening of oceans, formation of stable shelves on continental passive margins, MORB basalts, ocean plate stratigraphy, subduction and formation of juvenile island-to-mature continental arcs, accretionary wedges, supra-subduction zone ophiolites, exhumation of eclogites, continent-continent collisions and sutures, and post-collisional crustal melt granites. Thus evidence for and constraints on the early operation of the Wilson Cycle come from a whole gamut of geo-data. Significantly many rock-groups resulting from the above events occur in a predictable sequential and/or time order within Phanerozoic orogens, and in the same order in Proterozoic orogens. Likewise, magmatic rocks that have diagnostic geochemical-isotopic signatures in modern orogens, like alkaline basalts in rifts, OIB in mid-oceanic islands, IAB in juvenile-mature arcs, basalts in ophiolites, calc-alkaline tonalites in continental arcs, and alkaline post-collisional granites have similar trace-element characteristics in Proterozoic equivalents. Seismic sections of continental crust across Phanerozoic orogens typically mark sutures, which are mirrored in seismic profiles across Proterozoic orogens. Because all these crustal growth products were the result of specific tectonic processes within the modern Wilson Cycle, it would be surprising if similar processes were not in operation in earlier times. But the exigencies of a higher heat flow and hotter mantle in the early Earth necessitate some variations in the styles of crustal and tectonic evolution. This talk will emphasize differences in the geological-geophysical make-up of the upper and lower crust, which we must consider in any evaluation of the history of the Wilson Cycle. More emphasis should be placed on ocean plate stratigraphy, which documents the travel history of an ocean from ridge to trench. This is one of the prime processes of the Wilson Cycle that can be recognised in orogens from the Archaean to Cenozoic.

NOTES

Mesoproterozoic terrane collision in the Namaqua belt of south-western Africa - Time for revision of deeply entrenched views?

SH Büttner
Rhodes University

In the 1980s, when terrane accretion tectonics were a novel concept, the Namaqua belt in South Africa and Namibia was interpreted as a province of amalgamated tectonic terranes that developed in a Mesoproterozoic Wilson-cycle type context. Main arguments were the different lithostratigraphy in different regional entities, and the presence of regional shear zones separating these “terranes”. At about 1200 Ma a major collision event was proposed to have taken place.

In the last decades a wealth of data has become available that appears in conflict with this interpretation, and still no direct evidence of collision-related tectonics or metamorphism exists in the Namaqua belt (e.g., suture zones with ophiolites and/or HP-metamorphism). Nevertheless, most literature places new findings into a collisional orogenic context.
The evolution in the Namaqua belt is characterised by long-standing HT-LP metamorphism (~>700°C/5-6 kbar) that existed over ~250-350 million years. Sapphirine and osumilite indicate UHT conditions in places. The HT/UHT peak is always followed by an episode of isobaric cooling, and the petrologic record ends with equilibration at upper amphibolite facies conditions. Rapid vertical crustal movement has not been demonstrated for the Namaqua belt. HT/UHT episodes took place at ~1299-1351 Ma and, predominantly, at ~1200 Ma, followed by a further heat pulse at 1100 Ma. Elsewhere HT- and UHT-metamorphism may have taken place as late as ~1030-1080 Ma, but there seems not to be any spatial or regional pattern related to the proposed “terranes”. Similar variation in regional distribution and age exists for the generation of granitic magma. The orogenic evolution ends with pegmatite swarms (~950-1000 Ma). T_{DM} ages in all “terranes” reach back to the Palaeoproterozoic (~1.9-2.2 Ga).

Regional deformation patterns include large-scale dome-and-basin structures and complex polyphase folding and shearing that developed over several contractional and extensional phases. These structures post-date the 1200 Ma (“collisional”) thermal and magmatic event, but mostly pre-date the 1100 Ma plutonism. At orogen scale different crustal entities were juxtaposed along regional ductile shear zones.

The long-lasting HT/UHT history between ~1350 and 1000 Ma with slow cooling and heating episodes at near-constant pressures, and the regional deformation events postdating the thermal peak, are not well compatible with crustal thickening and continent collision processes. By contrast, all observed features in the Namaqua belt are well compatible with extensional and contractional episodes, and regionally and chronologically variable heat influx in a back-arc mobile belt near continental margins of Mesoproterozoic Rodinia.

NOTES

The Classic Wilson Cycle Revisited

Ian W.D Dalziel[1] and John F. Dewey[2]
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2. University College, High Street, Oxford OX1 4BH, UK.

When the authors were undergraduate students in the 1950's, the distinction between the olenellid benthic trilobite faunas of northern Scotland and the Great Northern Peninsula of Newfoundland on the one hand, and the benthic redlichiids of England and the Avalon Peninsula of Newfoundland on the other, were explained by some type of geographic barrier. Had there been a deep ocean basin separating the two faunas, or perhaps a 'geanticline'? It was in the first application of developing plate tectonic theory to the pre-Pangaea world that fifty years ago J. Tuzo Wilson asked the question: "Did the Atlantic close and then reopen?", the basis of the concept of the "Wilson Cycle".

The accordion-like motion of the continents bordering the Atlantic envisioned by Wilson in the 1960's, with proto-Appalachian Laurentia separating from Europe and Africa during the early Palaeozoic in almost exactly the same position that it subsequently returned during the late Palaeozoic amalgamation of Pangaea, now seems an unlikely scenario. Nonetheless many modern reconstructions still cling to this concept which demands a wide Iapetus Ocean during the Ordovician Period. Indeed such continental separation has been invoked as an explanation for the "Great Ordovician Diversification Event".

However, the palaeomagnetic data for early Palaeozoic times can equally well be satisfied by changing the relative palaeolongitudes of the Iapetus-bordering continents so that proto-Appalachian Laurentia is opposed to proto-Andean South America. In this case the Iapetus Ocean would have been far narrower. Indeed there is now increasing evidence that the Grenvillian orogens of present-day eastern North America and western South America were juxtaposed at the end of Precambrian times and that the Iapetan margins of Laurentia and Gondwanaland intereacted tectonically during the early Palaeozoic with the Precordilleran (or Cuyania) terrane of northwest Argentina being a Laurentian fragment derived from the Ouachita embayment in the Laurentian margin.

In this contribution we will integrate the well known Palaeozoic history of the continents currently bordering the North Atlantic Ocean basin with that of the southern continents to present a radically revised scenario of the classic Wilson cycle. Tuzo Wilson's concept of ocean basin opening and closing is retained, but the process we envisage additionally involves thousands of kilometers of motion parallel to the margins of the opposing continents as well as more complex tectonic interaction between them.

NOTES

Dyke Swarms of the Canadian Shield: Initial Stages of Precambrian Wilson Cycles?

Henry C. Halls
Department of Chemical and Physical Sciences
University of Toronto

If plate tectonics has operated at least to early Proterozoic times, examples of Wilson cycles prior to the one described by Wilson, should be identifiable. In comparison to the opening and closing of the Proto-Atlantic ocean between ~ 700 and ~300 Ma, earlier manifestations of the Wilson cycle are cryptic owing to a more incomplete geological record. Here we examine events that may have heralded the onset or termination of a Wilson cycle. The most commonly preserved remnants of rifting events in the Precambrian are dyke swarms which survive erosion because they represent the deep, plumbing system of igneous activity. Evidence of major rifting around cratonic nuclei in the Precambrian is best seen in the Archean Superior Province of Canada, and other smaller cratons (e.g. Slave, Dharwar, Zimbabwean, Kaapvaal and Yilgarn) that are criss-crossed by multiple episodes of swarms. In the Superior Province, and most of the other Archean cratons, the swarms are interpreted, following Burke and Dewey (1973), as “failed arms” of hot spot - generated triple junctions that evolved along the craton margins. Often the dykes radiate from the focus or area above the presumed hot spot and after several hundred kilometers, gradually die out in the craton interior. Approaching the craton margin the dykes become more altered, and are ultimately covered by sedimentary sequences or terminate at orogenic fronts. All of the failed arm dyke swarms in the Superior Province have significantly different (>50 Ma) ages from neighbouring foci, so that a line of hot spots with similar ages that would define the trend of a rifted margin is not found. Five Canadian examples of potential Precambrian Wilson cycles will be discussed which involve “failed arm” dyke swarms (the 2.45 Ga Matachewan, 2.1 Ga Marathon and the 1.27 Ga Mackenzie swarms), and collisional orogens (~1.8 Ga Trans Hudson and ~1.05 Ga Grenville).

NOTES

A revised 300 Ma geodynamic history for the Iapetian Wilson cycle, based on Hf isotope arrays.

Bonnie J. Henderson[1,2], **W.J Collins[2]**, J. Brendan Murphy[3], Martin Hand[1]

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2. NSW Institute for Frontier Geoscience, University of Newcastle, Newcastle, Australia
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Since Wilson's 1966 proposal for a proto-Atlantic (Iapetus) Ocean along the eastern margin of Laurentia, geologists have variably constrained the timing of ocean opening to the Late Neoproterozoic, most recently to ~615 Ma. A compilation of hafnium isotopic arrays for detrital and magmatic zircons from Avalonia and Ganderia in the northern Appalachians, and comparisons with Hf isotopic data compilations from cratonic Amazonia, Baltica and Laurentia permits recognition of earlier events, including the opening of a "Proto-Iapetus" Ocean at ~750 Ma.

Geological similarities between Ganderia and Avalonia are confirmed by Hf arrays and show that both initiated near the former Grenville suture, probably along the Laurentian margin, not from Gondwana as commonly thought. Moreover, the presence of in situ 750 Ma calc-alkaline granites in Avalonia requires that subduction had begun by at least 750 Ma. Indeed, the zircon age spectrum for Avalonia extends continuously from ~400 Ma to 800 Ma, overlapping with the final stages of suprasubduction zone magmatism in the Valhalla Orogen (~870-740 Ma), to the north.

We suggest that southward propagation of Valhalla subduction initiated a continental-type arc between ~800-750 Ma in the former Grenville orogen, along the Laurentian margin. Penecontemporaneously, the Asgard Sea progressively opened as Baltica and Amazonia drifted from Laurentia. Geodynamically, the setting is similar to Paleo-Tethys opening after Pangea amalgamation. A uniform shift in the Hf isotope array toward more juvenile values between 800-700 Ma suggests the Avalonian/Ganderian arc retreated to form a thinned microcontinental ribbon at least by 700 Ma. Extension-related 760-680 Ma alkaline granites in the central Appalachians attests to ongoing subduction retreat. The intervening backarc basin became the Proto-Iapetus Ocean.

Between ~750-650 Ma, the continental ribbon transferred by subduction retreat across the Asgard Sea, closing it and colliding with the Gondwanan margin at ~650 Ma, consistent with paleomagnetic, geological and paleontological evidence. Accretion of the ribbon is also reflected in the reversal of εHf values to progressively more negative values between 650-600 Ma, which is also recorded in other northern peri-Gondwanan terranes, such as Iberia and Cadomia.

Avalonia and Ganderia separated from Gondwana by about 500 Ma, forming the Rheic Ocean. These terranes show a Hf isotopic trend toward more juvenile values, again consistent with crustal thinning during arc retreat. Avalonia migrated northward, initially closing the Tornquist Sea as it collided with Baltica, then closing Iapetus as it finally re-amalgamated with Laurentia. Thus, the Hf isotope arrays permit recognition of hitherto unrecognized earlier events. Proto-Iapetus and Iapetus together have a 300 Ma-long history recorded by zircons in the adjacent, retreating arc systems, and neither formedby Atlantic-style ocean-opening.

NOTES

Sea level reconstruction from Strontium isotopes; a record of the Wilson Cycle back to the Neoproterozoic

Douwe van der Meer
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Plate tectonics result in the opening and closing of oceans, termed the 'Wilson Cycle', resulting in sea-level variation through time. Published eustatic sea level curves of the seventies and eighties have caused a scientific breakthrough and emergence of sequence-stratigraphy as hydrocarbon exploration tool. However much debate has taken place on the validity of the curves as reconstructing a global average eustatic sea level is hampered by a non-agreement of sampled sites due to differing local tectonics, deposition and long wavelength dynamic topography as a result of mantle convection. In particular, the overall amplitude of global Phanerozoic long-term sea-level is poorly constrained and has been estimated to vary between ~400m above sea level to ~50 m below sea level. In order to overcome the current limitations of sea level reconstruction, we propose an alternative method to estimate global sea-level change. We utilise the Phanerozoic-Neoproterozoic $^{87}Sr/^{86}Sr$ record, which at first order represent the mix between inputs from continental weathering and mantle input by volcanism. By compensating for weathering with runoff estimates from the 3D climate model GEOCLIMtec, the corrected $^{87}Sr/^{86}Sr$ record reflects mantle input variation only. By applying linear oceanic plate age distributions, we obtain a sea level and continental flooded area curve. When compared with other sea level and flooded area curves, we observe that our results are generally within the range throughout the Phanerozoic. A Phanerozoic first order Wilson cyclicity of ~250 Myr is observed, possibly extending into the Neoproterozoic. We propose that the here obtained first-order sea-level curve, is used as base line for sequence-stratigraphic studies at global and basin scale.

NOTES

Natural Resource Evaluation within a Global Tectonic Framework: The Past is the Key to the Future

G. R. Nicoll, J.C. Wrobel-Daveau, and G. Baines
Halliburton

Plate tectonics and the supercontinental cycle represent a fundamental geological paradigm that can be used to better understand and predict the formation of hydrocarbon and mineral resources and help reduce geological uncertainty and financial risk during exploration.

Understanding the tectonic evolution of a region requires the synthesis of many disparate datasets; a rigorous approach to organizing data can allow geologists to rapidly examine and gain insight from all available data sources. For example, the temporal and spatial distribution of mineral deposits can be examined to provide key insight into global tectonic cycles and regional manifestation. The assembly and breakup of supercontinents can be investigated by considering porphyry copper deposits occurring above subduction zones, gold deposits forming in orogenic belts, tin-tungsten deposits in collapsing orogens, and some diamond-bearing kimberlites in prerift settings.

Such well-constrained temporal and spatial data have been used to build a global geodynamic model. This robust plate tectonic model provides a framework within which theories for the formation of known mineral deposits and their relationships to continental cycles can be tested.

As an example, the model can be used to identify Phanerozoic volcanic arc systems related to subduction. Detailed plate boundary definitions contained within the geodynamic model enable the construction of cumulate tectonic intensity maps that highlight areas of enhanced thermal activity, which can be considered a proxy for associated mineral rich fluid flow. The concepts of long-lived inheritance and reactivation of older structures can also be analyzed with these tools, highlighting the economic importance of these concepts in terms of achieving future exploration success. These model outputs show remarkable agreement with more than 85% of the known Phanerozoic porphyry and epithermal deposits at the regional scale, and the finer grained details show where potential new economic deposits could be located under cover.

NOTES

Lithospheric rheology and tectonic style in the Wilson Cycle

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The Wilson Cycle was named by Burke and Dewey in honour of Tuzo Wilson's suggestion that the Atlantic opened along the Appalachian/Caledonian site of Palaezoic continental collision, following the closure of an ocean (iIapetus) that had opened during the early Cambrian, a roughly concertina kinematics. However, Burke and Dewey's notion of the "Cycle" is not a simple "accordion" but, rather, a consequence of the complex kinematics of plate tectonics and the 300 My cycle of assembly and disruption of supercontinents yielding an immensely variable sequence of events and tectonic pathways from rifted continental margins through continent/arc collision to continent/continent collision, The immense spatial and temporal geological variability of orogenic structure and history partly results from the pathway kinematics of plate tectonics during the Wilson Cycle but also from the derivative thickness, layering, petrology, and rheology of the lithosphere, which cools and thickens with age. Quartz in the continental crust and olivine in the mantle are the principal controls on the interaction between the Byerlee fracture line and creep that generate "Christmas tree sailboards, and brittle/hard/strong, and ductile/soft/weak layers. Felspar-dominant and mafic underplates yield further rheological complexity. Metamorphic phase changes, especially in the blueschist and eclogite facies can yiel. fast and massive rheological changes. The argument that contrasts the "jelly sandwich" and "crème brulee" models is sterile because there is an enormous range of sailboards from the strong thick almost earthquake-free Archaean cratons to the hyper-extended rifted margins. In our view, the small number of earthquakes in the continental mantle is because lithospheric stresses are too low to intersect the Byerlee line, and temperatures and dryness prevent creep; hence the mantle is the dominant stress guide. Only in flexure, long wave-length lithospheric buckling, in hydrated mantle above subducion zones, and in very thin lithosphere can stresses become sufficiently large to generate earthquakes in the mantle. Flexural thickness of the lithosphere determines the stratigraphical history of foreland basins,peripheral bulges, and thick versus thin-skinned foreland fold-thrust belts. We illustrate these principles with an array of sailboards from a wide range of tectonic environments in a full "Wilson Cycle".

NOTES

Geodynamic models highlighting the roles of inheritance during a Wilson Cycle

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The Wilson Cycle is a fundamental concept in plate tectonics. The theory posits that subduction between an ocean and a continent initiates at a rifted continental margin, followed by closure of the ocean, and that future continental extension localises at the ensuing collision zone. Each stage of the Wilson Cycle will therefore be influenced by and develop its own structural and thermal heterogeneities. Here we use numerical experiments to investigate the role that the Wilson Cycle has in creating lithospheric heterogeneities and how these influence later stages of the cycle.

Rifted continental margins are likely locations for subduction initiation because inherited faults and locally-exhumed mantle create a region of relatively weak and thinned crust compared to typical continental crust. Conversely, rifts may localise on former collision zones for several reasons: orogens are thermally weak because of the increase in heat producing elements in their thicker crustal root, the inherited thrust faults form large-scale heterogeneities for rifts to initiate on, or extensional collapse of young orogens may lead to continental rifting. The present-day margins of the Atlantic and Indian Oceans illustrate that continental break-up can occur on both relatively young and very old sutures, such as Morocco–Nova Scotia and East Antarctica–Australia, respectively.

We highlight the impact of collision zone inheritance on continental extension and rifted margin architecture with geodynamic experiments of a Wilson Cycle of subduction, collision, and extension. We find that crustal rheology and the amount of coupling over the subduction interface exert first-order controls on the size of the collisional orogen. We employ a weakly-coupled subduction interface which allows continental crust to subduct to sub-Moho depths and build a mountain root. When extension occurs, the weak former subduction interface and the elevated temperatures in the crustal nappe stack work in tandem as the main localisers of deformation during continental rifting. Compared to rifting of undisturbed, laterally homogeneous continental crust, Wilson Cycle inheritance results in different dynamics of the crust and mantle, thereby impacting rift geometry, rift to break-up duration, and exhumation of subduction-related sediments and oceanic crust.

NOTES

A Phanerozoic deformable tectonic plate reconstruction model for the Atlantic margins

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Plate tectonic reconstructions are essential for placing geological information in its correct spatial context, understanding depositional environments, and for defining basin evolution. Furthermore tectonic reconstructions serve as the basis for palaeogeographic mapping. Traditional plate reconstructions perform rigidly which results in misfits between juxtaposed plate margins when restored to their past positions. This problem can be attributed to deformation prior to and during continental rifting and/or collision and continent-ocean boundary identification adds further to the problem of creating an accurate ‘fit’ between plates.

Plate tectonic reconstructions of the Atlantic margins without deformation taken into account are particularly problematic. The tectonic history of the Atlantic is complex with several crustal deformation events throughout the Phanerozoic. This is especially true for the rifting history of the North Atlantic margins prior to their Cenozoic breakup. To the south a triple junction spreading axis in the Central Atlantic propagated northwards separating Iberian and Newfoundland crust causing an anomalously large amount of crustal extension and exhumation of mantle material before splitting to form the Labrador/Baffin seaway and the aforementioned Cenozoic North Atlantic breakup. The Jurassic opening between West Africa and Eastern North America is complicated by the transtensional and transpressional history of Northwest Africa and its conjugate, while the Equatorial and South Atlantic openings are affected by internal Mesozoic shearing of Central Africa and the eastward encroachment of the Caribbean fragments to the northwest.

The research presented here is a deformable plate tectonic model for the entire Atlantic system within the framework of a rigid global plate model. The deformable modelling incorporates stretching (β) and shortening factors to calculate the extent of crustal deformation during the Atlantics pre- and syn-breakup events. Detailed geophysical and geological datasets, combined with published data have been used to constrain the Atlantics tectonic history and the deformable modelling is set in a global hybrid reference frame, allowing reconstructions back to the Latest Precambrian (550 to 0 Ma). Continent ocean boundary conditions have been constrained by in-house gravity modelling which in turn has been integrated with magnetic anomaly data to constrain breakup and subsequent post-breakup ocean basin formation.

The culmination of our modelling is a fully deformable Atlantic plate kinematic model allowing the reconstruction of geo-referenced datasets along with the tectonic plates to predict their palaeo-locations and geometries.

NOTES

Continent-Ocean Boundaries…the end of the line?

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The idea of a simple linear boundary between continental and oceanic crust is widely recognised as an oversimplification. Despite this, such boundaries continue to be mapped because of their perceived utility in palinspastic and plate kinematic reconstructions. To examine whether this perception is justified, we map more than 150 published continent ocean boundary estimates for extended margins globally. The maps show that the location of the continent ocean boundary is rarely consistently estimated within the ~10—100 km observational uncertainty that might be expected of the geophysical data used for doing so, and that the geographical range of estimates exceeds the width of single-study continent ocean transition zones. Instead, the global average disagreement between sets of three or more estimates is 167 km, and for the most part comes from interpretations published over the last decade. We interpret this to indicate an extra component of uncertainty that is related to authors' understanding of the range of features that are interpretable at extended margins under the constraints of currently available data and models of continental plate divergence. We go on to discuss the consequences of this uncertainty with examples from the literature and from the South Atlantic ocean. We conclude that a precise continent ocean boundary concept with locational uncertainty defined from the ensembles is of limited value for palinspastic reconstructions because the restoration process tends to bunch the ensemble within a region that is (i) of similar width to the observational uncertainties associated with continent ocean boundary estimates, (ii) narrower than the regions of uncertainty about rotated features implied by the propagation of uncertainties from plate rotation parameters, and (iii) coincident, within all the above uncertainties, with the more-easily mapped continental shelf gravity anomaly. Secondly, we conclude that estimated continent ocean boundaries are of limited use in developing or testing plate kinematic reconstructions because (i) reconstructions built using them as markers do not, within uncertainty limits defined from the ensembles, differ greatly from those using more-easily determined bathymetric or gravity anomaly contours, and (ii) because it is impossible to segment and date them with useful precision to use as markers of the edges of rigid oceanic lithosphere outside of the constraints of a pre-existing plate kinematic model.

NOTES

Deformable Plate Reconstructions Provide Insights into the Influence of Structural Inheritance on Continental Breakup and Ocean Formation

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Deformable plate reconstructions can further our understanding of the role of structural inheritance and the Wilson Cycle processes of rifting and mountain building in continental breakup and the formation of new oceans. Recent advances in deformable plate reconstruction methods provide us with accurately restored pre-breakup margin geometry, more detailed restored and reconstructed basement and structure maps, and the history of lateral strain and crustal thinning across the margin. This enables us to examine pre-existing structures and their role in break-up including: the evolution and orientation of rifting events; the reactivation of sutures and thrust fronts; the interplay between sutures of various ages; and the activation of major transforms from pre-existing sutures.

Rigid plate kinematic models alone do not adequately model the complex multiphase break-up history of margins. As continental crust is extended in rifted margins prior to breakup there is plate overlap along these margins when reconstructed using rigid plate kinematic models. In convergent margins shortening of the plates takes place and underfit occurs. We use a new quantitative method that has been tested and refined on the North Atlantic and Arctic margins as an independent means to quantify crustal extension and shortening, and more accurately restore the pre-breakup geometry of the margins. Quantification of stretching factors (Beta) for deformable areas is achieved by back-stripping Beta for each tectonic interval from total Beta derived mainly from gravity inversion and refraction seismic data. Deformation is restored through the use of triangulated irregular networks that couple strain with plate motion, incrementally restore crustal stretching for tectonic intervals, and estimate crustal thinning and lateral strain through time.

Restored and reconstructed basement terrane studies from the Iberia-Newfoundland and Ireland-Newfoundland margins illustrate the importance of removing the effects of multiple rifting episodes and hyperextension. In the Labrador Sea and Baffin Bay basement reactivation has influenced the location of transform faults in the Ungava and the Wegener Fault zones that can clearly be seen using deformable plate reconstruction modelling. In the Barents Sea the significance of the interplay between the Caledonian, Ellesmerian and Timanian sutures is clarified. These examples provide compelling support for the use of deformable plate reconstruction methods in determining the influence of inherited structural grain on basin palaeogeometry and the structural controls on sediment distribution during syn-rift phases of basin evolution.

NOTES

Structural inheritance during basin formation and deformation in continents

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A Pangea reconstruction of present day lithospheric thickness, obtained from Raleigh wave tomography, shows a remarkably good fit of currently disparate regions of thick lithosphere. The thick lithosphere occurs as a continuous arc at the centre of Pangea. Within the arc, thinner lithosphere is well correlated with the location of Late Neoproterozoic, Pan African and Brasiliano (650-550Ma), orogenic belts. These orogenic belts impose a strong anisotropy on the continental crust that has an influence on basin formation. Two types of basin characterize Pangea continental crust. Rift basins, tens of km. wide, linear, and structurally defined; and cratonic basins, several hundred thousand sqkm in area, sub circular, with no specific structural control in their formation. Pan-African, thrust related ductile fabrics and steep shear zones are seen to reactivate, influence and potentially initiate Phanerozoic rift basin formation. However, pre-existing structures do not appear to be active or influential in driving cratonic basin formation. This dichotomy is recorded in reflection seismic data from Gondwanaland. The continental margin of Namibia has a landward dipping basement fabric interpreted as crustal scale ductile shear zones inherited from Pan-African orogenesis. This strong fabric appears to have controlled the development of counter regional half graben during early rifting in the South Atlantic. In NE Brazil, the Brasiliano age Transbrasiliano lineament exhibits several periods of post-orogenic reactivation, and long periods of inactivity during passive subsidence. This same distinction is evident in the Congo basin of Africa where subsidence has occurred since the Neoproterozoic and continues today. Three basins are stacked vertically, reflecting long periods of passive subsidence interrupted by the reactivation of pre-existing structures. These observations indicate how major continental structures reactivate and influence rift basin formation and continental break up. They also show how such structure remains passive during the formation of cratonic basins, but can reactivate to deform them. This behavior points to a profound genetic difference, between rift and cratonic basins, and highlights the importance and variability of the impact of structural inheritance.

NOTES

The Sarandí del Yí Shear Zone, Uruguay: crustal reworking of the Río de la Plata Craton margin during Western Gondwana assembly

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The Sarandí del Yí Shear Zone is a crustal–scale shear zone that constitutes the eastern boundary of the Río de la Plata Craton, which is represented by the Piedra Alta Terrane in Uruguay. The Nico Pérez Terrane and the Neoproterozoic Dom Feliciano Belt are located to the east. Deformation in the Sarandí del Yí Shear Zone started under amphibolite facies conditions with dextral shearing. Subsequent lower–amphibolite to upper–greenschist facies metamorphism was related to sinistral shearing and was followed by a late cataclasis that reworked the easternmost border of the shear zone. However, the onset of the deformation could be placed at any time between the late Paleoproterozoic (< 1.7 Ga) and the late Neoproterozoic.

New geochronological and isotopic data were obtained from the mylonites of the Sarandí del Yí Shear Zone in order to assess the tectonothermal evolution of this crustal–scale structure. Data reveals that deformation along the Sarandí del Yí Shear Zone took place during the Ediacaran and was related to the juxtaposition of the Nico Pérez Terrane and the Río de la Plata Craton. Consequently, the shear zone reworked the easternmost margin of the Río de la Plata Craton. The switch from dextral to sinistral shearing points to a geodynamic change, which may be related to the late tectonic processes of the Brasiliano–Pan-African Orogeny that gave rise to the final amalgamation of Western Gondwana.

NOTES

Late Palaeozoic extensional reactivation across the Rheic-Rhenohercynian suture zone in SW England, the English Channel and Western Approaches

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The Devonian and Carboniferous successions of SW England were deposited in a series of E-W trending graben and half-graben sedimentary basins. These defined a south-facing proximal passive margin that developed as a short-lived marginal or successor basin to the Rheic Ocean. The southwards transition, to highly attenuated continental lithosphere of the distal passive margin, exhumed lithospheric mantle and an oceanic spreading centre is partially recorded in allochthonous units of the Gramscatho Basin and the Lizard Complex ophiolite.

SW England occupied a lower plate position during late Devonian Variscan convergence. The orogenic wedge, comprising the upper plate and frontally accreted elements of the distal passive margin collided with the continental slope in the earliest Carboniferous. Shortening migrated northwards through the proximal passive margin and was accommodated by the thick-skinned inversion of sedimentary basins and pre-rift basement above a mid-crustal décollement. The SSE-dipping Rheic-Rhenohercynian suture is imaged on seismic lines just offshore in the western English Channel and continues 250 km WSW through the Western Approaches to the present-day continental margin.

Variscan convergence ceased in the latest Carboniferous and was replaced by a NNW-SSE extensional regime that persisted throughout the Early Permian. The onshore expression of early post-convergence deformation includes widely developed shear zones and detachment faults that demonstrate the top-to-the SSE extensional reactivation of Variscan thrust faults. There is a progression to higher-angle brittle extensional faults during exhumation that cut-out earlier structures.

Offshore, reactivation of the Rheic-Rhenohercynian suture zone was accompanied by the development of the upper plate Western Approaches Basins that locally include substantial volcanic infill. Seismic reflection data allows the outcrop-scale observations from SW England to be placed into a larger scale model of post-Variscan extensional tectonics and basin evolution.

Thinning and exhumation of lower plate SW England, was accompanied by Early Permian bimodal magmatism (*c.* 295-270 Ma). The earliest stages of construction of the >40,000 km^3 Early Permian Cornubian Batholith developed local solid state fabrics and ductile shear zones compatible with a top-sense of shear to the SSE and coupling with penecontemporaneous thrust reactivation. Steeply dipping fracture networks, developed in both granites and their host rocks during continued NNW-SSE extension, controlled world-class magmatic-hydrothermal W-Sn-Cu-Zn mineralisation.

SW England and the adjacent offshore basins provide a superb Variscan example of the Wilson Cycle through both contractional reactivation of ocean margin rift faults during convergence to the later post-Variscan extensional reactivation of the suture zone.

NOTES

A half-turn in the Wilson Cycle: the role of inheritance at the Mid-Norwegian margin

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The opening of oceans along ancient mountain belts is commonly stated and appears to be justified in the case of the North Atlantic. A major question is when processes related to the orogenic cycle ends and rifting starts, spatially and temporally. Limited inboard by crust of normal thickness, the proximal domain of the Norwegian margin continues onshore, encompassing most of the structures normally interpreted to represent the Caledonian `orogenic collapse´ stage. We consider 3 aspects of inheritance as pertinent to the evolution of the Mid-Norwegian rifted margin: 1) inheritance of the post-orogenic rheological and structural template into the main stages of rifting, in particular the ones that controlled the architecture of the necking domain. This is best demonstrated in the Møre basin area, where differential reactivation of the Møre-Trøndelag Fault Complex and warped detachment fabrics controlled formation of the main breakaway for the distal margin. 2) inheritance of the early rift configuration, including variations in crustal thickness and rheology, into the stage of crustal necking. This appears to have controlled the variation between `core complex´ and segmented fault geometries along the Møre margin as well as differences in footwall response and erosion along the distal margin breakaways in the southeastern Møre and south Vøring basins. 3) inheritance of the post-rift crustal template into the `passive´ margin phase dominated by vertical movements. This controlled the flexural response of the deformed and tapered crustal beam and thus the basin-dipping geometry of nested erosional surfaces and a new phase of inboard fault reactivation concentrated in the Møre-Trøndelag and Lofoten-Vesterålen areas. Considerable topographic and geomorphic contrasts developed across reactivated fault strands since the Latest Cretaceous, demonstrating relationships between inherited structure and Scandinavian topography.

NOTES

Examining the relative roles of basement inheritance, plate boundary forces and intraplate geodynamics: the brittle deformation record of Paleozoic platform rocks of east central North America

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Sub-vertical systematic joints in Paleozoic cover rocks across south central Ontario, Pennsylvania, Michigan, Ohio, and New York state display regionally continuous trajectories and smaller domains of anomalous orientations. SE-trending joints extend from penetratively deformed Carboniferous to Devonian sedimentary rocks in the Appalachian foreland in the southeast into undeformed Ordovician to Pennsylvanian rocks in the north (south central Ontario) and northwest (Michigan basin). These fractures likely record tectonic loading events associated with phases of the Paleozoic Appalachian orogeny. A second set of regionally pervasive joints trends ESE. Based on their association with Jurassic ultramafic dykes, we ascribe these fractures to far field regional extension related to the 200-50 Ma breakup of the North Atlantic, development of the St. Lawrence rift system and reactivation of the Ottawa-Bonnechere graben. ENE-trending joints are ubiquitous throughout the region and are parallel to the current horizontal maximum in situ stress, suggesting a neotectonic origin.

Ordovician rocks exposed south of the Paleozoic-Precambrian unconformity in southeast Ontario contain a dominant set of NNE to NE-trending joints that closely tracks the structural grain of gneissic basement rocks of the Grenville orogeny to the north. Basement fractures do not cross the unconformity, suggesting a passive tectonic inheritance mechanism, which we attribute to compaction and hydraulic fracturing of the stratigraphically lowest units over a structurally-controlled corrugated basement. NNW to NS-trending joints and calcite veins in Devonian rocks east of Lake Huron, together with EW and NE-trending fractures measured on the Michigan Peninsula appear to define a concentric pattern of joint trajectories that is coincident with the geometry of the Michigan basin. These fractures may have formed in response to radial extension during the final phase of basin-centred subsidence in the early Carboniferous, and hence ultimately to mantle-lithosphere interaction.

Uranium-lead isotopic analyses were carried out on calcite vein material collected from outcrops and drill core at the Bruce nuclear site, east shore of Lake Huron. LA-ICPMS and ID-TIMS analyses yield ages for deeper Ordovician calcite veins of 445±42 Ma that approaches the depositional age of the host rock. Calcite veins within Devonian and upper Silurian rocks record numerous ages of precipitation from about 100 Ma to about 0 Ma, with no consistent relationship between age and depth. Preliminary geochronology therefore supports episodic fracturing and fluid flow from post-depositional compaction times to the current neotectonic regime.

NOTES

From orogen to rift: The role of reactivation and reworking.

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The Wilson cycle grew out of the idea that the “North Atlantic” must have closed and reopened. The closing of Iapetus created the Caledonian–Appalachian orogen, and the prelude to the opening resulted in an extensive rift system with several rift arms that were aborted during the opening phase. Wilson’s work focused on the reactivation of suture zones or orogenic belts on the plate-scale. Exactly how this plays out in detail is less clear, as it depend on both general and local factors. In this presentation we will look in some detail at the part of the cycle that takes us from the Caledonian orogeny in the south Scandinavian Caledonides through the transtensional Devonian evolution and the subsequent formation and evolution of the North Sea Rift. Were the Caledonian thrusts reactivated during Devonian extension, and what was the role of Devonian extensional structures during the Permian – Jurassic rifting in the North Sea area?

To some extent we see a general trend where, for each tectonic phase, there is an early-stage direct influence of preexisting structures that becomes less important over time. More specifically, during the extension following the Caledonian collision, Caledonian thrusts were immediately reactivated as low-angle extensional shear zones, then inactivated as they were cut by steeper Devonian extensional shear zones and faults. Some of those Devonian shear zones influenced the early-stage North Sea rift architecture, controlling at an early stage the way that the rift was segmented into domains of uniform structural patterns. As the rift filled up, new rift faults evolved, and the connection between these rift faults and the basement shear zone becomes somewhat more obscure. In the northern North Sea, this evolution culminates with the formation of the Viking Graben, which is the most prominent and deepest part of the second rift phase. This structure does not follow the location of the Permo-Triassic Phase 1 rift, for reasons that are not clear. Interestingly, its location is closer to the likely location of the Caledonian suture zone in the northern North Sea.

NOTES

The long-wavelength mantle structure and dynamics and implications for large-scale tectonics and volcanism in the Phanerozoic

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Arguably two most important observations about the Earth's dynamics are the present-day degree-2 mantle structure (i.e., two major seismically slow anomalies under Africa and central Pacific that are separated by circum-Pacific seismically fast anomalies) and supercontinent Pangea's assembly and breakup in the Phanerozoic. These observations raise some important questions. What are the mechanisms that control Pangea's assembly and breakup and are responsible for formation of long-wavelength mantle structure? Do we expect degree-2 mantle structure during Pangea time? In this presentation, I will discuss 1) how mantle dynamic processes may generate very long-wavelength mantle convection and structure, 2) how such processes may be responsible for Pangea formation and breakup, and the present-day degree-2 mantle structure, and 3) how we may build a general framework to understand the Earth's dynamic evolution in the Phanerozoic including large-scale volcanism and magmatism, continental vertical motions, and magnetic polarity reversals. I will show that moderately strong lithosphere with averaged viscosity 100's times higher than that of the upper mantle may lead to long-wavelength convection with predominantly degree-1 and -2 structure. I propose that degree-1 mantle convection be responsible for the assembly of Pangea that occurs over a major, cold mantle downwelling system in the African hemisphere. The circum-Pangea subduction, after the Pangea assembly, would lead to a major mantle upwelling system beneath Pangea, turning the mantle in the African hemisphere from the cold to hot, causing the breakup of Pangea, and forming the present-day degree-2 mantle structure. I will also discuss the implications of this scenario of evolution of mantle structure and Pangea for various of geological and geophysical observations.

NOTES

What happens to isotopically distinct mantle during the Wilson cycle?

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When considering the Wilson Cycle, we rarely think about the long-term effects of what happens to the mantle beneath an ocean basin during ocean closure. On the basis of the composition of mid-ocean-ridge basalts (MORB) erupted at present day spreading centres in the Indian Ocean, geochemists consider that the mantle beneath the Indian Ocean is isotopically distinct from that beneath the Pacific Ocean or the North Atlantic (Hart, 1984). So, what would happen to this mantle if and when the Indian Ocean closed? More intriguingly, when we look at Neo-Tethys MORB (Mahoney et al., 1998) and even Palaeo-Tethys MORB (Xu & Castillo, 2004) which had occurred in a geographically similar location to the Indian Ocean, we find robust clear evidence for the same distinct isotopic nature of the underlying mantle to that beneath present-day Indian Ocean. This raises the significant question of how mantle from one ocean basin might be preserved and re-cycled into succeeding ocean basins during the Wilson cycle.

Here, using bench-marked 3D spherical numerical mantle circulation models we will show what happens to circulating mantle during 119 myrs (Lithgow-Bertelloni and Richards, 1998) and 200 myrs of plate motion history (Seton et al., 2012). We will examine how mantle may be preserved within geographic confines so that it can contribute to succeeding ocean crust formation and how lateral isolation of large regions of the mantle would restrict homogenization of the upper mantle. We will explore the results of the mantle circulation models and how observed processes could explain geochemical features such as the DUPAL anomaly (Dupré and Allegre, 1983) and different depleted end-member chemistries beneath Indian Ocean and Pacific Ocean (Kempton et al., 2001).

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NOTES

Lasting Mantle Scars lead to Perennial Plate Tectonics

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Mid-ocean ridges, transform faults, subduction and continental collisions form the conventional theory of plate tectonics to explain non-rigid behaviour at plate boundaries [e.g., 1]. However, the theory does not explain directly the processes involved in intraplate deformation and seismicity. Recently, long-lasting lithospheric damage expressed as lateral heterogeneities has been linked to the origin of plate tectonics [2] and the initiation of spontaneous subduction at relic arcs [3]. Indeed seismological imaging suggests that mantle lithosphere heterogeneities are ubiquitous [e.g., 4–6]. However, the plate tectonic role of present-day mantle lithosphere heterogeneities within continent interiors is rarely considered. Here we show that deep lithospheric anomalies can dominate shallow geological features in activating tectonics in plate interiors. In numerical experiments, we found that structures frozen into the mantle lithosphere through plate tectonic processes can behave as quasi-plate boundaries reactivated under far-field compressional forcing. As a result, intraplate locations where proto-lithospheric plates have been scarred by earlier suturing could be regions where latent plate boundaries remain, and where plate tectonic processes are expressed as a “perennial” phenomenon (Figure 1).

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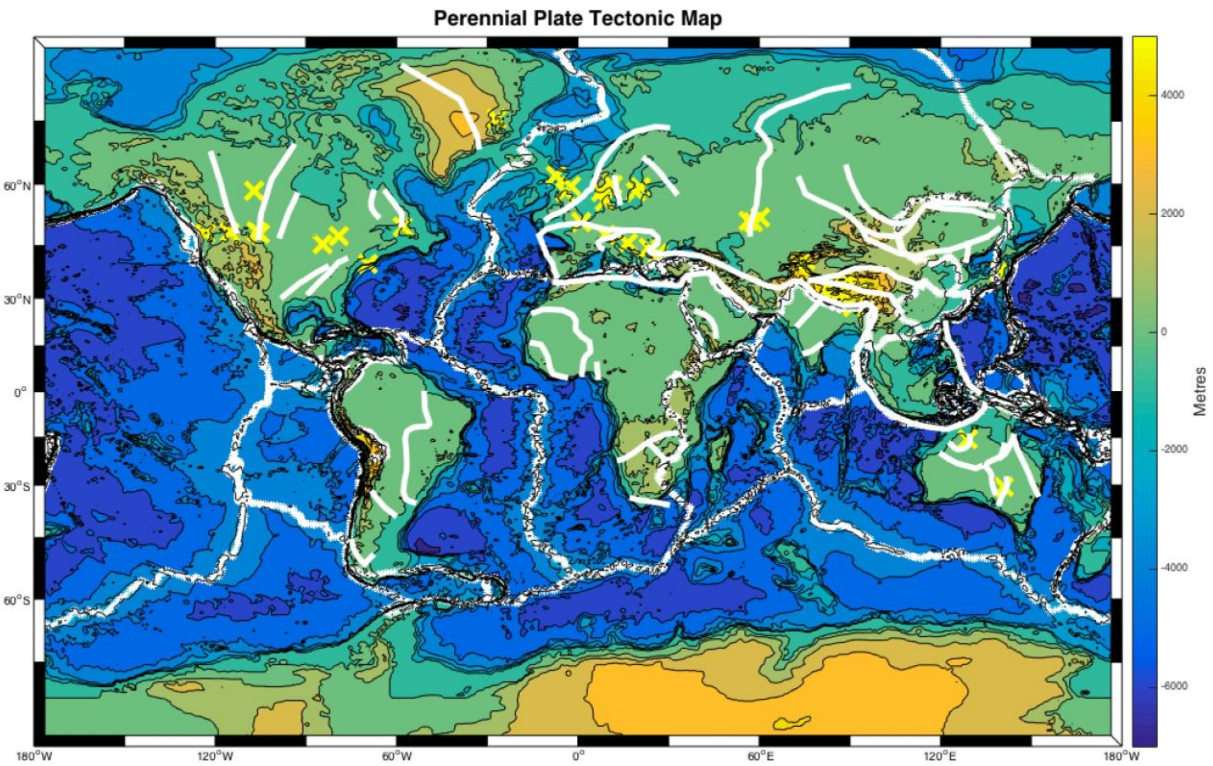

Figure 1: A perennial plate tectonic map. Present-day plate boundaries [7] with major paleo-suture zones and regions of mantle lithosphere scars. White lines are suture zones as modified from Burke et al. [8] and Hoffman [9]. Yellow crosses indicate seismic surveys where mantle reflections have been reported [5, 6, and references therein]. This work infers that mantle lithosphere scars control plate deformation. Ancient plate boundaries can cause mantle lithosphere heterogeneities and therefore have a timeless impact on the Earth.

NOTES

The Stability of Tibetan Mantle Lithosphere

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The large area of thickened crust beneath the Tibetan Plateau is a consequence of sustained continental convergence between India and the Eurasian land mass during the last ~50 m.y. Although the Tibetan crust has thickened there has been much debate about the consequences for its sub-crustal mantle lithosphere. Arguments that crustal thinning beginning in the late Miocene required an increase in the gravitational potential energy of the plateau led to the idea that the mantle lithosphere beneath Tibet had been replaced by asthenosphere, either by some form of convective thinning or a delamination process akin to retreating subduction of the unstable lithospheric mantle layer. Such ideas seem consistent with the history of magmatism and volcanism on the plateau. More recently, analysis of surface waves crossing the plateau has been used to argue that a relatively cold and fast Tibetan lithosphere remains present beneath the plateau to depths of at least 250 km. Because the surface wave data appear inconsistent with the idea that mantle lithosphere has been removed, we propose an alternative explanation that attempts to reconcile these conflicting ideas. This explanation rests on the idea that the thickened Tibetan mantle lithosphere has remained largely in place but, on thickening, has become unstable to an internal convective overturn that resulted in mantle material at near asthenospheric temperatures being emplaced below the crust and colder mantle from beneath the Moho being stranded above about 250 km depth. This mechanism is feasible if the Tibetan sub-continental mantle lithosphere is depleted and intrinsically less dense than the underlying asthenosphere. The mechanism is broadly consistent with the surface wave analyses (which cannot resolve the short horizontal wavelengths on which overturn is likely to occur), and it predicts the kind of short-wavelength variations that are often revealed by body-wave tomography. The thermal re-equilibration of the disturbed lithosphere may take 100s of m.y. but there is a rapid transient transfer of heat as the coldest parts of the mantle lithosphere are juxtaposed with the asthenosphere and the hotter parts juxtaposed with the base of the crust. Heat transfer at the base of the lithosphere could explain a short-term uplift of the surface (~500 m in ~10 m.y.). Heat transfer at the Moho could cause lower-crustal melting and volcanism, and could trigger retrograde metamorphic reactions in the lowermost crust that would contribute to further uplift. The increase in gravitational potential energy of the lithosphere associated with surface uplift thereby can explain the onset of extension in the plateau.

NOTES

Structural reactivation in plate tectonics: the roles of rheological heterogeneity and anisotropy in the mantle

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The lithospheric mantle is intrinsically heterogeneous and anisotropic. These two properties govern the repartition of deformation, controlling intraplate strain localization and development of new plate boundaries. Geophysical and geological observations provide clues on the types, ranges, and characteristic length scales of heterogeneity and anisotropy in the lithospheric mantle. Observations on naturally deformed peridotites establish that compositional heterogeneity and Crystal Preferred Orientations (CPO) are ubiquitous. Seismic anisotropy data indicate that deformation-induced olivine CPO form coherent patterns at scales of hundreds of km, implying an anisotropic thermo-mechanical behavior of the mantle lithosphere at the plate tectonic scale.

Joint analysis of geological and geophysical observations allows discussing the processes that produce/destroy heterogeneity and anisotropy and constraining the time scales over which they are active. This analysis highlights: (i) the role of deformation and reactive percolation of melts and fluids in producing compositional and structural heterogeneity and the feedbacks between these processes, (ii) the weak mechanical effect of mineralogical variations, and (iii) the low volumes of fine-grained microstructures and difficulty to preserve them. In contrast, olivine CPO and the resulting anisotropy of mechanical and thermal properties are only modified by deformation.

Based on this analysis and on numerical models, which explicitly consider the mechanical anisotropy due to a preferred orientation of olivine in the mantle, we propose that structural reactivation and, more generally, strain localization at the plate tectonics scale are, at first order, controlled by large-scale variations in thermal structure and in the orientation of olivine crystals in the mantle (mechanical anisotropy). In cold parts of the lithospheric mantle (<800°C), grain size reduction may contribute to strain localization, but the low volume of fine-grained domains limits this effect.

NOTES

Orogenic inheritance and continental breakup: Wilson Cycle-control on rift and passive margin evolution

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Rifts often develop along suture zones between previously collided continents, as part of the Wilson cycle. The North Atlantic is such an example, formed where the previously assembled supercontinent Pangaea broke apart along Caledonian and Variscan sutures. Dipping upper mantle structures in East Greenland and Scotland, imaged by seismological techniques, have been interpreted as fossil subduction zones and the seismic signature indicates the presence of eclogite and serpentinite. This inherited orogenic material may impose a rheological control upon post-orogenic extension and we use thermo-mechanical modelling to explore such effects. Our model includes the following features: 1) Crustal thickness anomalies, 2) Eclogitised mafic crust emplaced in the mantle lithosphere, and 3) Hydrated mantle peridotite (serpentinite) formed in a pre-rift subduction setting.

Our models indicate that the inherited structures control the location and the structural and magmatic evolution of the rift. Rifting of thin initial crust allows for relatively large amounts of serpentinite to preserve within the uppermost mantle. This facilitates rapid continental breakup and serpentinite exhumation. Magmatism does not occur before continental breakup. Rifts in thicker crust preserve little or no serpentinite and thinning is more focused in the mantle lithosphere, rather than in the crust. Continental breakup is therefore preceded by magmatism.

This implies that whether rifting forms magma-poor or magma-rich conjugate margins, might be a function of pre-rift orogenic properties. The inherited orogenic eclogite and serpentinite are deformed and partially emplaced either as dipping structures within the lithospheric mantle or at the base of the thinned continental crust. The former is consistent with dipping sub-Moho reflectors often observed in passive margins. The latter provides an alternative interpretation of ‘lower crustal bodies’ which are often regarded as igneous bodies. An additional implication of our models is that serpentinite, often observed seismically or exposed at the sea floor of passive margins, was formed prior to rifting in addition to syn-rift, fault-driven hydrothermal processes. Whether lower crustal and serpentinite bodies are produced previously or during rifting is of relevance for the estimation of thinning-factors of the pre-existing crust.

NOTES

The role of pre-existing rheological heterogeneities during the rifting to drifting process: insights from 3D laboratory experiments.

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The transition from continental break up to sea-floor spreading is a poorly resolved aspect of plate tectonics theory. The evolution and resulting structural patterns are controlled by plate fragmentation, pre-existing weaknesses, lithospheric decoupling, complex crust-mantle thermal interactions, or a combination of these factors. In this study we present a series of analogue models that investigate the role of inherited rheological heterogeneities during continental break up. Results are compared initially with the Red Sea-Gulf of Aden rifting system where lithospheric heterogeneities related to Neoproterozoic sutures are thought to be associated with strain localisation during rifting and subsequent evolution. These major morphotectonic features indicate that continental rifting was structurally controlled, but their role as stress guides, barriers to axial propagation or precursors to oceanic transforms is poorly understood.

The laboratory experiments comprise isostatically supported, brittle-ductile multilayer model lithospheres with in-built, variably oriented strength heterogeneities that are deformed using an extensional apparatus under orthogonal, oblique and rotational boundary conditions. Surface strain and dynamic topography are quantfied by high-resolution particle imaging velocimetry and digital photogrammetry. Preliminary results from homogeneous lithosphere models show that continous monitoring of deformation and subsequent analysis of the resulting fault patterns, dynamic topography, velocity fields and strain localization allow us to characterize the geometry, kinematic and mechanical behaviour of the extending lithosphere in great detail. Calculation of instantaneous strain fields can also be used to identify faults that are active or inactive at any given time, which provides information on the time dependence of deformation localization patterns.

In order to better characterise how pre-existing weaknesses (i.e., structural or thermal inheritance) influence the geometry of rifted margins we present new results from experiments containing rheological heterogeneities with various orientations and geometries. Our 3D lithsopheric extension experiments aim to clarify the geodynamic roles of such heterogeneities during the rifting to drifting process under a range of boundary conditions.

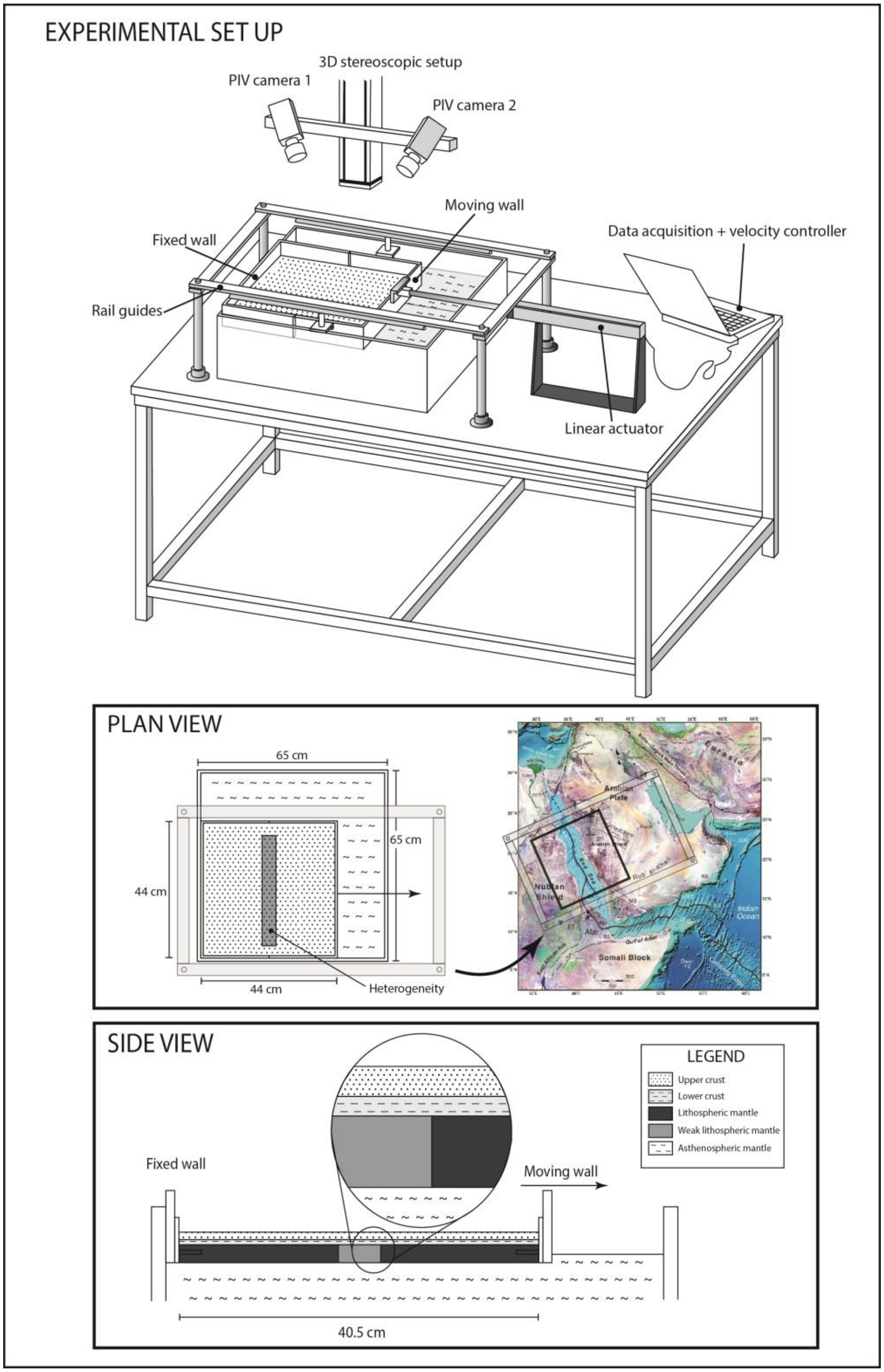

Figure 1. Experimental set up. Plan view figure includes a reference map (modified from Bosworth et al., 2005) with the approximated area represented in the experiments. Bottom is a side view of how the models are constructed.

NOTES

Controls on strain localisation in natural rifts

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Conceptual models predicting the geometry and evolution of normal fault arrays are vital to assess rift physiography, syn-rift sediment dispersal and seismic hazard. Observations from data-rich rifts and numerical and physical models underpin widely used fault array models predicting: i) during rift initiation, arrays are defined by multiple, small, isolated faults; ii) as rifting progresses, strain localises onto fewer larger structures; and iii) with continued strain, faulting migrates toward the rift axis, resulting in rift narrowing. Some rifts display these characteristics whereas others do not. Here we present several case studies documenting fault migration patterns that do not fit this ideal, and discuss what factors may be controlling strain localisation in each setting.

In this presentation we will begin by reviewing existing fault array models before presenting a series of case studies (including from the northern North Sea and the Gulf of Corinth), which document fault migration patterns that are not predicted by current fault evolution models. We show that strain migration onto a few, large faults is common in many rifts but that, rather than localising onto these structures until the cessation of rifting, strain may 'sweep' across the basin. Furthermore, crustal weaknesses developed in early tectonic events can cause faults during subsequent phases of extension to grow relatively quickly and accommodate the majority if not all of the rift-related strain; in these cases, strain migration does not and need not occur. We also show curious examples where pre-existing crustal structures are largely ignored during extension, potentially due to thermal anomalies in the lithosphere that play a greater role in localising strain overwhelming the control of structural inheritance.

We conclude that complexities such as the thermal and rheological properties of the lithosphere, specific regional tectonic boundary conditions, crustal weaknesses and intrastratal rheology variations, need to be incorporated into fault array numerical models to more accurately predict the evolution of rift-scale normal fault arrays. The ability to better model fault array evolution will improve predictions of tectono-stratigraphic setting and seismic hazard.

NOTES

Constraints from GPS observations on the balance of forces in the deformation of Anatolia and the Aegean

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We estimate the strength of the lithosphere in the Aegean and Anatolia, and the boundary tractions acting upon it, using a dynamical model that treats the lithosphere as a thin fluid sheet deforming in response to boundary tractions and to internal variations in its gravitational potential energy (GPE). This model has one free material parameter, the power-law exponent, n, of the vertically-averaged rheology of the lithosphere, and two parameters that specify the forces per unit length applied at the Hellenic plate boundary and in eastern Anatolia. Solutions to this model that best fit the velocities of ~300 reliable GPS sites in Greece and Turkey require $n>=3$ and an effective viscosity of the lithosphere of a few times 10^{21} Pa s at relevant strain rates. WRMS misfits are ~5 mm/yr. The best-fitting traction at the Hellenic plate boundary is equivalent to the lithostatic pressure in the column of oceanic lithosphere to its south, while that required at the eastern boundary is consistent with the lithostatic pressure associated with the high topography of that region. No additional force, such as might arise from slab ``roll-back'', or from convection in the mantle, is required to explain the observations. These results are explained by a simple scaling analysis. Feedback between strain rate and viscosity in the lithospheric rheology leads to the apparently plate-like motions in the Southern Aegean and Anatolia. Finer-scaled features of the deformation, including the partitioning between normal and strike-slip faulting across the region, are explained by the interplay between boundary conditions, internal variations in GPE, and the power-law rheology of the lithosphere.

NOTES

What is actually 'breakup'? Can we define a recipe of how to break the lithosphere?

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Although considered as one of the major steps in the Wilson Cycle, the process of lithospheric 'breakup' is actually still not properly defined. 'Breakup' is a term commonly admitted to designate the end of rifting and the beginning of oceanic drifting, facilitated by the final rupture of the continental lithosphere. Interestingly, apart from its first-order straightforward meaning, which probably led to the wide use of the term in the first place, no robust 'official' definition of breakup has been given in literature. This is most probably related to the fact that no consensus has been reached on the nature of the margin domains that record this geological process.

In terms of rifted margin studies, the basement and sedimentary characteristics of the distal and outer domains are indeed among the today's most debated questions. The architecture and composition of deep margins are rarely well constrained and hence little understood. Except from in a handful number of cases (eg. Iberia-Newfoundland, Southern Australia, Red Sea), basement samples are not available to decipher between the various interpretations allowed by geophysical models. No consensus has been reached on the basement composition, tectonic structures, sedimentary geometries or magmatic content. The result is that non-unique end-member interpretations and models are still proposed in the literature. So, although these domains mark the connection between continents and oceans, and thus correspond to unique stages in the Earth´s lithospheric life cycle, their spatial and temporal evolution are still unresolved.

This is unfortunate as these domains are fundamentally unique, making the connection between two distinct regions theoretically formed by two distinct geological processes: the rifted margin inboard, by definition primarily formed by lithospheric tectonic extension, and the oceanic crust outboard, primarily formed by asthenospheric magmatic addition. The dominant driving process responsible for the formation of these domains is thus questionable: which process - lithospheric or asthenospheric - is the dominant factor for their formation?

In this contribution, based on the mid-Norwegian - East Greenland rift system, we will discuss the definition of 'breakup' and introduce a first order conceptual model that proposes a combined influence of tectonic and magmatic processes on the outbuilding of the distal, outer and oceanic domains.

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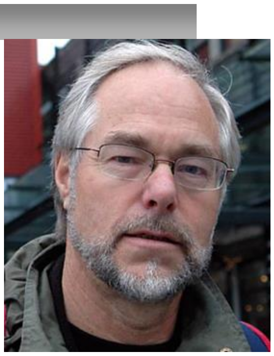

Possible role of salt accumulations in Wilson cycles

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Giant marine salt deposits form in many places on Earth, particularly in zones associated with oceanization and subduction processes, where periodic tectonic unrest and hydrothermal systems occur. The geodynamic evolution of these zones can be strongly influenced by the presence of huge amounts of salts, because of their corrosive and mechanically weak properties, which may also affect the crustal strength. Both numerical modeling and recent observations in the Red Sea Deeps and the submerged Brothers volcano off New Zealand, suggest that large volumes of salts form in active hydrothermal systems over short geological time spans.

It is cautiously suggested that these salt accumulations will remain buried at depth in those places (suture zones?) for long geological periods of time; e.g. during the next Wilson cycle. The presence of such salt accumulations may mechanically weaken the crust, promoting the oceanization process. This suggestion is mainly based on the conditioned permeable nature of salt bodies buried at depth. Indeed, salt rocks are impermeable at low pressure and temperature conditions, but Holness and Lewis (1996) demonstrated that halite, buried at depth (T>150°C, P>50 MPa), can achieve a sand-like permeability and a high plasticity. This behavior was ascribed to the presence of continuous water films on salt crystal surfaces allowing salts to be plastically deformed and moved along pressure gradients. The upwards transportation of salts, piercing the sediment succession, is promoted by their low relative density and high solubility, and by the generation of brines from percolating water through salt bodies buried at depth.

The preservation of salt on the surface depends on a dry climate. In a marine setting, salts may be preserved by a sedimentary cover and/or anhydrite/gypsum, as observed in the Red Sea and rift lakes in east Africa. In addition, salts may be protected from dissolution in seawater by dense brine ponds on the seafloor, as observed in the Red Sea Deeps. We, therefore, suggest that an intimate relationship between the giant salt accumulations and Wilson cycles exists.

Reference

Holness, M.B., Lewis, S., 1997. The structure of halite-brine interface inferred from pressure and temperature variations of equilibrium dihedral angles in the halite-H_2O–CO_2 system. Geochimica et Cosmochimica Acta 61 (4), 795–804.

NOTES

Fault strength and deformation-induced weakening: estimates from India and the northern UK

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A key feature of the Wilson cycle is the reactivation of pre-existing geological structures. However, quantifying the degree of weakening of the lithosphere by past deformation episodes remains challenging. This presentation will provide new estimates of the material properties of pre-existing faults and the surrounding un-deformed lithosphere using a range of fieldwork, seismological, and modelling approaches.

The Indian peninsular is presently breaking in earthquakes on thrust faults that are reactivated Mesozoic rift-bounding normal faults. Analysing the slip in the earthquakes, the surface ruptures produced by pre-historic events, and modelling the stress-state in the region, allows us to estimate the material properties of the faults and the ductile lithosphere. The faults have an effective coefficient of friction of approximately 0.1, much weaker than predicted by laboratory measurements.

During the Variscan orogeny, a range of structures inherited from Palaeozoic shortening and Carboniferous extension were reactivated in the northern UK, in the foreland of the mountain range. The tectonic setting is equivalent to the Tibetan foreland in peninsular India. Britain’s long history of detailed field mapping provides us with an excellent record of the geometry and amount of motion on the reactivated structures. Using similar conceptual approaches to those described in India, it is possible to estimate the strength of the faults, which is similar to the Indian examples. Additionally, the crucial geometrical information provided by the field mapping allows us to calculate the relative strengths of the reactivated faults and the surrounding crust. The pre-existing faults are more than a factor of 2 weaker than optimally oriented but un-faulted planes. This estimate provides a quantitative value for the deformation-induced weakening that allows the Wilson cycle to operate.

In summary, we have studied areas of present-day fault reactivation in India, and the geological record of basin inversion and fault reactivation in the northern UK. We have quantified the strength of the faults, and the degree of weakening that resulted from past deformation episodes; both of these quantities control whether the Wilson cycle can operate.

NOTES

The role of structural inheritance in controlling the structural evolution and consequences for prospectivity of the Utsira High, Southern Viking Graben

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Structural inheritance, where pre-existing lineaments exert a control during successive phases of tectonic deformation, is often underappreciated in studies of the kinematic and depositional evolution of extensional basins. This is reflected in the tendency for some structural models to invoke a homogeneous substrate upon which to illustrate the effects of different tectonic stresses on developed structural styles. The difficulty in recognising the role of basement lineaments can be partly attributed to poor early seismic data resolution which limited the imaging of subsurface structures, particularly offshore where these are often buried up to several kilometres. However, advances in seismic data acquisition and processing, including the advent of broadband seismic, have significantly increased the depth and quality of imaging and modern surveys now permit the opportunity to unravel successive phases of superimposed tectonism and importantly, assess the effects of structural inheritance on basin evolution.

The North Sea is data-rich and has undergone several phases of deformation from Palaeozoic to Cenozoic times making it an ideal natural laboratory to test and document the effects of inheritance. This study aims to use well calibrated, high fidelity 3D seismic data to test and document the effects of structural inheritance within the Utsira High region of the Norwegian Northern North Sea, an area of recent interest following the giant Johan Sverdrup oil field discovery. The Utsira High forms part of the footwall to the N-S striking Viking Graben, a component of the Jurassic trilete rift system which dominates the North Sea subsurface structure. The High itself however, is a NW-SE striking basement block, underlain by Early Palaeozoic (Caledonian) granite resulting from an earlier period of tectonism and is therefore an ideal location to test the effects of inheritance.

Regional well-calibrated seismic interpretation has evidenced punctuated rejuvenation of a Permo-Triassic fault defining the High margin throughout the Palaeozoic to Cenozoic. We show that this zone of weakness has been exploited during successive periods of rifting and shortening and has influenced the structural and stratigraphic architectures observed within the region. It has also positively influenced prospectivity through both reservoir deposition and formation of the Johan Sverdrup trap. This study highlights a dichotomy with normal fault models in emphasising the role of rift-oblique faulting during the evolution of the Southern Viking Graben and demonstrates the importance of integrating inheritance effects if we are to use structural models to replicate real earth processes.

NOTES

Reactivation of intrabasement structures during multiphase continental rifting – Implications for the geometry and evolution of rift systems

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Rift systems form within areas of relatively weak, heterogeneous lithosphere, with pre-existing structures within crystalline basement thought to play a vital role in the early stages of continental breakup. However, the extent to which the potential reactivation of these intra-crystalline basement structures during later rift phases may affect the geometry and evolution of rift systems remains poorly understood.

The greatest obstacle to understanding how intrabasement structures influence the overlying rift is the accurate interpretation of the structures within crystalline basement and constraining their 3D geometry. On seismic reflection data, crystalline basement contains relatively low acoustic impedance contrasts and is often buried by large thicknesses of sediment; appearing poorly reflective and showing no resolvable internal structure.

However, offshore SW Norway, intrabasement structures are exceptionally well-imaged due to large impedance contrasts within a highly heterogeneous and shallow basement. Here, we use borehole-constrained 2D and 3D seismic reflection data to constrain the 3D geometry of a series of prominent intrabasement reflections, before examining their interactions with the overlying rift. We observe two types of intrabasement reflections: (i) thin (100 m) reflections displaying a trough-peak trough wavetrain; and (ii) thick (c. 1 km), sub-parallel reflection packages dipping at c. 30°. Using 1D waveform modelling, we show that these reflections represent a layered sequence as opposed to a single interface. Integrating this with our seismic mapping, we correlate these structures to the established onshore geology; specifically layered mylonites associated with the Caledonian thrust belt and cross-cutting Devonian shear zones.

We observe multiple phases of reactivation along intrabasement structures during later tectonic events, in addition to a range of interactions with the overlying rift. Rift-related faults either (i) exploit planes of weakness within the shear zones; (ii) initiate in the hanging wall and merge at depth with the shear zone; or (iii) initiate independently from and subsequently cross-cut intrabasement structure. We find that reactivation preferentially occurs on thick, steeper ICB structures, Devonian shear zones, with faults exploiting internal mylonite layers.

Using a detailed 3D interpretation of intrabasement structure, correlated with onshore geology, we show that large-scale Devonian shear zones act as a long-lived structural template for fault initiation during later extensional events. Rift-related faults inherit the orientation and location of underlying intrabasement structures.

NOTES

Unusual examples of continental break-up on the North American margin.

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This paper focusses on some intriguing variations and deviations from the Wilson Cycle during Pangea break-up, in and around present day North America.

Non-Wilsonian opening, across the orogenic grain, appears to have been predisposed by major lithospheric shear zones in both the northwestern North Atlantic and the Arctic Eurasia Basin. In the North Atlantic, the Goban Spur - Flemish Cap conjugate margins are steep-sided and represent an Early Cretaceous transform margin. Later rifting and continental separation in the Labrador Sea, cross-cutting the Mesoproterozoic Grenville orogeny, probably represents northward propagation of this shear zone into Paleoproterozoic North Atlantic craton. Extension and subsequent breakup took place in the Labrador Sea as the former transform margin to the south transitioned to passive drift in the middle and Late Cretaceous. Further advancement of the rift/ocean into Baffin Bay required splitting the large Paleoproterozoic Rae craton.

On the east side of Greenland, the Cenozoic NE Atlantic essentially re-opened the Late Paleozoic Caledonian orogen. Linkage between the NE Atlantic and the Eurasia Basin utilized the super-regional De Geer lineament, initially by strike-slip motion and subsequently by oblique opening of the shear. Opening of the Eurasia Basin did not re-open pre-existing orogens, but rather cut orthogonally across them. Separation of the steep-sided, c.1500 km long and very narrow Lomonosov Ridge microcontinent from Eurasia again probably utilized a shear weakness, in this case related to the distal transform of the neighboring Canada Basin.

The pie-shaped Canada Basin formed behind the paleo-Pacific subduction zone by c. 70º counter-clockwise rotation of the Alaska-Chukotka terrane/microcontinent away from the North American craton. Similarly, the Gulf of Mexico, at the southern end of North America, also opened by c. 70º counter-clockwise rotation, in this case of the Yucatan microcontinent away from North America. Both of these small and isolated oceans are limited by continent-ocean transforms at their distal ends. Although these oceans opened synchronously with parts of the Atlantic, their oceanic crust never connected with that of the Atlantic. Both of these small oceans formed isolated but significant sediment sinks, housing major deltas and prolific reservoir and source rocks.

The position of both the Canada Basin and Gulf of Mexico relative to paleo-Pacific subduction require them to be classified as back-arc basins, but the high angle of opening with respect to the subduction zone is unusual for such basins. Notably, both oceans occur where Late Paleozoic orogens intersected the paleo-Pacific subduction zone at a high angle, and may thus be unusual examples of the Wilson Cycle. While the utilization of weaknesses from the orogens appears clear, the dynamics of this mode of basin formation require further research.

NOTES

Revisiting the Wilson Cycle in the North Atlantic: The importance of inheritance

Pauline Chenin, Gianreto Manatschal, Othmar Müntener, Duncan Erratt, Suzanne Picazo, Garry D. Karner, Christopher Johnson, Marc Ulrich

According to the Wilson Cycle, oceans open and close approximately parallel to ancient suture zones, suggesting a major control of inheritance in the extension and convergent process. While this paradigm is well illustrated in the northern North Atlantic where the rift follows largely the Iapetus suture between Norway and Greenland, this is not the case for the southern North Atlantic, where neither the westward, nor the northward propagating branch of the Central Atlantic rift, affected the Variscan sutures of Western Europe.
These observations suggest that inheritance is not necessarily reactivated during subsequent rifting events and begs the question about what may truly control the localization and details of rift systems.

One possible cause for the differing behavior of the North Atlantic rift with respect to the Caledonian and Variscan orogens may be their contrasting paleo-geographic settings. Indeed, the Scandinavian Caledonides resulted from the closure of one wide ocean between two cratonic shields, whereas the Variscides were built from the accretion of several terranes/micro-continents following the closure of a series of narrow oceans. The variability in the initial architecture of the intervening rift systems and in their subduction processes may have significantly controlled the subsequent orogenies.

The aim of this presentation is twofold: first we investigate how the first-order structural and lithological characteristics of narrow/embryonic versus wide/mature oceans, as well as the processes associated with their subduction and collision, characterize orogens. Second, we study how this variable orogenic inheritance may impact subsequent rifting.

Our results suggest that: (1) the margins from narrow/embryonic and wide/mature oceans are comparable, therefore the major difference between these end-members is the existence of a significant amount of normal oceanic crust; (2) subduction-induced processes significantly impact both the thermal state and the lithology/composition of the orogens that results from the closure of wide oceans; (3) orogenies subsequent to the closure of narrow oceans are essentially controlled by mechanical processes where the initial architecture of the rifted margin plays a dominant role; and (4) the difference in the composition of the mantle beneath these end-member orogens may account for the variability in the magmatic budget of subsequent extensional events, in particular, during orogenic collapse.

NOTES

Tectonic inheritance at multiple scales during 2+ Wilson cycles recorded in eastern North America

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Eastern North America displays a record of multiple complete Wilson cycles: assembly and breakup of Columbia, Rodinia, and Pangaea. During the successive events of assembly and breakup of supercontinents, tectonic inheritance ranged in scales from the entire continental margins to individual structures in both contraction and extension.

Salients and recesses of the frontal Appalachian-Ouachita orogen adapted during Pangaea assembly to existing shapes of embayments and promontories of the Iapetan rifted margin of Laurentia. Sutures in orogenic interiors more commonly truncate older structures.

Rift margins commonly do not coincide with older continental sutures, leaving part of one conjugate craton attached to the other. For examples, Amazonian crust sutured to proto-Laurentia during Rodinia assembly (Grenville orogeny) was left attached during Iapetan rifting, and Gondwana crust (Suwannee terrane) sutured to Laurentia during Pangaea assembly (Appalachian-Ouachita orogeny) was left attached during Atlantic rifting. In contrast, transform faults with large offsets of the rift margin commonly inherit location and orientation from previous cycles. In one prominent example, the Bahamas transform of the Atlantic margin reoccupied the trace of the Alabama-Oklahoma transform of the Iapetan margin, which reoccupied the trace of a probable transform offset of the rift margin of Columbia breakup. Transform inheritance is consistent with a temporally persistent lithospheric-scale transform-parallel fabric.

Synrift, rift-parallel and transform-parallel intracratonic basement faults indicate both extension and transtension inboard from the rifted margin. Although rift margins generally do not follow older sutures, some rift-parallel intracratonic faults do. For example, the South Georgia fault-bounded basin inboard from the Atlantic rift margin coincides with the Suwannee suture between Laurentia and Gondwana (Suwannee terrane) of Pangaea assembly. The rift-parallel intracratonic Rome trough and Birmingham graben of Iapetan rifting roughly follow the Amazonia–proto-Laurentia transform suture of Rodinia assembly; an along-strike gap in the intracratonic extensional structures, bounded by the transform-parallel pull-apart Rough Creek graben, coincides with the location of a releasing bend in the transform suture. Transform-parallel intracratonic basement faults further suggest inheritance from transform-parallel distributed-shear fabrics in the lithosphere.

Some large-scale frontal thrust ramps within the Appalachian thrust belt rise from the regional décollement over sub-décollement Iapetan synrift rift-parallel intracratonic basement faults (Birmingham graben). The deepest graben collected anomalously thick Cambrian shale, which is the weak-layer host of the Appalachian regional décollement. During Appalachian thrusting, tectonic thickening of the anomalously thick shale in the graben produced a distinctive thick ductile duplex.

NOTES

SDR dominated rifting in the southern segment of the South Atlantic: a high-strain, narrow rift?

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Whilst our understanding of rift formation and evolution has improved in recent years there remains a fundamental debate on how the volcanic edifices and magmatic underplate on volcanic margins form. The Argentinian and Uruguayan passive margins are classic examples of volcanic margins, dominated by extensive sequences of lava flows that form seaward dipping reflectors (SDRs) extending for widths of between 60-80 km on the continental margin before passing into Atlantic oceanic crust. Our new interpretation and velocity analysis of 2D seismic reflection data acquired by ION-GXT offshore Argentina and Uruguay shows that all the crustal extension and thinning appears to coincide with the location of the SDRs, with very little expression of 'classic' crustal thinning in the form of syn-rift faulting on the continental margin.

The exceptional ION data collected with 10 km long-offset streamers towed at a water depth around 10 m and imaging to depths of 40 km improves the seismic imaging by recording long-offset reflections to low-frequencies. Semblance velocity analysis has allowed us to observe a more detailed velocity structure within, and beneath, the SDR sequences than ever previously published. We see high velocity bodies (ca. 6.5 km/s) distributed at the seaward end of individual SDR packages separated by faults. Beneath the SDRs and the high velocity bodies the seismic velocities return to the typical values of metamorphic continental crust (ca. 5.5 km/s). We interpret the high velocity bodies to represent solidified, depleted, mafic magmas that fed the volcanic edifices producing the basaltic lava flows. These are separated into fault blocks with 5 or 6 high velocity bodies imaged along the dip of the margin that then pass oceanward into true oceanic crust. Magnetic anomaly data shows that the lava flows were extruded in less than 5 Ma. Stretching of the crust was focused over a 60-80 km wide zone before sea-floor spreading commenced and a steep gradient is observed on the Moho depth along the strike of the margin. This implies that stretching factors went from 1 to infinity in 5 Ma, indicating very high strain rates. For the first time we image structure beneath and within the volcanic extrusives on a magmatic margin showing that the earliest stages of break up in the southern South Atlantic comprised of crustal thinning located directly beneath lavas erupting from a chain of rapidly migrating volcanic centres in a high-strain rift, perhaps analogous to the present day Red Sea.

NOTES

Does Crustal Architecture Play a Role in the Location of Continental Break-up?

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It has long been considered that crustal heterogeneity plays a significant role in controlling the ultimate position and orientation of continental separation during lithospheric stretching. A number of recent studies, however, challenge this simple premise and suggest that the ultimate position of separation may be a more complex interplay of pre-existing structures, regional stress orientations, heat flow and lithospheric scale processes. Existing studies can therefore be rather contradictory even on the same margin, We focus on the South Atlantic where some studies conclude that crustal architecture influence break-up position, while others demonstrate that lithospheric-scale heterogeneity, such as the Cape Foldbelt in southern Africa, are entirely cross-cut by subsequent sea floor spreading. Much of this contradiction is associated with the specific parameters associated with the study area. This, however, makes it difficult to draw wider, generic implications.

In this study we take an alterative approach and evaluate quantitatively the relationship between break-up and pre-existing structures. We use Getech's global structural database to generate azimuth and frequency data for both onshore and offshore structures and classify the relationships as Parallel, Aligned, Oblique and Orthogonal. At a 1:10M scale of observation we conclude that 60% of rift structures are oblique to the onshore structures, which is in agreement with numerical models of rift evolution, but we do note regional variations. We then consider these regional variations by making observations at a 1:1M scale and conclude that although obliquity is dominant, there is significant variation associated with local geometry and that reactivation of the same structures in different stress systems also have to be considered.

The results of this study provide a quantitative assessment of the relationship between rift systems and underlying basement fabric which suggest that there really may be no simple answer to the question "Does crustal architecture play a role in the location of continental Break-up".

NOTES

The Concertina Coast: the role of basement inheritance during repeated reactivation events along Australia's northern margin since the Permian

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The present day configuration of Australia's northern margin includes a series of Phanerozoic sedimentary basins forming the North West Shelf. Their polyphase history, dominantly extensional, and closely associated with the breakup of Eastern Gondwana, includes the early formation of intracratonic basins (from the mid-Devonian), overprinted by Permo-Carboniferous rifting that generated the dominant NE-trending structural trends that persist to the present-day. Subsequent Mesozoic extension, associated with the formation of abyssal plains, further refined the margin, creating additional depocentres.

During this polyphase rift history, a number of periods of inversion have punctuated the margin. These include a Carboniferous event, the Meda Transpression, late Permian to Early Triassic event, sometimes referred to as the Bedout Movement (possibly transtensional), and two events, one in the Middle to Late Triassic, followed by another in the Late Triassic to Early Jurassic, often referred to as the Fitzroy events. These various events, recorded locally in specific basins, caused inversion, folding, uplift and erosion where documented, with the Fitzroy events described as transpressional, resulting from right-lateral oblique inversion. Subsequent inversion during the Cretaceous, also attributed to dextral transpression, caused long wavelength folding and fault inversion in some basins.

Whereas the effects of earlier inversions are somewhat sporadic across the North West Shelf, the effects of Neogene inversion have been documented across both the active and passive segments of the present day North West Shelf, and also appear to be strongly controlled by right-lateral oblique reactivation mechanisms, with associated seismicity and focal mechanism solutions.

The history of the North West Shelf therefore includes 6 discrete episodes of reactivation and inversion, apparently strongly dominated by oblique mechanisms, which punctuate the long, multi-phase extensional history. Whereas Neogene to Recent inversions can be attributed at least in part to plate collision (locally) and far-field stress (generally), the cause(s), distribution(s) and intensity of these previous events remains unclear. Distributions of Precambrian basement and lineaments beneath the shelf, seen in potential field data, seemingly exert strong controls on reactivation locations and geometries. Interactions of long-lived, reactivated basement trends with larger-wavelength dynamic topography may also be important in dictating where and when inversion events occur.
This presentation will examine the locations and manifestation of Late Permian to Recent events, and examine possible causes and consequences of repeated inversion of this rift/passive margin region.

NOTES

EVOLUTION OF THE ARCTIC FOLD BELTS

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Arctic is a tectonically unique Earth's realm whose continental crust is dominated by the northern extents of the major fold belts (FBs): the Neoproterozoic Timanian, early Palaeozoic Caledonian, mid and late Palaeozoic Ellesmerian, Uralian and Taimyr, Late Mesozoic Verkhoyansk-Chukotka and Brooks Range, and Cenozoic Eurekan belts. Some of them represent classical intracontinental FBs (i.e. Caledonides and Uralides) formed in a course of a continent-continent collision. These FBs reveal tectonic cyclicity interpreted by T. Wilson in terms of birth and closure of preceding oceans. Other FBs (e.g. Verkhoyansk-Chukotka and Brooks Range) fall into a different category, which was described by V. Khain as pericontinental fold belts mainly developed along continental margins surrounding Pacific (Palaeo-Pacific) oceanic realm. These are characterized by accretionary tectonics and do not reveal Wilson's cyclicity.

In a relatively confined area north of the Polar Circle, the FBs intersect and overprint each other forming a poorly understood tectonic grain beneath thick offshore sedimentary accumulations. Formation of this tectonically complex crustal realm spans at least 1 Ga, but a true Arctic part of its history can be traced starting from *c.* Devonian when continents started gathering in the Northern hemisphere to form the Wegener's Pangaea. During this time the Proto-Arctic continental rim can be approximated by an immense "C" facing towards Palaeo-Pacific. Inside "C", there were several small oceanic basins (*e.g.* Anyui, Angayucham and Oymyakon) separated by volcanic island-arcs from Palaeo-Pacific. The Proto-Arctic Ocean was completely closed during Mesozoic through accretion of several large continental and island-arc fragments to the Siberian margin, with the largest superterrane represented by the Arctic Alaska-Chukotka Microcontinent.

Despite a significant progress achieved in the past two decades owing to deep-penetrating seismic experiments and geological observations on the remote Arctic islands, many details of the Arctic geology are yet to be revealed. However, existing results highlight some specifics in tectonic history of the Arctic FBs, such as rejuvenation of northern flanks of some FBs (Devonian Ellesmerian compressional deformations and Triassic/Jurassic deformation of the Pai-Khoi – Novaya Zemlya FB), and numerous inversions affected Arctic offshore sedimentary basins. These facts can be better comprehended if portraying the Proto-Arctic and the modern Arctic as arenas of escape tectonics and jostling of continental microplates controlled by the large converging continental masses during collision of the latter and beyond.

NOTES

Basin development in Earth's earliest Rifted Margins: the initial Palaeoproterozoic opening and closure of Baffin Bay, Davis Strait and Labrador Sea

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In the rifted margin of central West Greenland evidence is preserved for the formation and destruction of a passive margin during one of the earliest complete Wilson Cycles on Earth. Validated and restored regional cross sections drawn through superbly exposed terrain provide insight into the geometry and dynamics of basin development and inversion tectonics that took place in a plate tectonic setting *c.*1.9-*c.*2.1 Ga ago. Restoration allows thickness of sedimentary graben fills, rate of accumulation of sediment in relation to fault-slip rates and basin aspect-ratios to be estimated, all of which invite comparison with basin dynamics of modern rifted margins and, in principle, allow deductions to be made about the rheology of the Palaeoproterozoic lithosphere.

Destruction of the passive margin was preceded by progradation of a turbidite flysch mega-sequence deposited in an accretionary prism that appears to have advanced from west to east (present day co-ordinates) onto the Greenland margin. The process was analogous to the advance of the Banda Arc fore-arc basin/accretionary prism onto the Australian plate in present-day SE Asia.

This direction of ocean closure differs from the hitherto favoured N-S shortening and (globally) E-W trending sutures held to characterise the entire West Greenland area during the Palaeoproterozoic between 66˚N and 73˚N. It implies that the Rinkian orogen developed during the destruction of the margin due to E-W closure of an ancestral Baffin Bay, rather than by N-S collision in a northern continuation of the Nagssugtoqidian orogen, and is consistent with recently published geochronological evidence from Baffin Island.

Validation and restoration shows in detail that the Palaeoproterozoic margin in West Greenland was characterised by NW- and SW-trending linked extensional fault systems defining a pattern of basin and sub-basins very much like present-day passive margins. Basin-bounding faults focused hydrothermal circulation systems in syn-sedimentary growth sequences where SEDEX-type and MVT-type Pb-Zn mineralisation systems and associated deposits formed under geothermal gradients likely to have been generally steeper than those of the Phanerozoic eon. After contraction during development of the Rinkian orogen inverted many of these faults, NW- and SW-trends were reactivated at *c.* 1.65 Ga during renewed rifting and the emplacement of the Melville Bugt Dyke swarm that mimic the earlier passive margin trends albeit with a dominant NW (present-day) coast- parallel trend.

Palaeoproterozoic faults were reactivated again in Mesozoic-Tertiary time during rifting events that formed modern Baffin Bay, Davis Strait and Labrador Sea. Basin-boundary faults can be traced onshore using total field magnetic anomaly maps to link with a system of NW- and SW-trending faults that reactivated much older Palaeoproterozoic trends whilst defining the present-day topography and the orientation of the major fjords. We conclude that Greenland first rifted from the Canadian shield in Palaeoproterozoic time at *c.* 2.1Ga with the formation of oceanic lithosphere and opposing rifted margins that closed again at *c.* 1.86 Ga. Renewed rifting in the mid-Proterozoic along the line of the closed ocean did not result in separation and the original lineaments are now stitched by Melville Bugt Dykes. During the current global Wilson Cycle, NW- and SW-trending ancestral Palaeoproterozoic faults were reactivated once more to form the present-day rifted margins of Greenland and Baffin Island and strongly attenuated continental crust in Baffin Bay.

NOTES

Tectonic inheritance during extension in rifts and passive margins: Greenland's playground for basement inheritance

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The extent to which continental rifting and margin development is influenced by pre-existing anisotropies has been debated since Tuzo Wilson's seminal 1966 paper on Atlantic opening and closing. Structural inheritance results from stress concentration and shear localisation manifested at all scales in the continental lithosphere. *Lithosphere-scale controls* include crustal thickness, thermal age and plate tectonic boundary conditions. *Grain-scale controls* include local environmental controls (depth, stress, etc), rock composition, grainsize, fabric intensity and the presence of fluids. Multi-scale g*eometric controls* are largely related to the size, orientation and interconnectivity of pre-existing anisotropies. If reactivation occurs, it likely requires a combination of processes acting across all three scale ranges to be favourable. This can make the unequivocal recognition of inheritance and reactivation difficult.

Most pre-existing crustal structures are likely to be oriented significantly oblique (<70°) to regional extension directions. Transtensional bulk strains are therefore widespread during reactivation leading to strain partitioning and/or multimodal fracturing where the (non-plane strain) deformation cannot be described or reconstructed in single 2D cross-sectional or map view.

Crustal-scale pre-existing structures are especially important due to their ability to efficiently concentrate stress and localise strain across a broad scale range. This aids the rapid propagation of high displacement rift-bounding faults. Large structures are also prone to reactivation due to the development of strongly anisotropic, weak phyllosilicate-rich fault rocks (friction coefficients <0.2).

Greenland's margins provide an excellent example of how changes in margin trend and geometry commonly coincide with changes in basement structure. Thus, intracratonic rifting and break-up between Greenland and Labrador shows strong evidence for basement inheritance. Relatively simple orthogonal margins are developed in the Archaean North Atlantic Craton that contrast with complex oblique-margin segments in Proterozoic shear belts (i.e. Ketilidian, Nagssugtoqidian). Distinct contrasts in fault style and geometry can be seen in steep belts and intervening fold belts, leading to the interpretation that brittle fault patterns are partitioned in to domains of “basement influence" (steep belts) and “non-basement influence" (sub-horizontal strata and fold belts).

In summary, pre-existing structures, particularly steep belts & shear zones, can influence deformation patterns across a range of scales. The deformation magnitudes associated with reactivation events may be modest compared to the regional-scale deformation of the crust. However, reactivation will almost always influence the development of smaller-scale (<1km) geological architectures and this in turn will impact on crustal processes such as fluid flow and the accumulation of natural resources (oil, minerals).

NOTES

Long-lived fault systems and their influence on the rift architecture of the NE Atlantic Margin and Barents Shelf

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The NE Atlantic Margin and Barents Shelf have developed through a repeated cycle of continental growth and continental break-up (Wilson, 1966; Doré et al., 1999). The middle Palaeozoic Caledonian Orogeny was responsible for generating the pervasive northeast trending structural grain that dominates the UK, Norwegian and southwestern Barents margins; it is widely accepted that inherited structural anisotropy has influenced the location, mode of development and morphology of basins and structural highs in the region (e.g. Doré et al., 1997).

This presentation takes an overview of two areas: 1) the UK and Irish continental shelf, between the West of Shetlands and the Porcupine Basin, and 2) the southeast Barents Shelf. Using a combination of potential field and seismic datasets, a structural framework for these regions is presented and the existence of long-lived discrete fault systems is discussed. Some of these faults have geometric and cross-cutting relationships indicative of a multi-phase kinematic evolution initiated during the Caledonian Orogeny, but which continued to influence rift architecture in the late Palaeozoic, Mesozoic and Cenozoic. The existence and development of long-lived fault systems is important to our understanding of regional tectonic evolution, and has implications for resource exploration. These fault systems also provide vital insight into the long-term behaviour of the lithosphere during repeated cycles of continental growth and break-up.

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NOTES

Tectonic Inheritance in the Alps and the Pyrenees: The Role of Post-Hercynian Strike-Slip Systems and the Palaeo-Tethys

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Both the Alps and the Pyrenees are located along large strike-slip systems of Permian age with a cumulative offset of some 1500 to 2000 km. These giant strike-slip systems have localised extreme stretching locally giving rise to Buchan-type metamorphism both in the Koralpe and Saualpe of the Middle Austroalpine units (in the sense of Tollmann, 1963, *Ostalpensynthese*: Franz Deuticke, Wien) and in the Palaeozoic core of the Pyrenees where a pull-apart basin became site of turbidite deposition. Almost while the sediments were being deposited, they became deformed by F1 nappes with a flat foliation and metamorphosed shortly after they were laid down in a regime of transtension. The same strike-slip finally destroyed the basin and led to upright F2 folding and steep S2 cleavage. The symmetric structure of the Palaeozoic Pyrenees was inherited by the late Mesozoic-Cainozoic Pyrenees despite the presence of a south-dipping subduction zone and the creation of the large Aquitaine molasse basin in the north.

In the Alps, the post-Hercynian structures were more complicated. The post-Hercynian strike-slip fault systems went through the external massifs in the Helvetic realm as well as through the Austroalpine units. In the southern Alpine area there were Permo-Triassic basins with east-west extension and the Liassic rifting creating major extensional low-angle faults have been reported to have caused the opening of the Alpine Ocean. While this was clearly the case in the southern Alps, in the Lower Austroalpine units, the situation appears to have been different. In the Albula Pass area, for example, the latest Triassic-Jurassic normal faults mapped within the Albula Nappe were north dipping and they became folded during the late Cretaceous south-vergent deformation. Only locally, where parts of the old normal faults provided flat, near-horizontal surfaces, the Cretaceous thrust faults (e.g., the sub-Ela thrusts) seem to have used them. But what was the cause of the south vergence to begin with? It seems that the thrusts generally followed not the individual north-dipping normal faults, but the general *basement fabric created by the extension*. However, the overall vergence of the Alps, of Eocene and later age, seems to have been determined by the internal fabric of the basement of the south-facing Atlantic-type continental margin of the Palaeo-Tethys here. Now that it is becoming increasingly more clear that there was no southern Hercynian Ocean ("Theic" or " Océan Centralien") the vergence of the Hercynian structures in the Alps needs to be re-evaluated.

NOTES

Wilson Cycle: its relevance to S Neotethys in the E Mediterranean region and the role of structural inheritance/ re-activation in the assembly of the Kyrenia lineament, N Cyprus

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How relevant is the Wilson Cycle, involving repeated opening and closure of Atlantic-type oceans, to the assembly of orogenic belts in general? Arguably the concept has skewed recognition of other types of orogenic assembly (e.g. related to Pacific-type ocean evolution). Here, we consider the rifting, spreading and continental assembly that characterise the Tethyan orogen (Alps to China). We focus on the E Mediterranean, in particular the Kyrenia Range, N Cyprus. The S Neotethys in the E Mediterranean region underwent continental breakup during Late Triassic, followed by northward drifting of variably sized and shaped continental fragments from Gondwana. The fragments migrated into a large pre-existing oceanic region (Palaeotethys) that was simultaneously subducting northwards beneath Eurasia. During late Mesozoic onwards, the S Neotethys itself subducted northwards, in time activating irregular and diachronous continental collisions and progressive continental assembly (in places after significant lateral displacement). Initial Late Cretaceous convergence resulted in deep burial metamorphism (up to HP/LT to the N of Cyprus), then rapid exhumation. Palaeogene active margin tectonics, magmatism and syn-tectonic sediment deposition were followed by Early-Mid Eocene, S-directed thrusting and folding (probably influenced by far-field collision to the N). Renewed convergence in the Neogene and related gravity-flow accumulation was followed by further S-directed compression in an oblique left-lateral stress regime during the Late Miocene (probably influenced by collision to the E). Strong uplift of the Kyrenia Range lineament took place during the Pleistocene related to incipient continental collision (probably related to collision in the S), as documented by a downward-younging flight of marine and continental terrace deposits. Each of the four deformation stages represents on-going development of the northerly, active continental margin of the S Neotethys that was strongly influenced by structural inheritance and re-activation. Compared to the Wilson Cycle concept, the tectonic development of the S Neotethys and the Kyrenia Range specifically has some similarities (e.g. rifting, spreading, collision) but shows much greater variety and complexity, particularly in the timing and processes of subduction and collision.

NOTES

Continental strike slip fault zones in geologically complex lithosphere: the North Anatolian Fault, Turkey.

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As part of the multi-disciplinary Faultlab project, we present new detailed images in a geologically complex region where the crust and upper mantle is bisected by a major continental strike-slip fault system. Our study region samples the north Anatolian fault zone (NAFZ) near the epicentres of two large earthquakes that occurred in 1999 at Izmit (M7.5) and Düzce (M7.2) and where estimates of present day slip rate are 20-25 mm/yr. Using recordings of teleseismic earthquakes from a rectangular seismometer array spanning the NAFZ with 66 stations at a nominal inter-station spacing of 7 km and 7 additional stations further afield, we build a detailed 3-D image of structure and anisotropy using receiver functions, tomography and shear wave splitting and illuminate major changes in the architecture and properties of the upper crust, lower crust and upper mantle, both across and along the two branches of the NAFZ, at length scales of less than 20 km. We show that the northern NAFZ branch depth extent varies from the mid-crust to the upper mantle and it is likely to be less than 10 km wide. A high velocity lower crust and a region of crustal underthrusting appear to add strength to a heterogeneous crust and play a role in dictating the variation in faulting style and postseismic deformation. Sharp changes in lithospheric mantle velocity and anisotropy are constrained as the NAFZ is crossed, whereas crustal structure and anisotropy vary considerably both parallel and perpendicular to the faulting. We use our observations to test current models of the localisation of strike-slip deformation and develop new ideas to explain how narrow fault zones develop in extremely heterogeneous lithosphere.

NOTES

The most notable Alpine tectonic phases during Maghrebides orogeny in the Kabylian domain (Centre-East of Northern Algeria)

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The Kabylian region [36.5-36.00N and 3.5-5.E] where are exhibited different geological domains belonging to the Algerian Maghrebides. This domain has undergoes during the Meso-Cenozoic, the consequences of opening, closing the Alpine ocean, as well as opening the current Algerian-Provencal basin.

During the early Secondary, from the Jurassic, the Maghrebides was the seat of a distension associated to an opening with sinistral movements of the central Atlantic. In the Djurdjura chain characterized by carbonate deposits Platform, the rifting stage is initiated from Triasic and the oceanization or a largest sea stage was maintained throughout Jurassic.

During the lower Cretaceous, the opening of the North Atlantic causes at scale of Maghrebides, a preliminary closure transpressional movement. It was generated an E-W sinistral shear zones that become dextral transpressive, from the Cretaceous to Eocene. The dextral movement is dated" middle Lutetian" in Djurdjura chain.
From middle Miocene, the N-S convergence which appears contemporaneous with the setting up of the western Mediterranean Sea. This phase marks the Maghrebides in Algeria and generates throughout the Kabylian domain the sliding of thrust sheets and tectonic fracturing. The Djurdjura chain in particular is already organized into a set of E-W overlapping nappes, shifted by conjugated NW-SE dextral and sinistral NE- SW strike slip faults.

In middle- lower Miocene, the distension occurs in Maghrebides and marks the Kabylian area, by generating the Soummam basin and the Tizi Ouzou basin, volcanic fissure in some coastal regions and the magmatism in Thenia region.

From the end of Miocene to early Pliocene, the convergence continues and the beginning of a collision is manifested by a calc-alkaline volcanism then alkaline mark almost the entire Northern Algeria, with East -West polarity. During the Pliocene, a distension ENE-WSW to E-W predominates. And from the Pleistocene NNW-SSE N-S compression tectonics takes relay and it revealed in Kabylia region through a seismic activity especially in the south domain as in the Babors chain.

Keyword: Alpine phases, neotectonics, Kabylian domain, Maghrebides chain.

NOTES

The origin of the Bitlis Massif and its importance for the understanding of the northern convergent plate boundary of the Arabian Plate.

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The Bitlis Massif is a deformed, fault bounded, slice of continental crust which has suffered widespread High Pressure - Low Temperature metamorphism. Its southern boundary with the Arabian Plate is defined today by low angle thrust faults. Its northern boundary is formed by a back thrust along the southern edge of the Mus Basin and Lake Van. To the west, adjacent to the East Anatolian Fault, the Bitlis Metamorphics plunge beneath a cover of ophiolitic rocks and Late Maastrichtian and younger sediments. To the east the Bitlis Metamorphics and their Tertiary cover plunge beneath low angle thrust sheets of melange. The Bitlis Block is interpreted to have formed part of the outer edge of the Arabian Plate during Permian – Early Triassic time. In Mid Triassic – Early Cretaceous time it formed an outer high covered with carbonates (here correlated with the exotic Bisitoun carbonates of Iran), and separated from the main Arabian Plate by a deep marine basin underlain by extended crust, basic volcanics and exhumed mantle. In Turonian – Early Campanian time the Bitlis Block was deeply subducted, and was overridden by an ophiolite. In Late Campanian – Early Maastrichtian time it was ejected from the subduction zone, precisely coincident with the final phase of the ophiolite emplacement on to the Arabian Plate. In Late Maastrichtian time conglomerates and rudist carbonates were deposited over parts of the now exhumed Bitlis metamorphic rocks. In Palaeogene – Oligocene time the Bitlis Block subsided and was buried by clastic and carbonate sediments and Eocene volcanics. It was locally affected by Late Eocene thrusting. By the Early Miocene a shallow water carbonate platform extended northwards from the Arabian Plate, across the buried Bitlis Metamorphics, and into the Mus and Van Basins. From Late Miocene time the Bitlis Block and the adjacent Mus and Van Basins were underthrust by the Arabian Plate. Relatively thin thrust sheets of the Bitlis Metamorphics and their cover rocks were thrust southwards at least 50 km across the Arabian Plate in Late Miocene – Quaternary time. The Pleistocene - Holocene Nemrut volcano with its spectacular caldera and ignimbrite sheets is located along the northern edge of the Bitlis Massif and interpreted to be underlain by the leading edge of the Arabian Plate.

NOTES

U-Pb zircon geochronology of Daraban Leucogranite, Mawat ophiolite, northeastern Iraq: A record of subduction to collision history for Arabia-Eurasia plates

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The Mawat ophiolite is part of the Mesozoic Neo-Tethyan ophiolite belt of the Middle East and lies in the Zagros Imbricate Zone of Iraq. It represents fossil fragments of the Neo-Tethyan oceanic lithosphere within the Alpine collisional system between the Arabian and Eurasia Plates. First U-Pb dating of magmatic zircon from the Daraban leucogranite intrusion in Mawat ophiolite reveal that melting of sedimentary material beneath the hot Zagros proto-ophiolite in an intra-oceanic arc environment led to anatexis at the subduction front and the generation of granitic melts at 96 Ma which were emplaced up to the level of the ophiolite Moho. This process was a response to the initial formation of the Neo-Tethys ophiolite above a northeast-dipping an intra-oceanic subduction zone at 96 Ma.

Published 40Ar/39Ar dating of individual muscovite from the same leucogranite dyke yields 37 Ma plateau ages, reflecting total resetting during the Arabia-Eurasia continental collision stage. Therefore, the granitic intrusion in Mawat ophiolite preserves a record of the subduction to collision cycle of the Zagros Orogenic Belt. The 59 Ma age difference between zircon and muscovite from Daraban leucogranite represent the duration of the subduction-collision cycle of the Zagros Orogenic Belt in Kurdistan region of Iraq and the time span for closure of the Neo-Tethys ocean along northern margin of the Arabian plate.

NOTES

The Wilson Cycle: the subduction initiation stage

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A critical stage in the Wilson Cycle is the change from an opening to a closing ocean basin. Subduction initiation is commonly identified as a major problem in plate tectonics, and said to be observable nowhere, yet in the west Pacific and eastern Indonesia there are many young subduction zones. Few observational or theoretical studies consider these examples.

Some subduction zones, such as the Banda Arc, developed by propagation of an existing trench by tearing along a former ocean-continent boundary or existing faults. This ‘solves’ the problem since the earlier subducted slab provides the driving force to drag down unsubducted ocean lithosphere. Elsewhere, former transforms are suggested as sites of subduction initiation although such models are speculations based largely on geochemical arguments and dubious plate tectonic reconstructions. None of these explanations account for young subduction zones in eastern Indonesia including those in which the subducted slab is not yet at 100 km depth.

Near to Sulawesi are examples of subduction zones at different stages of development. These examples show that subduction initiated at a point, such as a corner in an ocean basin, where there were great differences in elevation between ocean floor and adjacent thickened arc or continental crust. Subduction began at the edges of ocean basins, not at former spreading centres. The age of the ocean crust appears unimportant.

In the earliest stages extension on land is linked to offshore deep water toe thrust development and detachments in the upper crust. Subsequent overthrusting and flow of arc/continent crust is associated with granitic magmatism and deeper detachments leading to depression of adjacent ocean crust. Once the loaded oceanic crust reaches depths of c.100 km, transformation to eclogite probably leads to slab pull causing the new subduction zone to grow in both directions along strike; arc magmatism may begin.

The close relationship between subduction and extension is recorded by dramatic elevation of land, exhumation of deep crust, and spectacular subsidence of basins imaged by seismic and multibeam data. Exhumed granites and high-grade metamorphic rocks at elevations up to 3 km, separated by alluvial sediments from carbonate reefs now at depths of 2 kilometres, imply vertical movements of several kilometres in a few million years. These observations raise questions of whether subduction is driving extension or vice versa, the time required to move from no subduction to active subduction, and how these processes can be identified in the geological record.

NOTES

Temporal plume-intracontinent and plume-slab interactions explain tectonic history of East Asia during Cretaceous

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Although A-type granitoids, high-Mg basalts (e.g., picrites), adakitic rocks, basin-and-range-type fault basins and thinning of the North China Craton (NCC), and the southwest-to-northeast migration of adakites and A-type granitoids in southern Korea and Japan during the Cretaceous are thought to be attributable to the upwelling of hot asthenospheric mantle and/or ridge subduction, the genesis of these features remains controversial. Furthermore, the paucity of ridge subduction in a recent plate reconstruction model poses a problem because the Cretaceous adakites in southern Korea and southwest Japan could not have been generated by the subduction of the old Izanagi plate. Here, we suggest that plume-intracontinent (intracontinental plume-China continent) and subsequent plume-slab (the intracontinental plume-subducting Izanagi plate) interactions generated the various intracontinental magmatisms and tectonics in China, southern Korea, and southwest Japan. We support our suggestion using three-dimensional numerical subduction models designed to evaluate plume-slab interaction along southern Korea and southwest Japan, and show that the pulse-like magmatisms of adakites and A-type granitoids were generated by temporal plume-slab interaction. We also show that the southwest-to-northeast migration of the adakites and A-type granitoids in southern Korea and southwest Japan is correlated with the opposite migration of the East Asian continental blocks, which resulted in the temporal plume-slab interaction. This implies the existence of the intracontinental mantle plume in China, and the intracontinental mantle plume explains the A-type granitoids, high-Mg basalts, adakitic rocks, and basin-and-range-type fault basins distributed in China. Thus, the temporal plume-intracontinent and plume-slab interactions significantly contributed to the tectonic history of East Asia during the Cretaceous.

KEYWORDS: plume-intracontinent interaction, plume-slab interaction, numerical model, Cretaceous, East Asia, subduction, adakite, adakitic rock, A-type granitoids

NOTES

3D Wilson cycle: structural inheritance and subduction polarity reversals

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Many orogenies display along-strike variations in their orogenic wedge geometry. For instance, the Alps is an example of lateral changes in the subducting lithosphere polarity. High resolution tomography has shown that the southeast dipping European lithosphere is separated from the northeast dipping Adriatic lithosphere by a narrow transition zone at about the “Judicarian” line (Kissling et al. 2006). The formation of such 3D variations remains conjectural. We investigate the conditions that can spontaneously induce such lithospheric structures, and intend to identify the main parameters controlling their formation and geometry.

Using the 3D thermo-mechanical code, I3ELVIS (Gerya and Yuen 2007) we modelled a Wilson cycle starting from a continental lithosphere in an extensional setting resulting in continental breakup and oceanic spreading. At a later stage, divergence is gradually reversed to convergence, which induce subduction of the oceanic lithosphere formed during oceanic spreading. In this model, all lateral and longitudinal structures of the lithospheres are generated self-consistently, and are consequences of the initial continental structure, tectono-magmatic inheritance, and material rheology.

Our numerical simulations point out the control of rheological parameters defining the brittle/plastic yielding conditions for the lithosphere. Formation of several opposing domains of opposing subduction polarity is facilitated by wide and weak oceanic lithospheres. Furthermore, contrasts of strength between the continental and oceanic lithosphere, as well as the angle between the plate suture and the shortening direction have a second order effect on the lateral geometry of the subduction zone.
In our numerical experiments systematic lateral changes in the subduction lithosphere polarity during subduction initiation form spontaneously suggesting intrinsic physical origin of this phenomenon. Further studies are necessary to understand why this feature, observed in nature, is recurrent in our models. It is necessary to determine whether it is controlled by rheological properties, and/or is constrained by inherited lithospheric structures.

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NOTES

Subduction initiation in the Appalachian-Caledonide system: Implications for the Wilson Cycle

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The Appalachian-Caledonide orogen was the first to be interpreted as a zone of plate-tectonic collision. Wilson's original question "Did the Atlantic close and then reopen?" addresses only part of what was subsequently termed the "Wilson Cycle". The transition from an expanding to a closing ocean was not addressed by Wilson, and the initiation of subduction in new oceans remains a poorly understood part of the supercontinent cycle. The history of oceans formed since the breakup of Pangaea suggests that spontaneous subduction initiation at passive margins (or margin inversion) is rare.

In the Appalachian-Caledonide system, rifting continued to at least ~550 Ma, producing an ocean with numerous hyperextended passive margins and microcontinental blocks. These include both peri-Laurentian and peri-Gondwanan terranes; the latter have been grouped into domains characterized by platformal Cambrian environments (E. and W. Avalonia) and deeper-water successions (Ganderia and Megumia). W. Avalonia represents relatively juvenile continental crust, whereas Ganderia is more evolved; E. Avalonia may be heterogeneous, and Megumia shows a transition up-section from juvenile to more mature sources.

Arcs were present in the developing Iapetus Ocean by 505 Ma as recorded by ophiolites from New England to Scandinavia. Several arguments indicate that these arcs were not generated by passive margin inversion. Many show juvenile isotopic signatures. Also, the E. to M. Ordovician Taconian/Grampian orogens are interpreted as products of collision between arcs and the Laurentian passive margin, implying prior existence of subduction zones offshore. Approximately simultaneous collisions on the margin of Gondwana, leading to the Penobscot and Monian deformation events, is also hard to reconcile with coincidental margin inversion on SE side of Iapetus.

In an alternative hypothesis, we infer that subduction was initiated by incursion of arc systems from the external ocean into the young Iapetus, comparable to the recent migration of the Caribbean and Scotia arcs in the Atlantic. Almost simultaneous deformation on the Gondwanan and Laurentian margin of Iapetus can then be explained by interaction with a single, though complex and sinuous arc system. In preliminary test of this hypothesis, the kinematics of Penobscot deformation in coastal Maine show that the predominantly mafic Ellsworth terrane was thrust northwestward onto Ganderian continental margin units of the St. Croix terrane, consistent with the incursion model. These observations, and Wilson's original comparison with the Atlantic, suggest that spontaneous inversion of passive margins is an unlikely driving mechanism for the transition from ocean opening to ocean closing.

NOTES

Interpretation of Appalachian-Variscan Ophiolite Complexes: A tweeter in woofer's clothing?

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Subduction in both the Iapetus and Rheic oceans, the two Paleozoic oceans whose closure produced the Appalachian-Caledonide-Variscan orogen, began relatively soon after their opening. Vestiges of the oceanic lithospheres of both oceans are preserved as supra-subduction (SS) ophiolites and related mafic complexes. There are no adequate mechanisms to explain why SS ophiolites are obducted so soon after the ocean they formed in originated.

Published Sm–Nd isotopic data from these complexes indicate (i) derivation from highly depleted (HD) mantle with time-integrated depletion in Nd relative to Sm, (ii) that the extent of this depletion requires a melting event that occurred before either ocean existed, which implies (iii) that the HD mantle source was inherited from an older ocean (e.g. the Paleopacific) and captured within these Paleozoic oceans. Variation in density produced by Fe-Mg partitioning during this melting event would have rendered the older lithosphere more buoyant than the surrounding lithosphere, facilitating both its transfer from the older Paleopacific to the younger Paleozoic oceans, and the preferential development of oceanic arcs and future ophiolite complexes around this buoyant core. Such lithospheric capture is broadly analogous to the Mesozoic–Cenozoic capture of the Caribbean plate by the Atlantic realm, and may be the preferred site for oceanic arc development and ophiolite obduction. More generally, this mechanism of "plate capture" may (i) be an artifact of the geometry of supercontinent breakup, and (ii) explain the onset of subduction in an ocean soon after its formation. This analysis suggests that there is an important earlier history in many ophiolite complexes that has been previously unrecognized.

More generally, this analysis casts doubt on whether the oldest crystallization age obtained from supra-subduction ophiolites can be assumed to reflect the onset of subduction leading to closure of the oceanic tract in which the ophiolite was formed.

NOTES

Tectonic Evolution of the Gulf of Mexico and Caribbean Region: not an open and shut case

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Wilson (1966) proposed that the Caribbean lithosphere originated in the Pacific and migrated to its present position in a manner similar to ice-rafting in an Alpine glacial valley. Nevertheless, both *Pacific-origin* and *in-situ* (inter-American spreading) evolutionary models for the Caribbean region continue to be entertained. This talk reviews advances in our understanding of Atlantic plate kinematics, Caribbean subduction history, and circum-Caribbean sedimentary basin development, supported by seismic reflection data, that collectively demand derivation of Caribbean lithosphere from the Pacific since the Early Cretaceous. In addition, the Jurassic portion of this region's evolution involved the counter-clockwise rotation of Yucatan Block from the US Gulf margin in the Middle and Late Jurassic. I will present paleotectonic maps drawn in the mantle reference frame through time that integrate (1) Triassic Atlantic and western Pangean reconstruction; (2) rotational motions of Yucatán Block based on an aeromagnetic map of the Gulf of Mexico; (3) acknowledgement of the Proto-Caribbean passive margins formed as a function of Pangean break up; (4) Early Cretaceous origin for the Great Caribbean Arc that originally spanned the gap from Mexico to Ecuador; (5) acknowledgement that the Caribbean basalt plateau may pertain to the paleo-Galapagos hot spot, the occurrence of which may have been partly controlled by a slab gap beneath the Caribbean Arc/Plate; (6) Campanian initiation of subduction at the Panama–Costa Rica Arc; (7) inception of a north-vergent "Proto-Caribbean inversion zone" along northern South America to account for Cenozoic convergence between the Americas ahead of the Caribbean Plate; (8) Paleogene opening of both the Yucatan and Grenada intra-arc basins as mechanisms for allowing the Caribbean arcs to take on the pre-existing geometries of the Proto-Caribbean margins; (9) E-W translation of the Caribbean between the Americas since the Eocene. The importance of assessing tectonic evolution in the hotspot or local "Benioff Zone" reference frame is highlighted, and it is shown that more local plate motions can occur during the greater mega-regional spreading phases of the Wilson Cycle that complicate simpler perceptions of oceans opening and closing.

NOTES

Two many oroclines in Iberia? A Pangea's simple twist of fate

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The supercontinent Pangea formed in the Upper Carboniferous as a result of the Gondwana-Laurussia collision, producing the strongly bended Variscan-Alleghanian orogen. Iberia is interpreted to comprise two Variscan bends forming an S-shape mountain belt: the Cantabrian Orocline to the north and the Central Iberian bend to the south. Coeval formation of both oroclines, however, requires a large amount of N-S shortening (in present day coordinates), during Pangea's amalgamation. Contrary to the Cantabrian Orocline, neither kinematics nor geometry of the Central Iberian bend were well-constrained. New structural and paleomagnetic data from the southern limb of the Central-Iberian bend shows: (i) ca. 60° counter-clockwise vertical axis rotation during the Late Carboniferous to Early Permian - essentially the same as determined for the southern limb of the Cantabrian Orocline and (ii) no axial plane parallel shortening as the found in the Cantabrian Orocline. These results are incompatible with the hypothesized contorted S-shape for the Iberian Variscides. We argue that Central-Iberia, if really bent, only could acquire its curvature earlier than the Cantabrian Orocline, being an inherited structure. These results need to be include in global reconstruction as they may change the formation mechanism of Pangea.

NOTES

Tom Worsley and the Origin of the SuperContinent Cycle

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Over the past two decades, data from a wide variety of sources have led to the realization that Pangea was just the most recent in a series of supercontinents that have punctuated Earth history for billions of years. This record of episodic supercontinent assembly and breakup is now recognized as having profoundly influenced Earth's geologic, climatic and biological evolution. The cycle documents a fundamental aspect of Earth dynamics and is arguably the most important development in Earth Science since plate tectonics.

Often overlooked in this exciting development is its progenitor, Tom Worsley, who first proposed the existence of such a cycle in 1982 (*EOS* 63 (45), 1104). Although advocacy of long-term episodicity in tectonic processes predates plate tectonics, Worsley was the first to link such episodicity to the cyclic assembly and breakup of supercontinents. Contending that such a cycle would be manifest by peaks in collisional orogenesis lagged by rift-related mafic dike swarms, Worsley and his colleagues used available (Rb/Sr) data to argue that such episodes had punctuated Earth history at intervals of ~500 m.y. for at least the past 2.5 billion years. They predicted the existence of five supercontinents at ca. 0.6, 1.1, 1.7, 2.1 and 2.6 Ga (*AGU Geophysical Monograph* 32, 1985, 561-572), the dates of four of which correspond to the amalgamation of Gondwana, Rodinia, Columbia and Kenorland.

For the Phanerozoic, they modeled the cycle's influence on sea level by estimating the independent effects of sea floor elevation on ocean basin volume and epeirogenic uplift on continental platform elevation, and showed that predicted water depths at the shelf break closely matched first-order Phanerozoic sea level change for a supercontinent cycle of ~440 m.y. duration (*Marine Geology*, 1984, 58, 373-400). They further explored the cycle's influence on tectonic trends, platform sedimentation, ice ages and global climate, major events in biogenesis, the marine stable isotope record and a wide range of biogeochemical signals (*Paleoceanography*, 1986, 1, 233-263). That many of these influences have been borne out by more recent research and most of the predicted supercontinents (now defined more precisely by U-Pb geochronology) have been named is a testament to this early work and a tribute to the concept's originator.

NOTES

Posters

Monday 23rd May

1. **From Gondwana breakup to collision – A Wilson Cycle perspective**
   Ana D Gibbons (Statoil ASA, Norway)

2. **The World Stress Map Database Release 2016 - Global Crustal Stress Pattern vs. Absolute Plate Motion**
   Oliver Heidbach (German Research Centre for Geosciences, Germany)

3. **Middle America – intracontinental extension along ancient structures**
   Keith James (Aberystwyth University, Wales)

4. **Queue tectonics, roundabout tectonics, and the opening and closing of narrow ocean basins**
   Åke Johansson (Swedish Museum of Natural History)

5. **Extensional Evolution of the Lower Crust with Orogenic inheritance: Observations from the Basin-and-Range and the Pyrenees**
   Rodrigo D Lima (Institute for Geophysics, University of Texas at Austin)

6. **Marginal parts of a Wilson Cycle: an along-strike view of structural inheritance and continental growth**
   David Macdonald (University of Aberdeen)

7. **Kinematic and paleobathymetric evolution of the South Atlantic**
   L. Pérez-Díaz (Royal Holloway University of London)

8. **Large-scale pattern of mantle evolution through rifting in hyper-extended margins**
   Picazo, S (University of Lausanne, Switzerland)

9. **What can fracture networks tell us about structural inheritance (Gippsland Basin, southeast Australia)?**
   Anindita Samsu (Monash University, Australia)

Tuesday 24th May

1. **The Conversion of Mechanisms Controlling Salt Diapirs in Jianghan Basin, Middle Yangtze Craton**
   Min Caizheng (China University of Geosciences, China)

2. **The characteristics of Cenozoic episodic rifting in Baiyun Sag, Northern South China Sea: Evidence from the Structural Characteristics**
   Li Gang (China University of Geosciences, China)

3. **Formation of seaward-dipping reflectors: evidence from velocity analysis of long-offset seismic data from the South Atlantic**
   Carl McDermott (Imperial College London, UK)

4. **Localisation of deformation and seismicity in intraplate domains: Reactivation of paleo-structures crustal and lithospheric**
   Alizia Tarayoun (Université des Sciences de Montpellier, France)

5. **Tectonic evolution of a pull-apart basin, constraints from gravimetric survey (Sorbas Basin, SE Spain).**
   Lorenzo Valetti (University of Manchester)

6. **Analysis of gravity measurements in the Ulleung Basin (East Sea/Sea of Japan) and its implications for the Moho depth variations**
   Kim Yoon-Mi (Korea Institute of Geoscience and Mineral Resources, Korea)

7. **The influence of basement uplifting on the salt tectonics deformation of intracontinental rift basin: Zifusi depression, Jianghan basin**
   Yulu

Wednesday 25th May

1. **The occurrences and origins of deformed structures in the Upper Cretaceous deposits in Jordan**
   Ikhlas Alhejoj (University of Jordan, Jordan)

2. **3D Wilson cycle: structural inheritance and subduction polarity reversals**
   Stephane Beaussier (Geological Institute, Zurich, Switzerland)

3. **Are Subduction-related processes more significant than continental insulation in controlling mantle dynamics post-supercontinent formation?**
   Philip J. Heron (University of Toronto, Canada)

4. **And the Variscan orogen buckled**
   Daniel Pastor Galán (Universty of Utrecht)

5. **Supercontinent and Superplate?**
   Daniel Pastor Galán (Universty of Utrecht)

6. **Modes of reactivation of the Late Paleozoic-Mesozoic extensional basins during the central Apennines Wilson Cycle**
   Enrico Tavarnelli (Università degli Studi di Siena, Italy)

7. **Structural inheritance and tectonic inversion in foreland thrust belts: an Apennine-Adriatic perspective**

Enrico Tavarnelli (Università degli Studi di Siena, Italy)

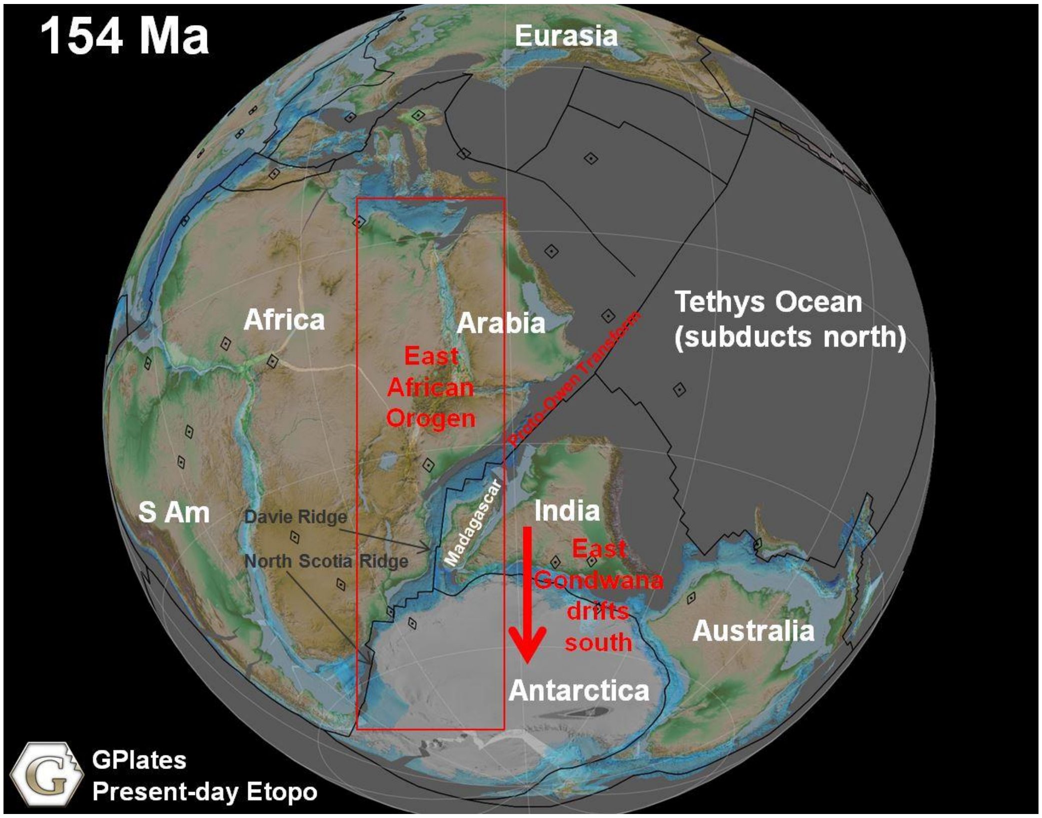
8. **The Atlas of the Underworld and global slab kinematics**
   Douwe Van Der Meer (Utrecht University, Netherlands & Nexen Petroleum, UK)

Poster Presentation Abstracts

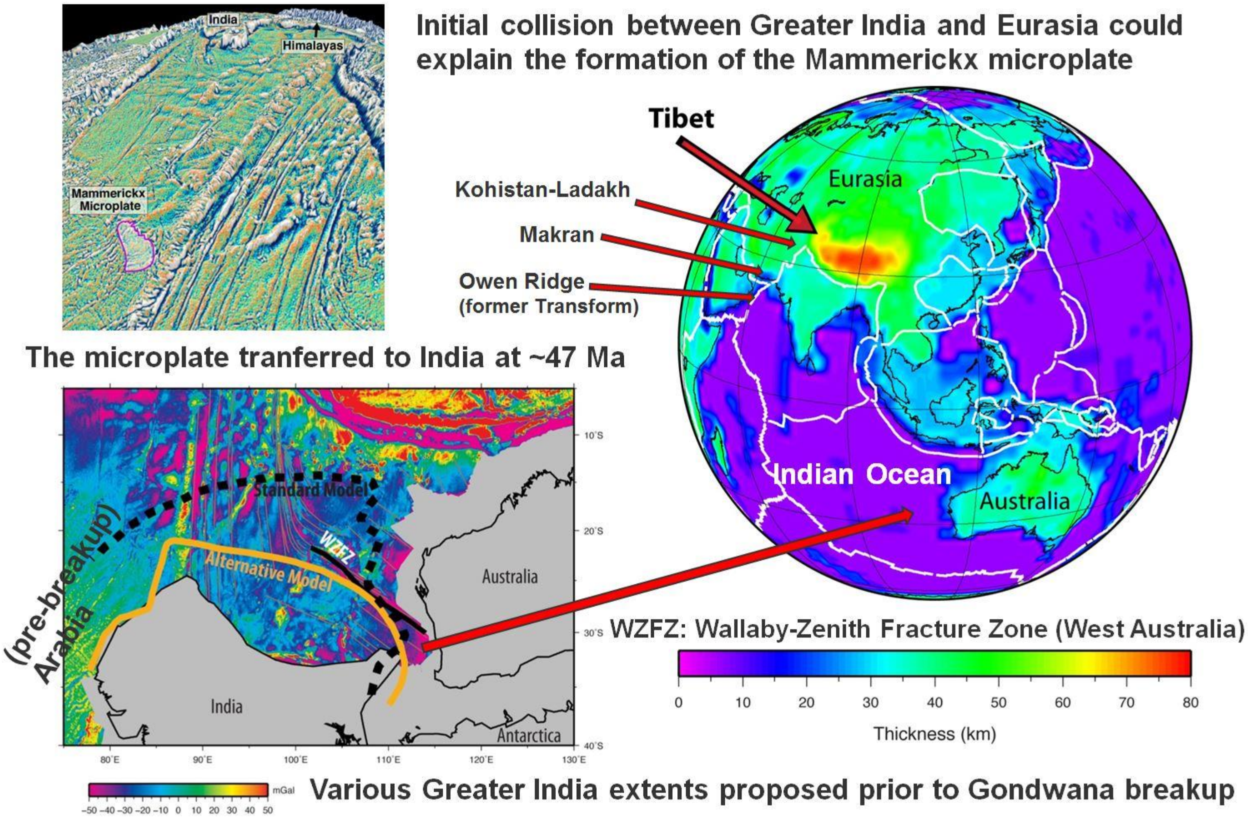
From Gondwana breakup to collision – A Wilson Cycle perspective

Presenting author: **Ana D Gibbons** *(*Statoil ASA, Norway*)* email: *angi@statoil.com*
Co-authors: R. Dietmar Müller, Sabin Zahirovic, and Kara J. Matthews *(*University of Sydney, Australia)

The Wilson Cycle invokes inherited weakness to localise continental breakup, forming new oceanic basins until collision and orogenic collapse restarts the process. Gondwana should be a prime example of such behavior but its break up is more convoluted. The southern portion of Gondwana breakup (below) adheres well to Wilson Cycle concepts. Between Madagascar and Mozambique, the Davie Ridge (below), adjacent to a former transform fault, corresponds to the direction of initial divergence (N-S), as did the North Scotia Ridge transform (below), which formed in the early Weddell Sea between Falklands and Antarctica. These ridges seem to be in line with and within the Mozambique Belt, as part of the East African Orogen (below), reconstructed roughly to be 1500 km wide (E-W). The diffuse former suture zone links the Mozambique Belt to the Nubian Shield, between which the East Africa Rift is forming an embryonic ocean basin. According to the Wilson Cycle, the Mesozoic breakup should have been localized here.



Further north, Gondwana breakup does not entirely fit the paradigm. In the Jurassic, India-Madagascar drifted from Africa-Arabia, forming margins 500-1000 km from the East African Orogen, and a Tethyan transform (Owen Ridge) formed at ~45 degrees to the former East African trend. Essentially, the Indian Ocean formed east of the Owen Ridge, which allowed Greater India to move north to finally form the Himalayas via collision. Several hotspots (Reunion, Marion, Crozet) aided Greater India's escape, but earlier contenders may have existed. For example, if Vema and Comores seamounts were formed by long-lived stationery hotspots (black diamonds, above), they would have been located within 400 km of the Gondwana breakup zone. The transform itself likely initiated as a triple junction north of and between India and Arabia. Most triple junctions in the Indian Ocean are proximal to hotspots (within 400 km).



The Owen Transform formed after Cimmeria drifted from Gondwana to Eurasia, forming the margin where Greater India collided. The geometry of Cimmeria was likely influenced by the Hercynian/Variscan orogeny, much of which has since been overridden by the Alpine-Himalayan orogenies, located on either side of the Owen Transform. Geological evidence suggests that Greater India collided with such a backarc (Kohistan-Ladakh, above) in the Early Eocene, which is still cited as the onset of collision between India and Eurasia. However, clues from oceanic crust that constrain the passage of India reveal that a microplate (Mammerickx, above), which formed at the India-Antarctic ridge, was transferred from the Antarctic to Indian plate at ~47 Ma after a ridge-transform reorganization. This was likely caused by counter-clockwise motion of the Indian plate, and NW Greater India colliding with the Eurasian Margin (near Makran/Owen Transform), provides a robust explanation.

Our current plate model only needs minor adjustments to account for an initial 47 Ma continental collision by either extending the pre-collision margins of NW Greater India or

Eurasia by 300 km in total. This is reasonable given that neither of these margins are still intact and therefore cannot be precisely restored by paleomagnetic methods or otherwise.

The World Stress Map Database Release 2016 - Global Crustal Stress Pattern vs. Absolute Plate Motion

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The World Stress Map (WSM) Project was initiated in 1986 under the auspices of the International Lithosphere Program in order to compile the global information on the contemporary crustal stress state. The data come from a wide range of stress indicators such as borehole data (e.g. hydraulic fracturing, borehole breakouts), earthquake focal mechanism solutions, engineering methods (e.g. overcoring), and geological data (e.g. inversion of fault slip measurements). To guarantee the comparability of the different data sources each data record is assessed with the WSM quality ranking scheme. For the 30th anniversary we compiled a new WSM database with 42,410 data records which is an increase by >20,000 data records compared to the WSM 2008 database. In particular we added new data from more than 3,500 deep boreholes and put special emphasis on regions which previously had sparse or no published stress data such as China, Australia, Brazil, Southern Africa, Middle East and Iceland. Furthermore, we fully integrated the Chinese stress database and the Australian stress database. The resulting data increase reveals several areas with regional and local variability of the stress pattern. In particular we re-visited the question whether the plate boundary forces are the key control of the plate-wide stress pattern as indicated by the first release of the WSM in 1989 [Zoback et al, 1989]. As the WSM has now more than 10 times data records and thus a better spatial coverage we first filter the long-wave length stress pattern on a regular grid. We determine at these grid points the difference between absolute plate motion azimuth using the global plate model HS3-NUVEL1A [Gripp and Gordon, 2002] and the mean orientation of the maximum horizontal stress. The preliminary results show that the earlier findings are still valid in principal. However, all plates show in some parts significant deviations from this general trend; some plates such as the Australian Plate show hardly any correlation at all. These deviations seem to be either due to mantle drag forces, different plate boundary forces acting in different directions, additional internal body forces or major structural inhomogeneity's.

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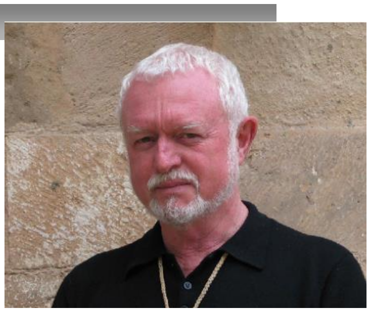

Middle America – intracontinental extension along ancient structures.

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Recently published local and global data clarify geology in Middle America. The Gulf of Mexico and the Yucatán and Caribbean manifest a regional tectonic fabric, resulting from Triassic - Recent reactivation of old structures. N60^{o}W transform motion, parallel to major fractures and faults of the western Central Atlantic and North America, accommodated Gulf of Mexico – Caribbean opening. Rifting occurred along N35^{o}E tectonic lineaments, reversing Palaeozoic (Appalachian/Caledonian) convergence. Crustal thicknesses and gravity data record thinning away from cratons. Deep seismic data from the Gulf of Mexico reveal salt-bearing rifts bounded by basement highs, basinward thinning of continental crust, outboard seaward-dipping wedges and thin (?oceanic) crust, repeating the geology offshore eastern N America and the extended margins of the N and S Atlantic. The Caribbean interior shows the same architecture, capped by Upper Cretaceous basalts of seismic Horizon B””, similar to flows above extended crust offshore Norway and NW UK. Change of B” character from smooth (subaerial) to rough (subaqueous) occurs above a major, wedge-bounding fault with indications of shelf edge buildup. Diapiric piercing and tilting/uplift of this singular horizon recall salt rafting of igneous layers in Louisiana. Pre-B" seismic architecture indicates rift to carbonate platform, wedges of seaward-dipping reflectors and thinned crust above shallow Moho. Thick (10 km) layers of continental velocities below Central America and the Lesser Antilles accord with “extreme continental-like” high silica chemistry of volcanic rocks. They are dispersed continental fragments, similar to those revealed in recent years by velocity data and ancient inherited zircons in the Izu-Bonin, East Java, Luzon, Solomon and Vanuatu arcs. Lesser Antilles xenoliths include granite, metamorphic rocks, calcareous metasediment, gypsum and rounded quartz grains. Eocene ash fall zircons on Barbados record Antillean volcanism; admixed Palaeozoic/Proterozoic zircons record ancient arc roots. The Antillean continental velocity layer extends to Barbados. Here, seismic and oil data relate the Eocene Barbados Scotland to the fluvial/deltaic Misoa and the underlying La Luna source of the Maracaibo Basin. The Scotland carries orogenic and cratonal detritus, mudcracks and freshwater molluscs, indicating a local, continental origin. Inherited zircons from Cuba, Hispaniola, NW Venezuela, Margarita, Trinidad, Granada and Carriacou indicate autochthonous, ancient crustal foundations. Radical rethink of Yucatán - Caribbean palaeogeography is indicated. Located between the Gulf of Mexico and northern South America they probably carry hydrocarbon potential. Four times larger in area, they are as poorly known as was the North Sea in 1965.

Queue tectonics, roundabout tectonics, and the opening and closing of narrow ocean basins

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Plate tectonics naturally involve the formation and widening of ocean basins as well as their subsequent closure and disappearance. Especially for narrower oceanic basins, this process typically occur by introversion, in which the bounding continents return to more or less the same positions as prior to ocean opening. This is often envisaged in terms of a classical Wilson cycle where the original continent rifts and the two parts drift apart in opposite directions, followed by a reversal in plate motion, leading to subduction, ocean closure and final continent-continent collision.

However, such reversals of plate movement may be hard to justify from a geodynamic point of view, and may not always be in accord with the overall movement of continental plates when going from one supercontinent configuration to another. An alternative view of looking at this process may be called “queue tectonics”. Just as sometimes a gap may be opened in a line of slowly moving cars, as one car moves ahead of the other, and subsequently be closed again (hopefully not by a full collision) as the car behind catches up, a large continent that moves ahead may be stretched, perhaps along a pre-existing suture or other line of weakness roughly perpendicular to the direction of movement, so that a narrow ocean basin opens. This basin may widen due to ocean floor spreading, but eventually close again in more or less the same relative position, as the continent lagging behind catches up with the forerunner. Examples of oceans opened and closed in this manner would be the Mozambique and Adamastor oceans during the Neoproterozoic transition from a Rodinia to a Gondwana configuration (cf. Johansson 2014).

Another process by which narrow ocean basins may open and close may be called “roundabout tectonics”. As large continental landmasses move by rotational movement, such as during the transition from Rodinia to Gondwana, not only may gaps open perpendicular to their movement direction, but also in longitudinal direction as different parts of the continent move at different speed, in a way akin to the openings between cars in separate lanes moving around a roundabout. Possible examples of such longitudinal ocean basins, where the movement between the neighbouring continents is dominantly transtensional and later transpressional, would be the ones along the Damara orogen between the Congo and Kalahari cratons, and the Eastern Ghats orogen between India and Antarctica.

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Extensional Evolution of the Lower Crust with Orogenic inheritance: Observations from the Basin-and-Range and the Pyrenees

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Continental margins exhibit a range of widths and symmetries defined by the patterns of localization during extension and rifting. The formation of such crustal-scale zones of localized strain occurs early in rift evolution, and the rheology of the lower crust plays a large role in this localization. In particular, domains of low viscosity can control the bulk lower crustal strength relative to the upper crust and lithospheric mantle. Many rifted margins inherit earlier orogenic structures, fabrics, and metamorphic/igneous mineral assemblages, and even though these can predate the rift by 10' to 100's myr, there are hypothesized mechanical linkages between such inherited crustal fabrics and subsequent rift propagation. In the study I used microstructural observations coupled with phase equilibria modeling to further evaluate the role of preexisting orogenic fabrics in continental extension. Exposures of mid- to lower-crustal rocks were investigated in this study; the Funeral and Black Mountains of the Death Valley (DV) region, California, and from the Mauleon Basin of the Western Pyrenees. The Death Valley region sits within the Basin-and-Range region of broadly distributed Cenozoic extension, over a relatively flat and deep (~30-35 km) moho. In contrast, in the Mauleon basin Cretaceous extension was more localized in older Hercynian orogenic crust, which appears to have accommodated mantle exhumation early in the rifting evolution. In both areas, lower crustal rocks are characterized by inherited migmatitic fabrics overprinted by zones of localized, extensional-related fabrics consisting mineral assemblages that define an overall P-T cooling path. The high-temperature fabrics record decompression-melting following late- to post-orogenic collapse. Yet, these areas show contrasting retrograde assemblages and microstructures, inferred to reflect differences in melt segregation and loss at the km-scale, which affected lower crustal fertility and mechanical properties. At subsequent extensional stages, mid- to lower crustal deformation was controlled by high-strain zones consisting retrograde reaction products from the inherited (post-orogenic) fabrics. The transposition of the inherited fabrics associated to crustal thinning over a cooling path is documented with quartz fabrics analysis; while in the DV extensional fabrics are characterized by interconnected "weak" layers, the Mauleon rift-related deformation show minor fluid-assisted reactions and more high-T embrittlement. Therefore, weakening and strain localization during extensional stages is directly controlled by the preexisting, post-orogenic thermal evolution, compositional and fabric development.

Marginal parts of a Wilson Cycle: an along-strike view of structural inheritance and continental growth

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The Wilson cycle predicts continental growth by accretion of continental margin, forearc, arc, and back arc terranes during the closing limb of the cycle. The cycle is usually illustrated in a section normal to the centre of the orogen. In this paper we consider a portion of an active margin along strike from an actively spreading back-arc basin. We examine the role of arc-arc cusp migration, structural inheritance, crustal extension, and strike-slip faulting in continental growth, using Sakhalin, Far East Russia, as an example.

Sakhalin was the forearc to the Sikhote Al'in arc (K2-Pg), the last of three Mesozoic arcs accreted to East Asia. In this paper we propose a model whereby subduction progressively shut down by southward migration of an arc-arc cusp from a position north of Sakhalin in the latest Cretaceous to its present position in Hokkaido, leaving Sakhalin isolated in a retro-arc position. Neogene arc activity was concentrated farther south in Japan, with significant back-arc extension in the Sea of Japan. Tectonism in Sakhalin focused on two discontinuities in the old forearc.

First, the Tatar Strait Basin, which lies north of the Sea of Japan, formed along the old arc-forearc boundary. It extended strongly in the Miocene, partly separating Sakhalin from the Russian mainland. In contrast to the Sea of Japan, there is no evidence that extension in the Tatar Strait was sufficient to generate Cenozoic oceanic crust. However, volcanism on Sakhalin is geometrically linked to, and partially synchronous with, extension in the Japan Sea. The revised tectonic model which incorporates these new data suggests that volcanism on Sakhalin relates to the extensional event in the Sea of Japan. The Tatar Strait basin is important as extension is unlikely to be fully recovered during final closure, indicating that continental growth can occur even away from the areas of maximum extension.

Second, later basin formation in the northern part of the Tatar Strait was driven by transtension resulting from dextral movement on a releasing bend in the strike-slip plate boundary, linked to the cusp between the Japan and Kuril arcs. This deformation focused on the forearc-basin-accretionary complex boundary.

Kinematic and paleobathymetric evolution of the South Atlantic

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The opening of the South Atlantic Ocean is one of the most extensively researched problems in plate kinematics. In recent years focus has shifted to the early stages of continental separation. General agreement exists about ocean opening being the result of the diachronous separation of two major plates, having involved a certain degree of intracontinental deformation. However, in order to achieve their best fits, most modern models assign most of this intracontinental deformation to narrow mobile belts between large, independently moving plate-like continental blocks, even though timings and motions along their boundaries are not well known. Aiming to step away from the very large uncertainty introduced by this approach, here we present a model of oceanic growth based on seafloor spreading data (fracture zone traces and magnetic anomaly identifications) as a context within which to interpret intracontinental tectonic motions.

Our model results are illustrated by an animated tectonic reconstruction. Spreading started at 138 Ma, with movement along intracontinental accommodation zones leading to the assembly of South America by 123 Ma and Africa by 106 Ma. Our model also provides an explanation for the inception and evolution of the Malvinas plate and its connection with the formation of a LIP south of the Falkland-Agulhas Fracture Zone. Finally, we challenge the view of narrow deformation belts as the sole sites of stress accommodation and discuss the implications of our model in terms of the distribution of intracontinental strain.

However, paleobathymetry (depth variations through time) also needs to be considered for a fuller understanding of the ocean's evolution and development of its petroleum systems. At first order, this is controlled by plate tectonics, which determines changes in the geographical location of the lithosphere, along with thermal subsidence, which controls changes in its vertical level. Thermal subsidence is modelled by applying plate-cooling theory to a high-resolution seafloor age grid derived from the plate kinematic model. Then, this thermal surface is refined to account for other factors that affect bathymetry at smaller scales or amplitudes, both within the ocean and the continent-ocean transition zones. The results are a series of paleobathymetric reconstructions of the South Atlantic, which provide a fuller picture of its evolution from Cretaceous times to present.

Large-scale pattern of mantle evolution through rifting in hyper-extended margins

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New ideas and concepts have been developed to understand and be able to give a simplified large-scale view of the evolution of the mantle lithosphere in hyper-extended magma-poor rifted margins based on the ancient Alpine Tethys rifted margin. In contrast to the classical assumption assuming a simple, isotropic mantle lithosphere, these new models integrate observations from exposed and drilled mantle rocks and propose that the mantle lithosphere evolved and was modified during an extensional cycle from post-orogenic collapse through several periods of rifting to embryonic oceanic (ultra-) slow seafloor spreading. But it is, at present, unclear how far these ideas can be generalized at Atlantic type rifted margins.

In our presentation, we review the available mantle data from dredged samples in the North Atlantic and from ophiolite massifs and xenoliths in preserved passive margins i.e. the Alpine Tethys, the Pyrenean domain, and the Dinarides and Hellenides. We revisit the available terminology concerning mantle massifs and xenoliths and compile the available data to identify different mantle domains. We define chemical and petrological characteristics of mantle domains based on clinopyroxene and spinel compositions and compile them on present-day and paleo-geographic maps of Western Europe. Finally we link the observed distribution of mantle domains to the post-Variscan extensional cycle and link domains to processes related to the late post-Variscan extension, the rift evolution and refertilization associated to hyper-extension and the development of embryonic oceanic domains.

What can fracture networks tell us about structural inheritance (Gippsland Basin, southeast Australia)?

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Heterogeneities in basement rocks are thought to influence crustal deformation at multiple scales. This influence can be expressed by fracture localization and development in stratigraphic units overlying basement structures. In the literature, such basement control on younger structures is described as *structural inheritance*, an equivocal term that is often used interchangeably with *reactivation*.

We aim to evaluate whether inheritance can be detected from structures in cover rocks that (i) show apparent similarities in orientation, but no direct physical or genetic link, with structures in the underlying basement and (ii) are not consistent with known far-field paleotectonic stresses. The mechanisms responsible for these types of structural inheritance are distinct from those of reactivation, which is a comparatively well-understood process characterized by repeated displacement along pre-existing faults.

In this study, we characterize fracture patterns at outcrop to regional scale to delineate the relationship and mechanical interaction between the basement and cover rocks in the Gippsland Basin, where both sequences are exposed within close proximity of each other along the coastline. The ‘basement’ underlying the basin comprises Devonian metasediments and granites. Deposition of the sedimentary ‘cover rocks’ began with the onset of rifting in the Early Cretaceous during the break-up of Gondwana.

We apply digital mapping techniques to complement direct observation of brittle structures in outcrops. Fractures and fracture zones are traced on images acquired with an unmanned aerial vehicle (UAV) and processed using a digital photogrammetry workflow. The deformation history of the area is inferred from the orientations, curvature, infill, offset, and spatial distribution of fractures in these sequences. In the cover rocks, meter-scale joints and faults exhibit orientations that are similar to kilometer-scale structures identified from high-resolution bathymetric data.

North to northeast-trending faults, fracture zones, and joints in the cover are oriented sub-parallel to Devonian-aged fold axial traces and fold accommodation faults in the nearby basement. Similarly oriented basement structures (likely faults and shear zones) are identified in aeromagnetic data from the adjacent onshore study area and the offshore area hundreds of kilometers to the southeast. These observations suggest that north to northeast-trending brittle structures in the cover are influenced by the basement. As the study progresses, we will incorporate kinematic indicators, time markers, and fault response modeling to establish whether the apparent basement-cover relationships are driven by reactivation of Devonian-aged faults or relate to different processes involving local stress heterogeneities or inherited basement anisotropy.

The Conversion of Mechanisms Controlling Salt Diapirs in Jianghan Basin, Middle Yangtze Craton

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Due to the significant influence on hydrocarbon accumulation, salt tectonics have become the focus in structural analysis of the petroliferous basins. Previous studies on this topic were mainly concentrated in the passive continental margins, such as the Gulf of Mexico and West African Margin, but rarely in the intracontinental rift basin. Jianghan Basin, developed in the middle of the Yangtze craton, is a typical salt-bearing intracontinental rift basin. The evolution processes of Jianghan Basin have been divided into two stages, including the syn-rift stage started from the Late Cretaceous and the post-rift stage started from the Early Neogene. A Paleogene salt deposition is mainly preserved in the Qian-4 Member of Qiangjiang Formation in the middle of the basin.

In this paper, detailed interpretation of seismic profiles, thousands of drilling data and field investigation are used to study the conversion of mechanisms controlling diapirs in this basin. In the late syn-rift stage, salt rock with different thickness began to flow due to the intense extension of the basin, and a large number of diapirs generated in different regions at the same time. However, the activity of diapers varied greatly in different regions during the post-rift stage. In the northern part of the basin, the gravitational forces promote the continuous growth of diapirs with a thick sedimentary strata overlying the salt layer. While in the southern part, diapirs were dormant due to the thin overlying strata in the early post-rift stage, and reactivated until the overlying strata accumulated to a certain thickness. Other places with thinner sedimentary strata overlying the salt layer, diapirs were no longer active during the post-rift stage for the lack of sediment loading.

This study results show that: In the post-rift stage, the flow and accumulation of the salt in Jianghan Basin is mainly related to regional extension, while in the post-rift stage differential loading becomes the dominant driving force, and the salt diapirs are driven purely by gravity without lateral tectonic forces.

The characteristics of Cenozoic episodic rifting in Baiyun Sag, Northern South China Sea: Evidence from the Structural Characteristics

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The Baiyun Sag, located in Pearl River Mouth Basin of Northern South China Sea where the lithosphere thinned strongly, is a significant Cenozoic tectonic unit. The study area experienced episodic rifting which was interpreted through the analysis of the tectonic-sequence surface, syn-sedimentary faults' activity and the back-stripping of the basins' Cenozoic evolution into rifting and post-rifting stage. The study suggested there are mainly two chasmic activities: The first episode of the Zhu-qiong movement (middle Eocene) and the second episode of the Zhu-qiong movement (from late Eocene to early Oligocene).However, we always know less about the structure of Baiyun Sag because of the lack of clear understanding of the geometry and kinematic characteristics of the faults controlling the Baiyun Sag.

Based on the main body for the three-dimensional, local for two-dimensional high quality seismic reflect data of 40×40 close interpretation of the main faults in the whole area, this paper precisely describes its three-dimensional shape and analyzes its geometry and kinematic characteristics, defining all the main faults and the structure of them. Results show that the structure of Wenchang formation is controlled by the first episode of Zhu-qiong movement, and this stage is the time when the study area rifted strongly characterized by high faults' activities rate, it thus has the typical rifting characteristics and develops half-grabens from the global aspect. Through the accurate interpretation of the geometry and kinematic characteristics of the main faults, we can define the high-angle half-grabens in the west area, and low-angle half-grabens in the east area, and half-grabens and ramp sag in the central area, which are affected by deposit structure. The rift structure of Enping formation is controlled by the second episode of Zhu-qiong movement, and it is the transformation stage of the Baiyun Sag. The main faults activity rate becomes lower, and the scale is smaller, large-scale faults hardly developed as well. In this stage, some areas behave typical inheritable characteristics, characterized by high-angle half-grabens similar to the Wenchang formation; the other areas behave typical transformational characteristics, characterized by several separated sags' transforming into one large main sag. It appears to be caused by the ductile thinning and necking of the crust in response to hot lithosphere stretching.

Key words: episodic rifting; Baiyun Sag; half-graben; structural characteristics; Pearl River Mouth Basin

Formation of seaward-dipping reflectors: evidence from velocity analysis of long-offset seismic data from the South Atlantic

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Seaward-dipping reflectors (SDRs) are a key characteristic of volcanic passive margins. Where they have been drilled, they are shown to be made of packages of thick sub-aerial tholeiitic lavas and thin tuffs that are interbedded with thin layers of terrestrial sediment. This combination has posed many problems for conventional seismic imaging. The high-velocity contrast between basalt and sediments means that a significant part of the seismic energy appears at large source receiver offsets (> 4 km), while the near offsets are influenced by peg-leg multiples. Further, in areas with thick basaltic sequences, high-frequency seismic energy tends to experience increased scatter when compared to the low-frequencies. Here we use long-offset, low-frequency seismic reflection data to gain new insights into the structure and hence formation of SDRS.

The seismic data were acquired by ION-GXT offshore Argentina and Uruguay between 2009-12 using 10,200 m long-offset streamers towed at a water depth of 10 m. We selected two dip-lines for analysis: one offshore Uruguay and one offshore Argentina. Both lines image zones of SDRs with widths of 80-100 km and thicknesses up to 7 km with a frequency bandwidth of 3-40 Hz. We prepared the gathers by extensive de-noising and multiple removal which targeted several types of multiples such as internal, water related, and apex shifted multiples. Semblance velocity analysis was then conducted on super-gathers made from stacking 10 adjacent CMPs. A long-offset NMO correction was used to take into account the streamer length used. The velocity analysis was completed every 250 m to ensure capturing the lateral velocity variations and the final velocity models were combined with pre-stack time migrated images.

Along-strike the velocity of the SDR packages, which averages ~4.7 km s^{-1} varies by up to 1 km s^{-1}, with the highest internal velocities observed within the thickest volcanic packages. Both beneath and at the down-dip end of individual SDR packages we have identified high-velocity bodies with velocities of 6.3-6.9 km s^{-1}. These features occur at a spacing of less than 10 km, are typically 5-10 km wide, with an average thickness of 3 km and are observed on both of the analysed profiles. In a number of places the individual SDR units and associated high-velocity bodies are separated by normal faults. The sequence then passes oceanward into true oceanic crust. Beneath the SDRs and the high velocity bodies the velocities reduce to more typical values of metamorphic continental crust (5.5 km s^{-1}).We interpret the zones of anomalously high-velocity as depleted mafic or ultramafic solidified magma, intruded within crystalline continental crust. We propose that the intrusive bodies are the origin of the magmas that fed the sub-aerial tholeiitic lava flows forming the SDRs.

Localisation of deformation and seismicity in intraplate domains: Reactivation of paleo-structures crustal and lithospheric

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The St Lawrence valley, eastern part of Canada has known a succession of two complete Wilson cycles leading to a strong structural inheritance. We can observe in this area, but also in other intraplate domains, numerous earthquakes. This is not explained by the plate tectonics theory which proposes rigid plates leading to the concentration of the deformation at plate boundaries. The mechanisms involved in the intra-continental deformation are poorly known at present and still discussed. A theory suggests that the intraplate deformation is due to the reactivation of crustal and lithospheric paleo-structures.

Yet, a question rises. Can the structural inheritance alone explain the deformation observed?
In order to improve our understanding of these earthquakes, we propose to develop a mechanical numerical model representing the behaviour of the lithosphere in intraplate domains. This model will integrate the different forces acting on lithospheric scale, the rheology of the lithosphere as well as the structural inheritance. These models will be validated by newly calculated strain rates.

We therefore propose to precisely characterize the variation of strain rate measured by GPS in the St Lawrence valley. This part suffered five earthquakes with a magnitude above 6 between XVII and XIX centuries. This area presents actually the structures of the paleo-rift Iapetus (700 Myr) bordered to the West by the Grenvillian craton (1.3 to 1 Gyr) and to the East by the thrusted units of the Appalachian orogen (450 Myr).

Tectonic evolution of a pull-apart basin, constraints from gravimetric survey (Sorbas Basin, SE Spain).

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The continental collision between the Alboran domain and the Iberian passive margin gave rise to the Mesozoic to Neogene fold and thrust belt of the Betic Cordillera (southern Spain). The Sorbas basin is part of a group of intramontane Miocene basins situated in the Internal Zone of the Cordillera, where the basement edifice formed by the stacking of metamorphic tectonic units underwent rapid exhumation and collapse during Late Oligocene – Early Miocene. The deformation that shaped the intramontane basins is closely related to the complex dynamics of the Cordillera's exhumation, which are thought to be driven by the westward motion of the Alboran basin subducting slab rollback and relative stretching of a wedge shaped area, containing the basin and bound by major strike slip faults such as the Alhama de Murcia, Palomares, and Carboneras fault zones (Rutter et al., 2012); continuing via the Trans-Alborán Shear zone to the Moroccan Rif belt. Recent field studies have shown that accommodation space was created through extensional faulting taking place at the same time as the uplift of the basement massifs and strike-slip faults seem to have played a major role, acting as transfer faults linking the extensional detachments. Most previous work was focused on the fact that the Sorbas basin is clearly fault-bounded against uplifted basement rocks of the S. Alhamilla and S. Cabrera and concentrated on the younger, upper Miocene portion of the sedimentary sequence. However, the geometry of the basin/basement boundary hasn't been studied in detail and the nature of the early fault interaction between the basement the lower portion of the sequence has only very recently been considered. Amongst the reasons for this gap in knowledge is the fact that most fault contacts are buried under overlying Messinian and Pliocene deposits.

We therefore carried out a geological mapping and structural analysis of the boundary between basement and basin sequence in the southern Sorbas basin, focusing on the characterisation of linked syn-depositional detachment and strike-slip faults throughout the Miocene. A detailed gravimetric survey of the Sorbas basin has also been completed with the aim of investigating the shape of the basin's base, as well as constraining how the extension is accommodated by faulting. Fieldwork data so far seems to indicate the presence of a strike-slip corridor bounding the Sorbas basin represented by the southern basin boundary fault zone to the south, which comprises a series of *en echelon* right lateral fault planes such as the Gafarillos FZ system, and the northern boundary fault zone, which is buried under the upper sedimentary sequence. These faults are linked to a series of detachment faults which can be followed along the eastern Sorbas basin at the basin/basement contact and presents impressive examples. However, the current geodynamic picture is complicated by the late Miocene tectonic convergence movements ongoing today, which have created regional thrust structures which produced severe reorientation of previous extensional faults and in some cases inversions.

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Analysis of gravity measurements in the Ulleung Basin (East Sea/Sea of Japan) and its implications for the Moho depth variations

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The Ulleung Basin, one of three major basins in the East Sea/Sea of Japan that formed during the Middle Oligocene to Early Eocene, is considered to represent a continental rifting end-member of back-arc opening. Although the characteristics of the overlying sedimentary layers have been addressed by previous studies, the nature and structure of the crust in the Ulleung Basin are poorly known. In this study, we examine the gravity anomaly of the Ulleung Basin using more extensive data sets than before, particularly focusing on the thickness of the crust. Our analysis shows that the crustal thickness varies from 16 to 22 km, but within the central part of the basin, the variation is only about 10-20%. Such finding appears to be consistent with previous studies using ocean bottom seismometers, although the resolution of those studies may be consider as marginal. The almost-uniformly-thick crust that is thicker than normal oceanic crust (~ 7 km) is consistent with previous observations using ocean bottom seismometers and recent deep seismic results of the Yamato Basin. Another important finding is that the small residual mantle gravity anomaly highs in the northern part of the basin are aligned in the NNE-SSW direction which correspond to the orientation of the major tectonic structures on the Korean Peninsula, raising the possibility that this feature is a consequence of localized extension and extra crustal thinning at the time of basin formation. Another explanation is that it is the result of small post-rift underplating at the base of the crust. Two important processes appear to have formed the Ulleung Basin following its formation: post-rifting magmatism which occurred in the north, especially in the northeast sections of the Ulleung Basin, and the deflection of crust in response to preferential sediment loading towards the south. Based on our inference of almost-uniformly-thick crust, we argue that a large mantle upwelling that took place at the time of Ulleung Basin opening resulted in a widespread lateral flow that not only smoothened but also thickened the lower crust.

The influence of basement uplifting on the salt tectonics deformation of intracontinental rift basin: Zifusi depression, Jianghan basin

Yulu
China

Salt tectonics have been found in many basins of various types all over the world, such as craton basin, rift basin, continental collisional basin, foreland basin and so on. It's one of the most hot issues in petroleum geology nowadays. Jianghan basin is a typical intracontinental rift basin characterized by salt, where salt tectonics form an unique structural style, allowing investigation of how basement variability affects the migration of salt. Jiangling depression lies in the west part of Jianghan basin. Early Shashi stratum is the main salt layer there. In its south part, Zifusi depression is a representative zone of salt tectonics. This depression is interpreted to be salt influenced, displaying classical half-graben geometries by basement normal faults at the north and a basin-ward slope at the south. Anticline is found above the footwall in the northern domain. In contrast, the southern domain is marked by detachment structures. What's more, the thickness of pre-salt and supra-salt units also show different regularities of distribution in plane. Using seismic data and wellbore data to examine structural styles there, we find the reason for these differences: the up-lifting of basement in the north may play as a major control factor on the mobile salt and structural deformation. The addition of up-lifted basement results in:(1) salt flows laterally from where it deposited originally so that the suprasalt sediments become concave mini-basin; (2) salt that flowed to the south gathers and swells on the slope with detachment structures on its top; salt that flowed to the north swells on the uplifted side of basement-involved fault and forms anticline; (3) the fault controlled depocenter shifts to the center of mini-basin, and syn-rift strata are thin above the swell while thick in area of withdrawal. This can be helpful to explain how structural style we find today formed in Zifusi depression.

The occurrences and origins of deformed structures in the Upper Cretaceous deposits in Jordan

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In this article a variety of deformation microstructures focused in the Upper Cretaceous rocks of Jordan are described and attempts are made to explain them, their formation and the mechanisms that had lead to their development. The discussed structures include: Undulations, brecciated chert (Cataclasts), slicken sides, nodular, deformed fossils, boundage, geodes, stylolites, flow channels and flowage Structures.

Three types of deformation forces or combination of them are made responsible for the different types of deformational structures: stress fields acting in ENE- WNW, SE-NW and NNW-SSE directions, shock waves produced by earthquakes or meteoritic impacts, and compaction resulting in density inversion and over-pressurized groundwater.

Tectonic stress fields acting in ENE- WNW, SE-NW and NNW-SSE in a sequence producing in addition to faults and folds, ductile deformed fossils in horizontal directions, stylolites, and slicken sides.

Shock waves of very strong earthquakes or meteoritic impacts producing brittle deformed fossils embedded in soft materials, very strongly smashed chert beds, undulations in the competent chert beds with no undulations whatsoever on the incompetent over and underlying limestones and slicken sides reactivated by such shock waves.

Compaction resulting in density inversions and hence upward migration of less dense sandstone blocks into the overlying more dense but very wet clay and mud layers.

Over pressurized groundwater in the Lower Cretaceous sandstone aquifer caused by the retreat of the Tethys where this groundwater was triggered by shock waves to cause liquefaction in the friable or very weakly cemented sandstone, and hence its upward migration of water transporting sand grains into and through the overlying clay and marl layers.

Chemical precipitation and replacement of organic matter by silicates producing silica geodes.

3D Wilson cycle: structural inheritance and subduction polarity reversals

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Many orogenies display along-strike variations in their orogenic wedge geometry. For instance, the Alps is an example of lateral changes in the subducting lithosphere polarity. High resolution tomography has shown that the southeast dipping European lithosphere is separated from the northeast dipping Adriatic lithosphere by a narrow transition zone at about the “Judicarian” line (Kissling et al. 2006). The formation of such 3D variations remains conjectural. We investigate the conditions that can spontaneously induce such lithospheric structures, and intend to identify the main parameters controlling their formation and geometry.

Using the 3D thermo-mechanical code, I3ELVIS (Gerya and Yuen 2007) we modelled a Wilson cycle starting from a continental lithosphere in an extensional setting resulting in continental breakup and oceanic spreading. At a later stage, divergence is gradually reversed to convergence, which induce subduction of the oceanic lithosphere formed during oceanic spreading. In this model, all lateral and longitudinal structures of the lithospheres are generated self-consistently, and are consequences of the initial continental structure, tectono-magmatic inheritance, and material rheology.

Our numerical simulations point out the control of rheological parameters defining the brittle/plastic yielding conditions for the lithosphere. Formation of several opposing domains of opposing subduction polarity is facilitated by wide and weak oceanic lithospheres. Furthermore, contrasts of strength between the continental and oceanic lithosphere, as well as the angle between the plate suture and the shortening direction have a second order effect on the lateral geometry of the subduction zone.
In our numerical experiments systematic lateral changes in the subduction lithosphere polarity during subduction initiation form spontaneously suggesting intrinsic physical origin of this phenomenon. Further studies are necessary to understand why this feature, observed in nature, is recurrent in our models. It is necessary to determine whether it is controlled by rheological properties, and/or is constrained by inherited lithospheric structures.

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Are subduction-related processes more significant than continental insulation in controlling mantle dynamics post-supercontinent formation?

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Continental lithosphere inhibits heat loss from the Earth's interior, relative to oceanic lithosphere, due to its thickness and the warmth of the radioactively enriched crust (the "thermal blanket" effect). As a result, it has been suggested that insulation may cause the formation of reservoirs of heat accumulating beneath slow-moving supercontinents leading to their break-up [e.g., 1–6]. However, several processes unfold during the supercontinent cycle, more than one of which might result in an elevation in sub- continental mantle temperatures. A consensus has been formed that subcontinental mantle upwellings appear below large continents extensively ringed by subduction zones [7–9]. Plumes can be generated with an oceanic super-plate (e.g., the Pacific ocean) and therefore without the need for continental insulation [10]. Therefore, the significance of the role of continental insulation in the supercontinent cycle is contentious. Here, we present 2-D and 3-D Cartesian geometry mantle convection simulations with thermally and mechanically distinct oceanic and continental plates. The evolution of mantle thermal structure is examined after continental accretion at subduction zones (e.g., the formation of Pangea) for a variety of different numerical experiments. Our results show that in low-Rayleigh number models the impact of the role of continental insulation on subcontinental temperatures increases, when compared to models with higher convective vigour. As a result, previous numerical experiments that implemented low Rayleigh number mantle convection would have heightened the importance of an insulating supercontinent. We also find that heating below a supercontinent in a high-Rayleigh number flow occurs almost entirely as a consequence of the influence of subduction initiation at the continental margin, rather than the influence of continental insulation. Furthermore, our results infer that subduction and mantle viscosity can control the location of subcontinental mantle plumes, manifested on the Earth's surface as large igneous provinces (LIPs), following the formation of a supercontinent. For studies featuring a low viscosity lower mantle, plume positions beneath the continent become locked to the continental margins (i.e., the circum-supercontinent subduction zone). The plumes form at a distance of 2000 - 3000 km from the margins of the supercontinent, which is comparable to the LIP distance from the nearest subduction location for Central Atlantic Magmatic Province, Karoo Ridge, and Bunbury Basalts [11].

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And the Variscan orogen buckled

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The Western European Variscan shows a “S” shape pattern interpreted as a double orocline consisting of a northern and southern arc. The northern arc, known as Cantabrian Orocline, was developed after closure of the Rheic Ocean and the building and collapse of the Variscan orogenic edifice and, therefore, is considered post-Variscan in age. On the other hand, neither the geometry nor the kinematics of the so-called Central Iberian orocline, situated at the south of the Iberian peninsula are properly known. However, it seems reasonable to think that both oroclines developed at the same time as other coupled oroclines. We present widespread evidences of buckling around the whole orocline at different lithospheric levels. A major change in the stress field, from the Variscan (E-W shortening in present day coordinates) to the oroclinal development (N-S in present-day coordinates) is required to produce buckling of the Variscan orogen, what caused this dramatic stress field is still unknown, but following the tectonic settiong of the Carboniferous-Permian, it was likely related with a global scale process.

Supercontinent and Superplate?

Daniel Pastor-Galán and Rob van der Voo

During Earth’s geological history, landmasses tended to amalgamate into supercontinents and then break-up again. This caused a profound effect on the evolution of the Earth's interior and surface: the land-sea distribution changed, and hence the global hydrosphere, climate and life. The geological record, including the endowments of natural resources, is largely controlled by these cycles. Unraveling the geodynamic mechanisms responsible for this extreme end-member is key to our understanding of plate tectonics. Pangea, the most recent supercontinent, provides our best opportunity to evaluate supercontinent assembly and dispersal: the role of opening and closing oceans, the long term interactions between lithosphere and deep Earth, mountain building, and their role in the evolution of hydro- and biosphere. Whereas the distribution of land and sea is well-reconstructed for the amalgamation of Pangea, major problems remain for the plate tectonic evolution of this supercontinent: (i) the controversial paleomagnetic evidence for large-scale Late Carboniferous-Early Permian [310-270 Ma] rotations that predict massive shortening or extension (>>1500 km), not easily explained by the geological record and (ii) immense volcanism within the Pangean superplate and its unclear links to mantle dynamics.

Modes of reactivation of the Late Paleozoic-Mesozoic extensional basins during the central Apennines Wilson Cycle

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In several mountain belts the effects of cyclic opening and closure of oceanic basins (“Wilson Cycle” model) have been extensively documented. However, the understanding of structural inheritance concepts are still in progress, also due to variability of pre-thrusting basin architecture, amount of reactivation of pre-existing discontinuities or anysotropies, and modes of reworking of the inherited weakness zones.

The Apennines thrust belt of Italy represents a natural laboratory to study the effects of the “Wilson cycle”. In fact, the area underwent: i) extension during the Late Paleozoic rifting and Mesozoic Thetys ocean opening; ii) the Apennine compression active since the Paleogene; and iii) late/post-orogenic extension since Miocene to Present. The best study area where the repeated effects of rifting and mountain building processes are evident due to exceptional exposure and availability of abundant subsurface data (exploration wells and seismic profiles) are the outer central Apennines of Italy.

In this study we integrate field structural studies and subsurface data with the aim to reconstruct the structural setting of the outer central Apennines fold-and-thrust belt along regional cross-sections. In particular, the interpretation of geophysical data (seismic reflection profiles, gravity and magnetic data) indicates a thick pre-Jurassic sedimentary sequence filling late Paleozoic(?)–Triassic extensional basins, lying underneath the main topographic culminations of the Central Apennines fold-and-thrust belt (e.g. the Umbria-Marche and Gran Sasso mountain ridges). These deep-rooted basins underwent positive inversion during the Neogene compression and thrust–fold development. The reconstructed thick-skinned inversion tectonic model explains co-existing limited amount of shortening and remarkable structural elevation of the mountain front.

The inherited basement discontinuities strongly controlled the geometry and segmentation of the post-thrusting normal faults as suggested by the distribution of Quaternary extensional structures and present-day seismicity.

The outcomes of this study indicate that prominent mountain ridges occurring in foreland thrust belts are often related to the deep-rooted, basement-involved positive inversion of pre-existing extensional basins.

Structural inheritance and tectonic inversion in foreland thrust belts: an Apennine-Adriatic perspective

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Orogenic belts that formed at the expenses of previously rifted regions usually bring the structural signature of inherited extensional structures within the thrust belt architecture. The switch in deformation from extension to contraction lead to positive inversion tectonics resulting from different thrust-normal fault interactions. The identification of inversion structures in foreland thrust belts is critical since it has a direct impact on both the unravelling of the structural style and on hydrocarbon prospectivity in both mature and under-explored regions. The Apennine-Adriatic thrust belt-foreland system in central Italy offers a unique scenario for unravelling concepts of structural inheritance and tectonic inversion allowing a straightforward comparison between the outcropping thrust belt structures with those buried in the adjacent deformed foreland. In this contribution, inversion structures from the thrust belt and foreland domains of the Apennine-Adriatic system are investigated and compared in order to reconstruct their styles and to put some constraints on a more regional context.

Individual structures are reconstructed within the central sector of the outer Apennine carbonate-dominated thrust belt. Contrasting styles of inversion, resulting from Pliocene-Quaternary selective reactivation of pre-existing Mesozoic normal faults (transpressional reactivation or thrust shortcut), characterize the differently-oriented oblique and frontal thrust ramps constituting the curved thrust systems. They are associated with various thrust-related folding mechanisms giving rise to coexisting and laterally changing fault-bend, fault-propagation and push-up fold structures. By takingadvantage of recently-reprocessed seismic data from the Italian Adriatic Sea, inversion structures are also investigated in the deformed foreland. In this area, the compressive deformation is mild and basin inversion is promoted resulting in different structures along various structural trends. Pulses of inversion occurs repeatedly over the Cretaceous-Tertiary times and are coeval with the emplacement of the surrounding thrust belts. The characteristics of the Adriatic foreland structures are typical of intraplate deformational settings as described in other inverted foreland domains.

Structural reconstructions on both the outer thrust belt and foreland regions suggest that inversion tectonics plays a significant role during the evolution of the Apennine-Adriatic thrust belt-foreland system, giving some important constraints on reconstructing the styles of contractional deformation. Moreover, the various styles of inversion here reconstructed can create different scenarios for assessing hydrocarbon prospectivity. Consequently, a reappraisal of the possible exploration targets within the Apennine-Adriatic system may unlock potential for future exploration.

The Atlas of the Underworld and global slab kinematics

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Seismic wave tomography allows identifying bodies of subducted lithosphere, or slabs, in the upper and lower mantle. Subduction leaves a distinct geological record which can be systematically correlated to upper and lower mantle slabs. Here, we present the Atlas of the Underworld, a documentation of ~100 slabs across the Earth's upper and lower mantle correlated to their geological records. This document allows to place kinematic constraints on mantle downwelling in unprecedented detail. Average upper mantle transit times are similar to lower mantle sinking rates of 12.5 ± 2.5 mm/yr, with much higher and more variable upper mantle sinking rates buffered by a transit time at the 660 km discontinuity. The variation in slab sinking rates is predominantly acquired when slabs are still connected to surface plates. In addition to the sinking rate change at ~660 km, we show sinking rate changes at ~900 and ~1500km, consistent with proposed mineral phase changes in the lower mantle. A 4-6 fold average sinking rate slowdown within the upper mantle is associated with only a 2-3 fold slab thickening or buckling and no significant lateral slab widening. Hence, ~50% of slab volume may already be recycled in the upper mantle, potentially allowing chemical mantle segregation on billion year timescales. Extrapolating lower mantle slab volumes back to the Archean would suggest that approximately one third of the lower mantle volume may derive from subducted lithosphere, leaving some two-thirds primordial. Crust subducted to the base of the mantle over the course of a billion years could account for the volumes in Large Low Shear Wave Velocity Provinces.

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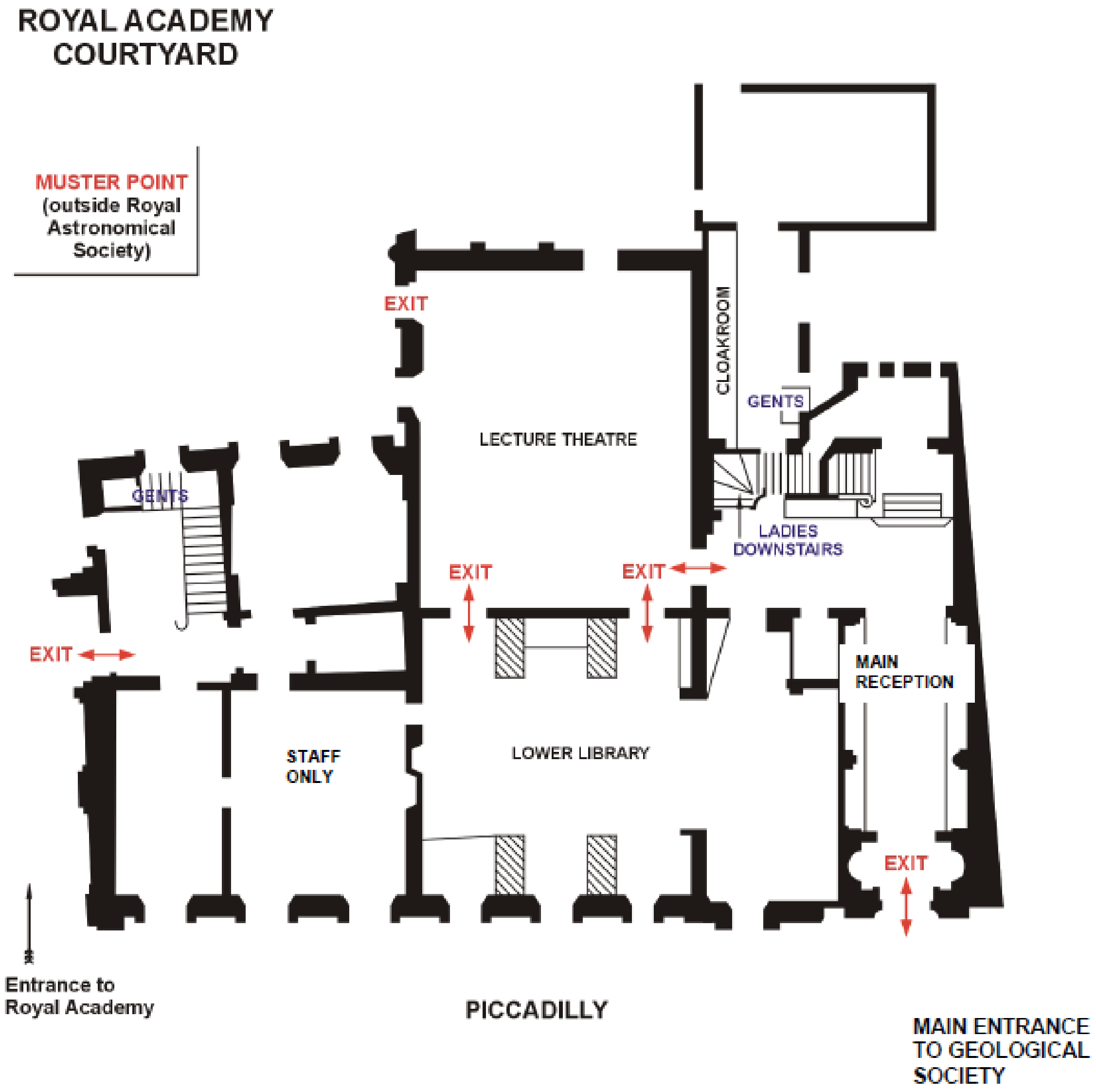
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