Interplay of heatflow, subsidence and continental break-up: a case study workshop

8-9 October 2018

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Thermal histories during Subsidence and Uplift, and Kinetic Modelling of Petroleum Generation, as controlled by Mechanics and Thermodynamics; Case Studies from the UK Central Graben and Uinta Basin USA Andy Carr, *Global Exploration Systems Ltd*
The value of deep seismic data: An example from North Western Australia that exposes ancient in-place oceanic lithosphere Paul Bellingham, *Ion Geophysical*
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Effect of mantle buoyancy on tectonics and subsidence during rifting. Insights from long-term 2-D geodynamic modelling Theunissen Thomas, *University of Bergen*
Enigmatic thermal pulse and subsidence retardation during early stages of lithosphere thinning explained by asynchronous depth-dependent necking Pauline Chenin, *Université de Strasbourg*
New insights from modern deep seismic into the mechanics and rheology of the crust during back-arc rifting, propagator rifting and a ductile transition from rift to drift. The tectonic architecture and evolution of the Offshore Papuan Plateau, PNG Jean-Claude Ringenbach, *Total*
A Bayesian approach to inverse thermal history modelling in sedimentary basins and the inference of erosion Andrea Licciardi, *Université de Rennes*
The structure and nature of the basement at magma-poor rifted and hyper-extended margins Tim Reston, *University of Birmingham*
Dynamic Topography and Rifting: A Global Model N. Hodgson, *Spectrum*
Ark-CLS Poster Wyville-Thomson Ridge Modelling Bennett Haworth, *Ark*

Oral Presentation Abstracts (Presentation order)

Day one: 8th October 2018
Framework Sessions

KEYNOTE: Heatflow and subsidence at distal rifted margins: achievements and future challenges

G. Manatschal, P. Chenin, R. Lescoutre
IPG-EOST, Université de Strasbourg/CNRS

Research into the formation of deep-water rifted margins is incontestably undergoing a paradigm shift. The existence of either exhumed mantle and/or thick magmatic additions associated with hyper-extended crust is proving fundamental in controlling the heatflow and subsidence history at distal rifted margins. Access to new data sets from distal domains, in particular heatflow and subsidence data, show that classical depth-uniform, pure-shear rift models, which are successfully applied to proximal margins, are not able to predict the evolution of distal rifted margins. Many questions remain open despite significant advances in the understanding of extensional processes in distal margins and their link to sedimentary and magmatic processes. The aim of the presentation will be threefold: 1) review the present understanding of distal rifted margins, 2) discuss the main observations conflicting with classical rift models, and 3) discuss the future challenges that need to be faced to progress in the understanding of distal rifted margins.

Drilling of distal rifted margins in the North-Atlantic resulted in a very biased view of rifted margins, suggesting that they are either volcanic or non-volcanic. Three decades later and thanks to intense mapping and drilling of distal rifted margins by academic consortiums and petroleum companies, a much clearer view of the crustal architecture of distal margins has emerged. On a first order, three rift domains can be generally identified based on recurrent architectural features, namely the proximal, distal and oceanic domains. The formation of each of these domains is presumably controlled by particular physical processes, which are linked with changes in the bulk rheology of the extending lithosphere and the possible appearance of magma. It appears that most margins evolve through three main deformation stages, here referred to as an initial/diffuse stage, a necking/localizing stage, and a breakup stage. However, the definition and mapping of such rift domains and sub-domains remains debated, in particular in the case of voluminous magmatic additions, polyphase rifting or low magmatic budgets during breakup. Furthermore, rifted margins show a large architectural variability along dip and strike as expressed by domains width, symmetry/asymmetry and magmatic budget.

Understanding this complexity is important, not only to apprehend the thermal history, but also to predict potential source rocks and reservoirs. Indeed, while the thermal and subsidence evolution of proximal margins can be apprehended by depth-uniform, pure-shear extension, in which the thermal, magmatic and subsidence history are directly related to the amount of extension (ß-factor), new data show that this model fails to predict the evolution recorded at the distal domain. There are numerous examples showing that, at the time of major lithospheric thinning/necking, the future distal margin is uplifted. Another widespread observation is that, in many rifted margins, the onset of magma emplacement post-dates major crustal thinning and that vertical movements and magmatic activity can still be observed after lithospheric breakup and onset of seafloor spreading. These observations violate two key assumptions made in classical rift models: 1) that extension, thinning, subsidence, magma production and thermal systems are coupled; and 2) that rifted margins are passive after breakup and subsidence is only controlled by thermal equilibration and sediment loading.

In order to predict the heatflow and subsidence histories, and hence petroleum systems at distal margins, it is of primary importance to be able to map and restore these domains. This requires to (re)define: 1) location and timing of rift domains (i.e. necking and breakup), 2) extension rates, 3) initial (inherited) rheology of the lithosphere and its evolution during extension, 4) the magmatic budget and hydrothermal fluid systems, and 5) the creation and filling of accommodation space during extension. The impact of deep-seated processes such as mantle plumes need also to be integrated where applicable.

In order to better calibrate the heatflow and subsidence histories of distal domains, the number of datasets from natural rift systems need to be multiplied. More realistic physical models need to be developed and their predictions need to be tested against these data.

The pronounced 3D structural, magmatic, isostatic and thermal variability observed along dip and strike of distal margins requires that models can adapt to different time-space evolutions of rift systems and integrate the importance of inheritance and plumes/mantle dynamics. It will be necessary to map the along strike segmentation, the degree of asymmetry and the structural, magmatic and stratigraphic variability of distal domains to integrate them to and/or compare them with numerical modelling studies. Taking mantle processes into account is mandatory to properly describe the thermal evolution of the distal domain since the heat flux from the mantle becomes important when the crust is significantly thinned, in contrast to the proximal domain where heat flow variations are essentially controlled by variations in radiogenic heat production. Fluids associated with magma and mantle exhumation may also play an important role and may be linked to short-term thermal events. In addition, they may control the early diagenetic evolution of the sediments and the formation of source rocks.

These insights challenge much of our preconceived ideas on potential plays in the distal domain and prompt us to rethink rifting processes and their evolution through time and space. The prediction of heatflow and subsidence is at present limited by the physical understanding of the processes at play during the formation of distal margins. In particular deep-seated mantle processes and their link/control to surface processes necessitate a geological understanding of lithospheric/asthenospheric-scale extensional systems, which can only be achieved through the feedbacks between observational/analytical and modelling approaches. Progress would be much faster if the existing high-quality 3D geological and geophysical data available in industry could be used to test and calibrate the ideas developed in the research community.

The most fundamental lesson we can take with us when going forward in exploring deep-water rifted margins is that we cannot simply apply the knowledge learnt in the proximal domain to the distal domain. In order to become predictive, the key learnings of the latest research and exploration experiences need to be integrated and distal domains have to be treated as a new and distinct play fairway.

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KEYNOTE: Integrated subsidence analysis as the foundation for predictive petroleum systems modelling: why thermal boundary conditions require whole-lithosphere modelling

Lorcan Kennan[1], Christopher Willacy[1], Ikae Brown[2], Peter Chia[2], Michael Spaak[1], Edith Hafkenscheid[1], Quintijn Clevis, Olaf Podlaha[1] and Olivier Meuric[1]
[1] *Shell Global Solutions International*
[2] *Shell Development Australia*

It has long been recognized that basin subsidence is driven by crustal and mantle thinning and, once thinning has ended, by the cooling of the lithosphere. The stratigraphic architecture of a basin can thus, in principle, be used as a proxy for heat-flow into the overlying sediments. However, it is also the case that observed heat-flow and subsidence are often different to expectations derived from simple lithosphere thinning models. Other processes may be in play including sediment thermal blanketing, mantle decompression melting and permanent or transient underplating, mineralogical phase changes, and syn-deformation shear heating. Analytic solutions and numerical models of all these processes show that, considered in isolation, they can apparently influence model outcomes such as temperature, heat-flow and maturity significantly. In addition, forward numerical models which couple temperature-dependent rheology and lithospheric strain show spatially and temporally complex decoupling of crust and mantle deformation and overlying accommodation space creation.

Petroleum systems analysts are faced with the task of making useful and predictive models of temperature, maturity, pore pressure, and hydrocarbon fluid generation, migration and retention. They must do so in a timely manner, responding to business needs. Their models need to be faithful to basin geometry and assorted well data, without getting lost in a tangle of plausible, but poorly-calibrated physical processes, which amplify uncertainty and suggest, at worst, that almost anything is possible.

We will illustrate some of these problems with case studies of the Exmouth Plateau, Australia and the Vøring Basin. Our models for these areas suggest that at least some of the misfits and paradoxes addressed in this conference, can be resolved through a holistic approach to basin analysis, forward model-building and model-calibration.

The Exmouth Plateau, Northwest Australia: In early 2015, Shell acquired a seismic reflection and refraction survey over the SW Exmouth Plateau in cooperation with Geoscience Australia. Up to 18 km of sediment, including what was interpreted on 90s-00s vintage seismic as "transparent lower crust", is observed overlying what appears to be mostly normal thickness oceanic crust, approximately 6-7 km thick, with no indication of significant faulting and no apparent syn-rift. The relatively shallow water strata of the Mungaroo Delta at 3-4 km depth appear to be the upper part of a basin fill for which the modern Niger Delta may be an analogue. The combination of apparently simple crustal structure and unusually thick sediment provides an excellent opportunity to evaluate the role of sediment blanketing as an influence on heat-flow and subsidence. Basic backstripping shows that the basement depth is more or less as expected for an old (Late Jurassic or older) ocean crust of 6-7 km thickness from published "standard models" and scattered surface heat-flow observations are broadly as expected over oceanic crust.

The observed Permian(?) to Late Jurassic tectonic subsidence appears, at first, to fit with classical ocean crust subsidence models, superficially suggesting that sediment thermal blanketing is not a major issue. However, we get unexpected results in our basin models if we apply a typical oceanic heat-flow to the base of the sediment pile – models run too hot and overmature. If we use a more geodynamic approach in our numerical models and include thinning of initial crust and mantle, upwelling the lithosphere, magmatic underplating and subsequent mantle cooling, we find that predicted temperature and maturity matches observation. The sediment pile suppresses heat-flow out of the underlying mantle to about half the value in models with thin or absent sediment cover, and heat generation within the sediment pile contributes the other half. Unlike an unblanketed oceanic heat-flow model, the basement heat-flow history is not approximately exponential in shape but drops to only 27 mW/m^2 within 90 Ma and remains almost constant up to the present. The shape of the heat-flow curve is complex and driven by the evolving thickness of the sediment pile. We see a further twist if we calculate the subsidence driven by the cooling of the model oceanic lithosphere. Sediment blanketing also drives a flattening of subsidence after c. 90 Ma and reduces the thermal subsidence from the expected by at least 800 m and does not fit other palaeowaterdepth reconstructions. The apparent mismatch between heat-flow, subsidence and lithosphere thinning and thickening is, however, relatively easily resolved. We can offset the effect of sediment thermal blanketing by allowing the lithosphere to thicken to about 25-30 km more than our idealized sediment-free oceanic benchmark model, consistent with observed upper mantle shear wave velocity in this area. Intriguingly, the base-sediment heat-flow in the revised model which better fits the observed subsidence varies by only 2 mW/m^2 from the initial mode in which the lithosphere was too thin.

The Exmouth Plateau area is also strongly influenced by a second thermal event, related to late Jurassic and early Cretaceous breakup of Greater India and Australia. We constrain the amount of mantle thinning by limiting the isostatic response to match only minor uplift and erosion in the study area, but still sufficient to generate some decompression melting consistent with the observation of low-volume but regionally widespread sills. Once again, sediment thermal blanketing is important. In the absence of sediment, the thinning could increase heat-flow by >10 mW/m^2 but with thick sediment cover heat-flow increases briefly by only 2-3 mW/m^2. Other than local impact of sill emplacement and hydrothermal fluid flow, the effect of mantle thinning is limited only to uplift and erosion, without any regional, deep-seated Late Jurassic “heat-flow spike”.

The Vøring margin, Norway: Shell, and other companies, have drilled in the Vøring area with limited success. Few wells penetrate below the uppermost Cretaceous, and deep stratigraphy, temperature and maturity are relatively poorly known. Prior to drilling the Dalsnuten well on the Gjallar Ridge, and in post-drill review, Shell prepared a number of basin models which revealed the importance of magmatic underplating and its role in determining the maturity of deeper strata, and which prompted the development of practical steps for identifying when it would be a key risk to petroleum systems.

The depth to the Moho is well-constrained by seismic refraction data, but the nature of the crust is less clear. The high-velocity lower crust has been interpreted as eclogitic crust of Caledonian age, magmatic underplate, or an indeterminate mixture of the two. However, the spatial extent of sills and volcanic vent complexes is coincident with the high velocity crust suggesting it may be largely magmatic. Immediately to the northwest of the study area, thick wedges of seaward dipping reflectors reach almost to the Moho and the magmatic interpretation is less contentious.

The sediment-backstripped depth of the Gjallar Ridge appears to be slightly shallower than the deep basin to the southwest, and the timing of hyperextension beneath these basins appears to be relatively early, with degraded fault scarps bounding the Haltenbank being back-filled by Cretaceous strata. Thus, a continental end-member interpretation of the area might, at first sight, suggest that the Gjallar Ridge is a remnant horst between an early Cretaceous rift, with the true early Cenozoic magmatic margin lying to the Northwest. However, it is equally possible that crust and mantle thinning are decoupled. Palaeocene to present thermal subsidence is significantly larger than expected for an early Cretaceous rifting event, suggesting the underlying mantle had been thinned over a wide area. In addition, ongoing extensional faulting over the Gjallar Ridge area is associated with uplift and erosion rather than the creation and infilling of accommodation space. Elevation of the Gjallar Ridge relative to the inboard Cretaceous has been maintained to the present, suggesting significant permanent magmatic underplating.

While debate continues on the relative proportions of continental and magmatic crust, we tackled the sensitivity of temperature and maturity under the Gjallar Ridge by running a suite of basin models, which include crust and lithosphere thinning, underplating at the base of the crust and optional sills. The thickness of underplate in each model is constrained by the model uplift of hot mantle above the solidus and associated partial melting.

Basin models which include only crust and lithosphere thinning of early Cretaceous age run relatively cool, and immature. Those with moderate underplate (from c. 25% of the thickness of the lower crust) run significantly hotter and more mature. Peak maturity and present-day temperature at prognosed source rock level was more sensitive to the presence or absence of magmatic underplating than the absolute thickness of underplate. Gravity modelling was also used to test the competing crust and lithosphere thinning models. Mantle density is strongly temperature-dependent, and models with older extension and cooler, denser upper mantle misfit the observed gravity by > 100 mGal, unless the base crust is put deeper than the refraction Moho or an implausibly low crust density is used. The upper mantle thermal anomaly associated with intense Palaeocene lithosphere thinning and underplating does fit the data. The Dalsnuten bottom hole temperatures required a slightly elevated mantle temperature of c. 1450°C, consistent with the chemistry of basalts derived from the Iceland plume. Maturity data acquired some weeks after the well was drilled matched the predictions of the preferred models with significant lithospheric mantle thinning and thick magmatic underplate. The well was dry.

Key learnings: There are many ways to calibrate models to a limited amount of data and get "the right answer for the wrong reason". An apparently calibrated model may not be particularly predictive below the TD of existing wells or between them. An approach to model building and calibration driven by both data and geodynamic process can help resolve this and other problems. In practice, it can prove not only more effective, but also faster, than more conventional empirical approaches to calibration.

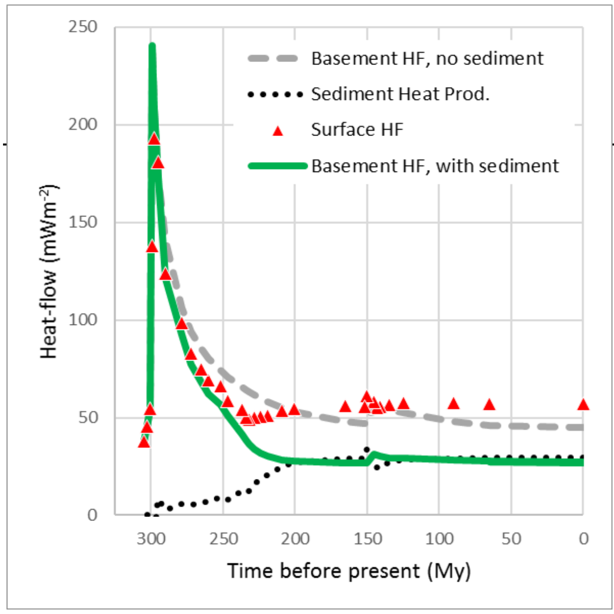
The models presented here, and others, suggest that many, if not most, discrepancies between subsidence, heat-flow and crust or lithosphere thickness, at least those which have practical impact on day-to-day basin modelling, can be resolved by:

1) systematically accounting for sediment thermal blanketing,
2) moving away from a decoupled view of "tectonic subsidence" and "sediment loading" because the former is not independent of the thermal blanket effect of the sediment cover in most basins of interest,
3) modelling crust and mantle thinning, and magmatic underplating (transient or permanent), constrained by geophysical data such as potential fields and seismic refraction,
4) optimizing models to fit a wide range of input data including not only traditional temperature and maturity measurements, but also gravity data and palaeowaterdepth or uplift/erosion indicators (in place of the more typical tectonic subsidence).

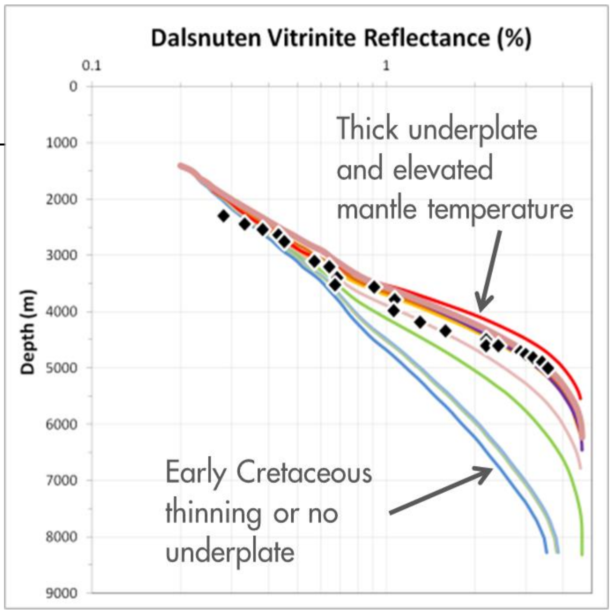
On all but lightly sedimented margins, base-sediment heat-flow histories are strongly coupled to sedimentation. If sediment is thick enough, heat-flow may be quite different to the predictions of simple geodynamic models, and may be much less sensitive to fine-tuning lithospheric boundary conditions than we expect. Thick sediment cover may also suppress the "heat spike" effect of later mantle thinning events. Subsidence and uplift history, however, remains highly sensitive to lithospheric thinning and thickening, and may be associated with generally raised or lowered heat-flow tens of millions of years after a driving lithosphere event.

It is not always necessary to identify the "correct" model to make a reasonable decision. It may be enough to estimate the sensitivity of important model outputs, such as source rock maturity in proposed kitchens, to a range of geodynamically-plausible provided model inputs broadly reproduce not only temperature, heat-flow and maturity data of direct relevance, but also seismic refraction, gravity and magnetic observations. This may be sufficient to eliminate those play concepts which are geodynamically implausible or even impossible, and this in turn can make a significant difference to play and prospect risking.

Doing this is a timely-manner remains a challenge. We need to evolve new ways of working with enormous amounts of data, using statistically robust approaches to know when our models are "good enough" and to consistently identify the types of data that might make them better. Last, but not least, we have to manage all the human relationships involved in gathering all the relevant data and communicating the results of our modelling efforts. These issues are in part addressed by other contributors to this conference.



Basement heat-flow in the Exmouth area (green) is significantly lower than expected from simple models which ignore sediment blanketing (grey dashed).



Vitrinite maturity predictions in the Dalsnuten well are highly sensitive to the presence of underplate. The unweighted expectation is for a gas or over-mature outcome.

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Session One
Case studies: Paleo Heat Flux: Insights from industry boreholes

Thermal regime Deep Water Sergipe and Potiguar-Ceara Basins Brazil related to fracture zones, active faults and volcanic activity. Observations from wells and seismic data applied to Petroleum Systems Modeling.

[1]**Fausto Mosca**, [1]Nathan Bruder, [1]Ted Godo, [1]Harry Aasmyr, [1]Corey Moss, [1]Brian LeCompte, [1]Hywel Upshall, [2]David MacConnell
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[2] *Occidental Petroleum Co.*

Murphy's New Ventures team has, over the last year, been evaluating the petroleum potential of the Sergipe-Alagoas and Potiguar-Ceará basins located in ultra-deep water offshore Brazil. One of the most important factors from a petroleum systems perspective, is the accurate assessment of the present day thermal regime and its evolution through time.

Temperature data has been collected through several different methodologies including: MDT, Production Tests and Corrected Bottom Hole temperatures. These temperature datasets are presented to provide a broader and unbiased foundation for the calculation of both present day and past thermal regimes.

Across these basins the calculated geothermal gradient ranges from 30 to 50 ^{0}C/km and appears to be dominantly controlled by fracture zones, active faults and volcanism, and a variety of crustal domains including continental to transitional, hyper-extended and oceanic.

One important observation from this evaluation is that high geothermal gradients are associated not only with fracture zones as expected, but also with the presence of transitional or hyper-extended crust creating both localized and regional thermal anomalies.

The distribution of these thermal anomalies deeply impacts basin modeling results in terms of both expulsion timing and present-day maturity. Ultra-deep water areas have previously been avoided due to the expectation of low thermal regimes. Now these same somewhat neglected areas have been demonstrated to have potential for significant oil and gas generation and expulsion.

To fully understand the distribution and impact of these thermal anomalies over time, a combined analytical effort is required. Long streamer and long record seismic data acquisition is essential in establishing the depth to the Moho and for the identification of the appropriate crustal type in order to provide the basis for the associated thermal modeling parameters. The mapping of various volcanic events and the determination of their timing, origin and impact on the local thermal regime is also critical in the building of a comprehensive model.

Though the driving forces for these thermal anomalies are still largely unknown, this initial evaluation concludes that following the early rifting phase sustained igneous activity from the Cretaceous to present day resulted in the temperatures not following a typical "cool down" trend. The regional thermal regime thereby remained substantially higher than established models would suggest.

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The Thermal History of Benguela Basin: Observations and Effects

Alex Bump, William Prendergast, Andy Witt
BP Exploration

Benguela Basin lies on the Atlantic margin of Angola, roughly conjugate to the Brazilian Campos basin. Like Campos, Benguela is part of the Early Cretaceous South Atlantic salt basin. Rifting began at about 132Ma, coincident with or slightly before eruption of the Parana-Etendeka flood basalts. Initial extension was widespread but quickly began focussing toward the line of eventual break-up. On the inner margin, faulting ceased by about 125Ma. Salt was deposited at about 114Ma and is clearly affected by faulting on the outer margin. Timing of initial oceanic crust is uncertain, but likely 110-105Ma.

Following the opening of the pre-salt play in Brazil, industry attention turned to the conjugate margin and Angolan acreage was snapped up with hopes of replicating the Brazilian success. Over the next 4 years, 5 pre-salt wells were drilled in Benguela, finding gas, CO_2 and water in varying quantities. Pyrobitumen, gas isotope reversals and fluid inclusions indicate that an early oil charge was cracked to gas. Bitumen reflectance indicates peak reservoir temperatures of twice the current values.

Combining these observations with further observations of volcanics, fluids and tectonic context make it possible to reconstruct a thermal history for the basin and even for the mantle beneath it. Flood basalts indicate initially elevated mantle temperatures. Anomalously low volumes of syn-rift volcanics and slightly thin oceanic crust suggest that mantle temperatures subsided during rifting. Late Cretaceous volcanism and widespread erosive unconformities indicate renewed mantle heat, followed by cooling over the Paleogene. The Neogene rise of the Bie Dome and emplacement of newly identified Pliocene volcanics suggests a final chapter of rising mantle temperatures. At the level of source and reservoir, the syn-rift heat spike generated most of the hydrocarbons but was dwarfed by the Late Cretaceous event, which cracked oil to gas and fully matured remaining sources. The Neogene event is (as yet) insignificant at reservoir levels.

Post-rift heating is not predicted by existing basin models but anecdotal evidence suggests that it may be widespread on passive margins, particularly on hyper-extended crust. As a basin covered by high quality 3D seismic and lying almost entirely on hyper-extended crust, Benguela offers a unique view of post-rift heating and the possibility of informing new predictive models.

NOTES:

Thermal model uncertainties in the Deep Water Gulf of Guinea off eastern São Tomé and Príncipe Islands

Christian Niño[1], Susana Fernandes[1], João Casacão[1], Francisco Silva[1], Diana Rocha[1]
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Predicting the thermal regime of the deep-water exploration blocks of São Tome and Principe islands constitutes quite a challenge. There are no deep temperature readings in the ultra deep waters of the Gulf of Guinea, east or west of the São Tomé and Príncipe islands. Only sparse Heat Flow (HF) measurements have been acquired during scientific research projects, which have been gathered and made available on the AAPG global HF database (http://www.datapages.com/gis-map-publishing-program/gis-open-files/global-framework/global-heat-flow-database). Most of the available temperature data for the exploratory wells in the nearby basins of North Gabon, Equatorial Guinea, Cameroon and Niger Delta evidence a high geothermal regime. No matter how stratigraphically and tectonically different these basins are, a common characteristic is to have geothermal gradients (GG) clearly above a normal trend of ~30°C/km. Even in the Niger Delta, where the continuous influx of recent sediments would be expected to decrease geothermal gradients, the temperatures are still quite high.

The Early Cretaceous-aged oceanic crust in the region would indicate a cold thermal regime. However, the emplacement of the Cameroon Volcanic Line (CVL), which records a non-linear age related volcanism and constitutes a regional upper mantle anomaly, seems to have played an important thermal role in the whole region since approximately 40-30 Ma (Burke, 2001; De Plaen *et al*. 2014).

The modeling of the thermal history of the basin should consider at least the effects of the initial rifting, the role of the transform faults and the impact of the CVL emplacement and its associated long-lasting volcanism. Different scenarios and analogues are currently being considered and will be discussed during the workshop.

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Session Two
Case Studies: Present day Heat Flux: Insights from surface heatflow or shallow boreholes

Pre-, syn-, and post-rift lateral variability in heat flow along the Labrador Sea

Mohamed Gouiza and Douglas Paton
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The Labrador Sea formed during the opening of the North Atlantic Ocean between eastern Canada and western Greenland. The main rifting phase occurred during the Cretaceous and continental breakup took place during the Late Cretaceous-early Palaeocene. Rifting in the southern part of the margin was characterized by crustal hyperextension and exhumation of serpentinized mantle prior to oceanic accretion. In contrast, magma-rich breakup is recorded in the north, with the emplacement of a large amount of volcanics (SDRs) in the continent-ocean transition domain. The change in the magmatic budget along the margin during breakup is coupled with a striking change in the syn-rift structural style, thus, indicating a variation in the tectonic processes driving lithospheric stretching along the margin.

Onshore the Labrador margin, present-day measurements indicate major lateral changes in surface heat flow. The southward increase in surface heat flow correlates with the younging of the pre-rift basement, which consists of Archean rocks in the north and Mesoproterozoic rocks in the south. Our work demonstrates that the laterally heterogeneous thermal structure existed prior to the initiation of rifting and influenced (1) the strength of the pre-rift lithosphere, (2) the tectonic processes driving deformation during rifting, (3) the nature of continental breakup, and (4) the post-rift stratigraphic architecture along the offshore Labrador Sea. The Labrador Sea is an interesting case-study that illustrates the interplay between inherited heat flow, rifting tectonic, breakup processes, and post-rift subsidence.

NOTES:

Thermal evolution of hyperextended margins: the examples of Iberia-Newfoundland and northern South China Sea rifted margins

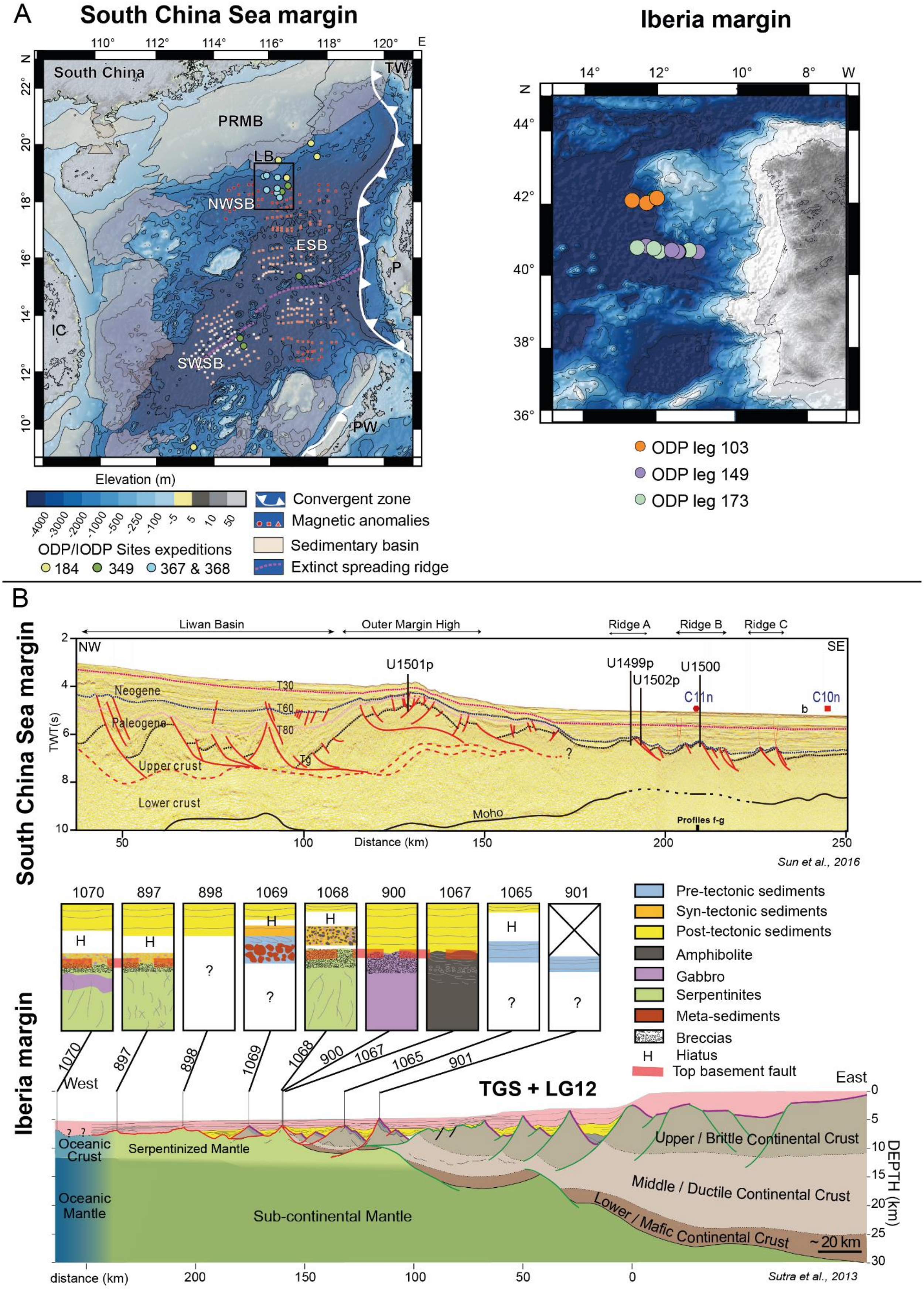
Michael Nirrengarten, Geoffroy Mohn, Magdalena Cretu, Frank Despinois, Laura Gutiérrez, Sveva Corrado, Andrea Schito, Stephen A. Bowden and IODP 367-368 Expedition Scientists

Unraveling the thermal evolution of distal rifted margin is fundamental to constrain rifting, breakup and post breakup processes. Despite the improvement of seismic imaging in distal rifted margins, their thermal properties remain poorly constrained by quantitative data. This lack of knowledge sources from the limited access to well data sampling the continent ocean transition. The IODP (International Ocean Discovery Program) and ODP (Ocean Drilling Program) expeditions performed both in the Iberia-Newfoundland and northern South China Sea distal rifted margins represent a unique opportunity to investigate their current and paleo thermal regime.

Both systems are commonly interpreted as magma poor margins showing no characteristic features of magma rich margin such as seaward dipping reflectors. However, their distal domains differ in many aspects including, among others, their initial pre rift conditions, extension rate, structural and magmatic evolution.

This study combines 2D tectono-sedimentary seismic interpretation with classical core analytics such as organic petrography and geochemistry with Rock-eval & Raman spectroscopy measurements. A 2D TemisFlow model has been performed in order to better quantify and evaluate the thermal evolution of this margin prior to extension, during rifting, breakup and post breakup time. Preliminary results of the northern South China Sea suggest a jump in the thermal maturity profile between the syn and the pre-rift sediments showing high thermal maturity with potentially nearby volcanic intrusion. These new results will eventually be compared and contrasted to those of the Iberia-Newfoundland conjugate margins. Altogether, these critical new datasets may improve our understanding of rifting and continental breakup processes.

Figure 1: *A, Maps of the northern South China Sea and Iberia rifted margins showing the location of the IODP/ODP sites used to calibrate our thermal modelling. B, Seismic profiles across the northern South China Sea (Sun et al., 2016) and Iberia rifted margins (Sutra et al., 2013). For the latter a summary of the drilling results are presented.*


A
South China Sea margin
110° 112° 114° 116° 118° 120° E
N 22° 20° 18° 16° 14° 12° 10°
South China
TW
PRMB
LB
NWSB
ESB
P
IC
SWSB
PW
Elevation (m)
-4000 -3000 -2000 -1000 -500 -250 -100 -5 5 10 50
Convergent zone
Magnetic anomalies
Sedimentary basin
Extinct spreading ridge
ODP/IODP Sites expeditions
184 349 367 & 368
Iberia margin
14° 12° 10° 8° W
N 44° 42° 40° 38° 36°
ODP leg 103
ODP leg 149
ODP leg 173
B
South China Sea margin
Liwan Basin
Outer Margin High
Ridge A
Ridge B
Ridge C
NW
SE
U1501p
U1499p
U1502p
U1500
C11n
C10n
b
Neogene
Paleogene
T30
T60
T80
Tg
Upper crust
Lower crust
Moho
Profiles f-g
TWT(s)
2 4 6 8 10
50 100 150 200 250
Distance (km)
Sun et al., 2016
Iberia margin
1070 897 898 1069 1068 900 1067 1065 901
H
?
Pre-tectonic sediments
Syn-tectonic sediments
Post-tectonic sediments
Amphibolite
Gabbro
Serpentinites
Meta-sediments
Breccias
Hiatus
Top basement fault
West
East
TGS + LG12
Oceanic Crust
Serpentinized Mantle
Oceanic Mantle
Sub-continental Mantle
Upper / Brittle Continental Crust
Middle / Ductile Continental Crust
Lower / Mafic Continental Crust
~20 km
DEPTH (km)
0 5 10 15 20 25 30
distance (km)
200 150 100 50 0
Sutra et al., 2013

NOTES:

Heat Flow variability across the offshore Brazilian Margin: Implications on basin modelling

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Across the offshore Brazil margin observations show surface heat flow ranges from 35 - 120 mW/m^2 in several basins across a variety of crustal domains. The data set is a compilation of published scientific measurements as well as propriety acquired heat flow measurements in a non-uniform geographic distribution. Careful analysis of the data set has allowed the determination of higher end heat flow measurements, 60 -120 mW/m^2, is not restricted only to un-attenuated continental crust as has been previously shown in onshore studies. The high heat flow measurements > 70 mW/m^2 extends across hyper-extended crustal regimes but are even observed onto oceanic crust. The implication of these observations directly impacts basin modelling calibration.

Further, an increase in geothermal gradient up to 45-50 °C/km is observed in deepwater well penetrations in hyper-extended crustal regimes approaching the ocean-continent boundary, which supports the observations of increasing heat flow.

Since some heat flow values and geothermal gradient measurement are clearly higher than expected on hyper-extended and oceanic crustal architecture, it is important to understand these observations in context of crustal composition, crustal thickness variation and potential dynamic mantle upwelling.

In this study, we highlight basin modelling challenges across the Brazil Equatorial Margin (Potiguar Basin) in calibrating to temperature and maturity data from deepwater wells, whilst honoring the heat flow observations and incorporating sensible geologic variations within the radiogenic heat contribution from the crust in Petroleum Systems modelling.

In the absence of deepwater well data, surface heat flow measurements in hyper-extended crustal regimes can be consulted in conjunction with any shelfal or onshore well penetrations to aid in thermal calibration of deepwater plays and capture uncertainty of source rock maturity in basin models.

NOTES:

Analysing heat flow and subsidence along a passive margin from thermal history reconstruction - a Case Study from the Eastern Gulf of Guinea (Rio Muni/Douala Basin)

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Thermal History Reconstruction (THR) using a combination of measured thermal maturity data (AFTA and vitrinite reflectance) from well and surface outcrop samples provides a 'non-model based' way of resolving heat flow and subsidence in sedimentary basins. In passive margin basins this includes syn- and post break-up heat flow and subsidence and the effects of exhumation events identified as cooling episodes in the thermal history. In this situation THR allows the timing and amount of missing section (i.e. 'hidden subsidence') and paleo-geothermal gradients to be estimated.

This paper presents a case study from the Rio Muni and Douala Basins of the Eastern Gulf of Guinea. Here data show well defined evidence for multiple thermal episodes under a declining heat flow regime, that represent discrete periods of burial and exhumation in the Late Cretaceous and Early and Late Cenozoic, following early Cretaceous rifting. The data enable the absolute timing of these episodes to be determined directly and allow the magnitude of exhumation at each event to be estimated.

Significantly, in favourable circumstances, a window onto an early phase of elevated heat flow in the Mid-Cretaceous is provided by the data. This provides a crucial control on the theoretical models of continental break-up as it allows an early episode of elevated heat flow to be distinguished from later thermal episodes caused by burial and exhumation under a lower 'normal' heat flow regime.

In addition, recent THR work has recognised a very late thermal episode (~2 Ma to present-day) that appears to affect wide parts of the Douala and Rio Muni basins. This is likely the cause of the relatively high present-day geothermal gradients recognised widely over the area and suggests that the 'high thermal regime' of the Douala and Rio Muni basins is a very recent phenomenon. If so, this has fundamental ramifications for models of heat flow and source rock maturity that have assumed this to be a long-lived thermal regime.

We draw attention to an extensive THR database along the West African passive margin that has valuable information to contribute in the research of syn- and post break-up heat flow and the processes of subsidence and exhumation, in addition to its more routine application in oil and gas exploration.

NOTES:

Estimating palaeoheat flow onshore east Greenland

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A suite of thermochronological data (apatite fission track and (U-Th-Sm)/He dating) is available from sub-vertical profiles sampled along the central Eastern Greenland margin between 68° and 76°N. The profiles sample the walls of high-relief glacial valleys (1-2 km) and include between 2 and 8 samples each, derived from pre-Devonian basement and Devonian and Carboniferous sediment. The measured AFT ages range from 267±13 to 9.3±1.2 Ma, with mean track lengths from 10.6±0.32 to 13.8±1.8 μm, and the AHe ages from 204±16 Ma to effectively 0 Ma (Bernard et al. 2016).

The data for each profile have been modelled jointly in order to extract the palaeotemperature gradient, and the approach allows for this to be considered constant or variable over time. We also have some limited measurement of thermal conductivity and heat production (U, Th, K) for the same lithologies sampled in the vertical profiles, which allows us to quantify heat flow from the gradient estimates.

The palaeotemperature gradients generally range from 20 to >50°Ckm^{-1} while palaeoheat flow estimates range from about 40mWm^{-2} to 150 mWm^{-2}. There is a clear correlation of high heat flow with granitic/gneissic basement, and lower heat flow for the sediments. The higher hear flow values reflect the combination of higher gradients and relatively high thermal conductivities (>3 Wm^{-1}K^{-1}). The higher values are at the limit of heat flow estimates from high heat production (HHP) granites, such as those in Scandinavia and southwest England. The heat production values, based on hand held gamma ray spectrometry and XRF measurements do not imply abnormally high contributions from in situ radioactive decay. Therefore, assuming the heat flow estimates are reliable, the granitic basement is very thick (more or less the whole crust), locally enhanced or depth dependent heat production contributions, or there are heat refraction effects enhancing vertical heat transfer. The latter effect is most enhanced for large contrasts in thermal conductivity between the granites and the country rock, and high aspect ratio (height/radius) for cylindrical granite bodies.

NOTES:

Day Two: 9th October 2018

KEYNOTE: Residual Depth Anomalies, Heatflow and Mantle Convection at Rifted Margins

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The success of rifting models often conditions the way in which we think about the large-scale structure and heatflow characteristics of deep-water margins. For example, generation of subsidence and/or uplift is usually linked to the isostatic interplay of crustal and lithospheric thinning, which are ultimately controlled by horizontal plate motions. Despite this success, there is growing evidence that both vertical movements and heatflow anomalies at these margins can be influenced by sub-plate processes. It is generally agreed that convective circulation of the Earth's mantle maintains plate motion. However, we know little about the spatial and temporal details of this circulation. It is reasonable to expect that this circulation pattern generates and maintains dynamic (i.e. transient) topography, as well as affecting heatflow, at the Earth's surface. On the continents, small dynamic topographic signals are difficult to measure because the density structure of the crust and lithosphere is poorly known. More rapid progress can be made by exploiting our quantitative understanding of the thermal evolution of oceanic lithosphere. Seismic reflection and legacy seismic wide-angle profiles have been used to measure residual depth anomalies worldwide. Positive and negative deviations from the global age-depth curve are common along deep-water margins and have amplitudes of +/- 1 km and wavelengths of 100-1000 km. Spherical harmonic analysis of these observations shows that the results of computational models that calculate dynamic topography from the distribution of mantle mass anomalies are substantially incorrect. However, observed residual depth anomalies are consistent with long-wavelength gravity anomalies and with upper mantle seismic tomographic anomalies. Along the West African margin, a series of broad structural domes straddle the continental shelf. Uplifted marine terraces, offshore stratigraphic geometries, and fluvial drainage networks suggest that these gigantic features mostly grew in Neogene times and influenced regional heatflow. Along the northwest shelf of Australia, oceanic depth anomalies show that a broad depression intersects the coastline. Here, we observe rapid post-Miocene subsidence which is recorded by a dramatic switch from aggradation to progradation within a buried coral reef. This switch caused organic-rich source rocks at depth to enter the hydrocarbon window and charge overlying structural traps. In the North Atlantic Ocean, buried ephemeral landscapes have recently been mapped on three-dimensional seismic surveys. Their existence implies that rapid (i.e. ~1 million year) transient uplift events occurred during Cenozoic times. We attribute these vertical movements to periodic fluctuations within the Icelandic plume. These three examples suggest that mantle convection plays a significant, and hitherto underestimated, role in moderating vertical movements, stratigraphic architecture and organic maturation at deep-water margins.

NOTES:

Session Three
Modelling Case Studies

Analysis of subsidence in a new-real estate domain: the sedimentary prism approach

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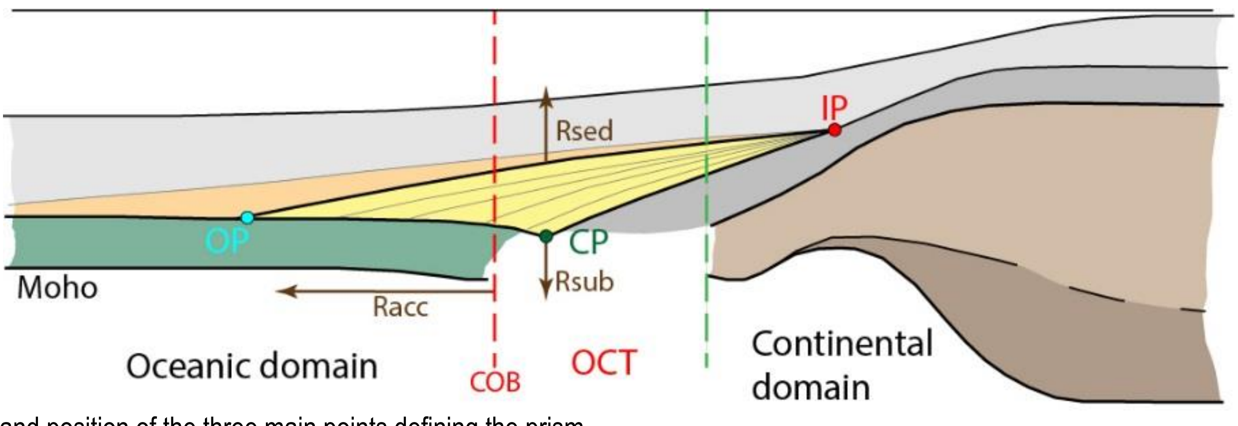
Nowadays the thermal evolution of passive margins is getting of high interest in petroleum exploration. Indeed, the use of basin modelling for the exploration of passive margins is crucial to test various geological scenarios such as the timing of deformation, age of source rock intervals, types of source rocks. Sensitivity analyses systematically suggest that the most sensitive parameter to model basins in passive margins remains the thermal history including the thermal peak during lithospheric break-up and its post-rift relaxation. New advances in thermomechanical modelling are currently providing new thermal constrains to such basin models. However, they need to be carefully calibrated with detailed structural interpretations, geothermometers, heatflow measurements and other available approaches.

In this study we propose a new approach, never tested before on passive margins, that focus on the characterization of accretion, sedimentation and subsidence rates along a sedimentary prism. This new method aims to quantify the thermal state at the onset of seafloor spreading at rifted margins as well as to indirectly estimate its impact on accretion, sedimentation and subsidence rates. Actually the observed subsidence has been compared to the Stein & Stein (1992) model and allows extracting the potential thermal support. Although the detailed analysis of the sedimentary prism represents a unique opportunity to better understand the combined effects of the early seafloor spreading, sedimentation and subsidence and their spatial variations along the margin. In our study we chose a divergent segment in the Equatorial Atlantic ocean, bordered by major transform fault zones and affected by important onshore and offshore pre- to syn-rift magmatic activity. A sedimentary prism can be imaged along this segment at the Ocean Continent Transition (OCT) by high quality 2D seismic lines and calibrated by several wells. It covers approximately 10 myr of sedimentary deposit before and after the lithospheric break-up (early Albian).

Fig. 1 Schematic section across the margin highlighting in yellow location and architecture of the sedimentary prism



and position of the three main points defining the prism.

The structure referred here as “sedimentary prism” is defined by three main points (in 3D corresponding to lines). These are the inflection point (IP), the continentward point (CP) and the oceanward point (OP) (see Fig. 1) corresponding to the continent and oceanward limit of the downdipping limits of the sedimentary prism onto oceanic crust or OCT. By making assumptions of rates of subsidence and spreading for points CP and OP and defining paleowater depth (drill hole data) for sediments near IP, the post-rift vertical and horizontal space creation and infill history can be defined (Fig. 1).

First results show that: 1) rates of rifting are inhomogeneous and diachronous. Early oceanic spreading seems to be controlled by local conditions and then by global processes; 2) bathymetry of first oceanic crust was anomalous shallow comparing to classical global models. Our results highlight that the subsidence and therefore also thermal stage of first seafloor spreading may not be captured by classical models describing the thermal state and evolution of oceanic crust at Mid Ocean Spreading Ridges. Three processes can control the anomalous subsidence history: 1) high thermal support during breakup, 2) high sedimentation rates, and 3) the proximity to the transform faults bounding the segment. Variation of subsidence/sedimentation along the segment may indicate that the conditions at segment boundaries are different from those within the segment.

In conclusion, our new method aims to determine the subsidence history of OCT using geometrical relationships derived from seismic data and calibrated by drill hole data. Preliminary results suggest anomalous subsidence and thermal evolution of OCTs. The method has been tested and has provided interesting quantitative results. Nevertheless, the sedimentary prism approach has to be tested and calibrated by more data and at different types of passive margins. However, it has the potential to give some new relevant guidelines to basin modelers modelling the subsidence and thermal history of OCTs.

NOTES:

Heat Flow Modeling in Hyper Extended Crust Basins: Chidley Basin Case Study, South Labrador Canada

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The Heat flow geological evolution in the Chidley Basin is controlled by heat transfer through the evolving hyper-extended crustal margin and synchronous deposition of sediments. Diachronous rift propagation took place during the Early Cretaceous until the Middle-Late Cretaceous, associated with the northward opening of the North Atlantic Ocean. It resulted in a succession of crustal zones typical of magma-poor margin: slightly thinned continental crust, highly stretched continental crust, transitional crust with mantle exhumation and oceanic crust. The estimated crustal thinning assumed from literature and calibration of the thermal basin model, suggests a total geometric crustal thinning from $\beta=1.2$ in slight thinned continental crust domain to $\beta=8$ in present day highly thinned transitional crust domain.

During the Upper Cretaceous post-rift period, the heat-flow in the rifted areas gradually decreased until steady state equilibrium is reached. Also, high Cenozoic sedimentation rate over the depocenters contributes to the decrease of the thermal gradient. The presence of transitional crust with low radiogenic content results in an overall low heat flow and thermal gradient. In the nearly undeformed continental crust areas, the heat-flow remains slightly higher since the radiogenic production is higher and sedimentation rate is lower.

Present day thermal gradients are the result of thermal equilibrium between past tectonic rifting events, recent sedimentation rate and thermal conductivity of sediments. Present day shelf temperature measurements in wells (DST, corrected log and BHT temperature data) indicate average deep thermal gradients of 30-36 °C/km. The simulated average deep thermal gradients in the slope and basin vary from 22-30 °C/km. Herein, sea bottom heat flow measurements, surface thermal gradients and fluid type and quality evidences were used to calibrate the model thermal evolution.

The modeling of burial history and heat transfer during rift evolution allowed estimating paleo-temperatures through geological time. The model predicts a high thermal gradient during Upper Cretaceous post-rift period, which is favorable for early hydrocarbon generation from Lower Cretaceous organic-rich source rocks. Timing of early hydrocarbon expulsion and migration related to Tertiary trap formation appears crucial for the evaluation of the hydrocarbon risk charge in the leads/prospects.

NOTES:

Present day lithospheric structure along a slowly rifted passive margin: Otway Basin, SE Australia. Thermal implications for hydrocarbon prospectivity

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[2]*Institute of Geology and Geochemistry of Petroleum and Coal, Aachen University*

The passive margin along the Otway coast of SE Australia has been subject to many thermal and heat flow studies in the past. Deep, 16sec. seismic recordings from Geoscience Australia imaging the Moho, allow us to gain a deep picture of the present day lithospheric structure along the margin. Together with well calibration data from hydrocarbon exploration wells we could estimate the present day lithospheric mantle thickness using isostatic principles. The Otway margin consists of 3 main zones. The inner rifted basin, the outer rifted basin and an area of un-roofed mantle. The seismic data images the deep crustal architecture of the present-day Otway margin (Figure 1). The interpreted Moho forms the lowest "visible structural feature". In this paper we present a method of calculating the base of the lithosphere from the interpretation shown in Figure 1 and how we can quantify uncertainties for that depth.

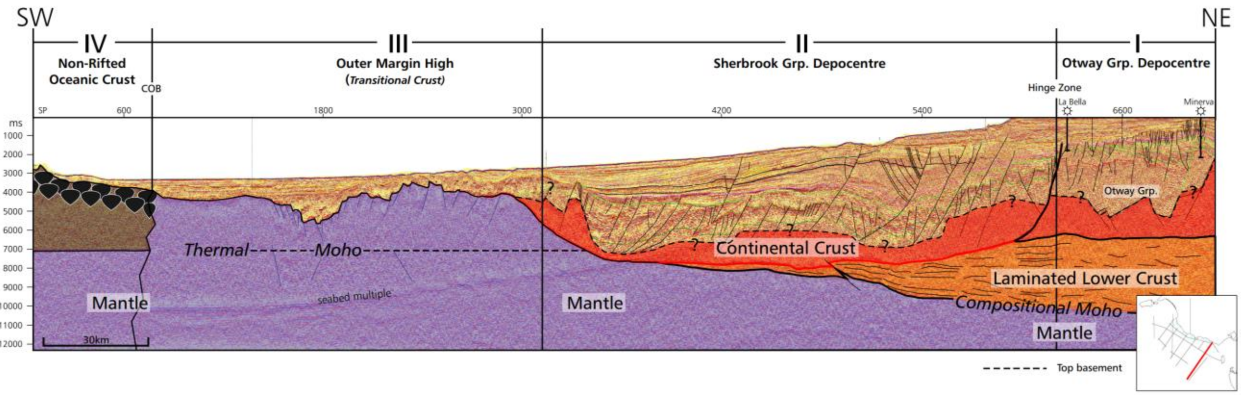


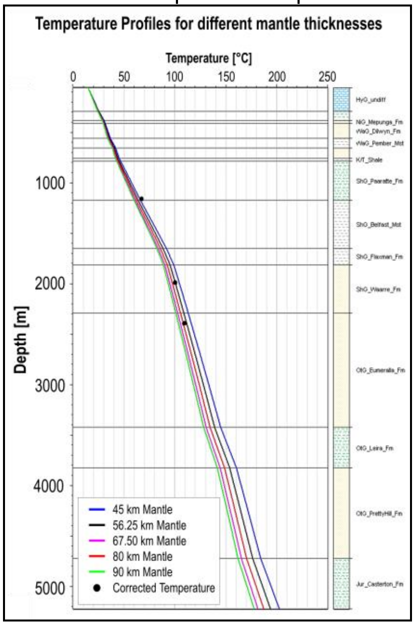
Figure 1: Structural zones I, II, III and IV of the Otway Continental Margin illustrated along seismic line GA137-09. The top basement reflector is poorly defined, especially below the Sherbrook Group depocenter. The lamination of the lower continental crust has been highlighted. The seismic has been flattened to half the water layer TWT – removing the water layer effect.

In Zone I we observe an initial rift phase (150-98 Ma) followed by a thermal subsidence phase during the deposition of the late Early Cretaceous Otway Group. With the start of the Late Cretaceous the main depocenter shifted into zone II with only minor extensional tectonics in Zone I. With continuous extension within Zone II along a deep detachment that has developed along the Moho reflector. This very slow extension continued until the mid-Eocene when first oceanic crust was created and the separation between the Australian and Antarctic plates occurred as the final act of the Gondwana break-up. Hyper-extension of the Otway margin lithosphere is documented by the presence of the outer margin high within Zone III, interpreted as unroofed mantle material. Serpentinization of the mantle peridotite has changed its density significantly. Hence the label "transitional crust".

The thickness evolution of the lithospheric mantle is a major uncertainty when analyzing the thermal history of a sedimentary basin. Traditional workflows invert the tectonic subsidence to stretching factors and thickness variations of lithospheric layers through geological time. This approach is widely used, but poorly calibrated, reducing quality of the generated thermal model for petroleum systems modeling.

To gain a present-day thickness model of the lithospheric mantle we present an estimative workflow that delivers workable scenarios of the present-day lithospheric layer thicknesses. Isostatic principles are used and an uncertainty quantification is included.

Step 1: Calculate the lithospheric mantle thickness assuming the margin is in isostatic equilibrium and flexural effects are ignored. Using the temperature profile of exploration wells (Figure 1) close to the rift basin edge we can vary the lithospheric mantle thickness as the main uncertainty until the observed temperature profile matches the calculated one (Figure 2). If the rest of the margin is in isostatic equilibrium to the calibration points, we can now calculate the required lithospheric mantle thickness using isostacy.



	density [kg·m^{-3}]	thickness [m]	Pressure at reference depth
Water	1,000	81.55	
Sediments	2,350	5,147.76	
Crust, upper	2,670	8,923.56	
Crust, lower	3,100	17,847.13	
Transitional Crust	2,900		
Oceanic Crust	2,950		
(lith.) Mantle	3,300	56,250.00	
(asth.) Mantle	3,200	50,000.00	
Reference depth		138,250.00	4.29 GPa

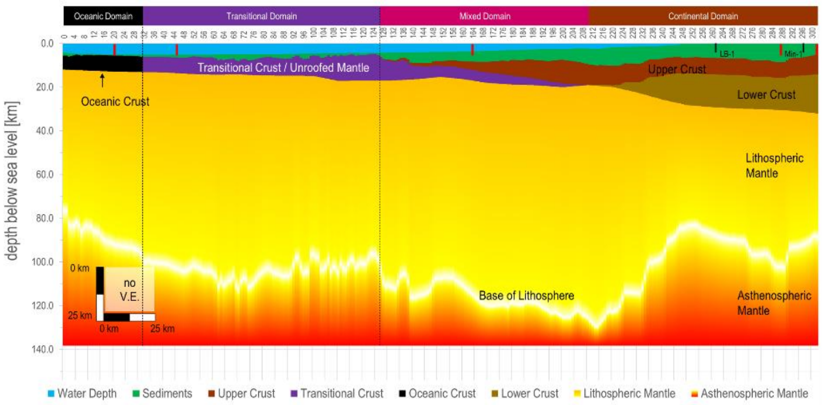


Figure 2: Comparison of temperature profiles based on different lithospheric mantle thicknesses in the Minerva-1 well (see Figure 1 for location). The densities used for the isostatic calculations are shown in the table above the resulting cross-section. Sediments in green, water in blue.

Step 2: Using free air gravity to calculate the potential error and related uncertainty from step 1. The free air gravity anomaly is sensitive to the crustal structure and can be used to quantify flexural effects. The uncertainties in the interpretation of the crustal geometries lead to a "correction" in the depth of the base lithosphere to match the observed gravity profile. The quantification of the error can directly be used as a means of defining the uncertainty for the calculated depth of the 1330°C isotherm to define the range of plausible temperature histories for petroleum systems modeling. The uncertainty analysis can define minimum and maximum paleo temperature scenarios that are geologically reasonable consistent with geological and geophysical observations. The quality and the confidence in the results of predictive workflows is highly increased.

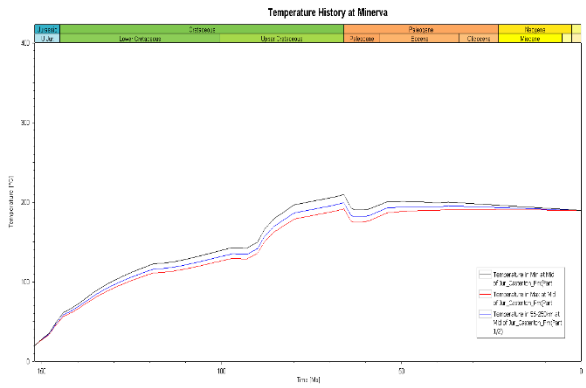


Figure 3: resulting minimum, maximum and most likely temperature histories at the Minerva -1 location for an Early Cretaceous layer

NOTES:

Modelling Petroleum Systems of Hyperextended Margins: the Angola Case Study

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The Kwanza Basin of Angola is a South Atlantic basin whose evolution was controlled by the Early Cretaceous rifting and later transition to a passive margin basin.

It is interpreted by several authors as lying over a Hyperextended Margin (e.g. Unternehr, 2010). In such a setting thinning of the lithosphere is not linear from undeformed continental to oceanic domain like in the pure shear model (Mc Kenzie, 1978) but present "hyperextended" portions where crust or mantle lithosphere has been preferentially removed (Huismans & Beaumont, 2011).

The Kwanza Basin infill is characterized by a thick Aptian salt layer that separates different petroleum plays. The post-salt plays were the first explored in the offshore, targeting Albian carbonates and Late Cretaceous - Tertiary clastics. The pre-salt play that was already tested in the onshore and shallow offshore generated great interest in deep and ultra-deep offshore during the last decade in search of analogs to the prolific mirror Campos and Santos basins of Brazil.

Massive investment and an intense drilling campaign of 23 exploration wells (2011 to 2016) were realized but gave contrasting results from the pre-salt play including giant oil and condensate discoveries, dry gas and CO2 rich accumulations, but also a number of dry wells.

This situation reveals a complex petroleum system that might only be understood at a regional scale,considering deep geodynamics and related thermal and geochemical processes. That was the objective of a regional petroleum system analysis that will be presented here.

The applied workflow included basin scale structural and facies mapping, well database construction, review and interpretation of organic geochemical data, integration of petrographic and non-organic geochemical data, and finally building and simulation of a 3D basin model to be used as an integration and visualization tool testing different hypotheses.

3D basin modelling of such a hyperextended margin was a challenging novelty and required the implementation of a specific workflow to face an unusual crustal structure and thermal history, both of them further complicated by a thick salt layer. After a detail try and error process a good calibration of the model was achieved.

Modelling results show that the thermal impact is higher than in a classical pure shear model and the difficulty consists in estimating the limits of the different crustal domains, the timing of rifting and the extent of the rise of the asthenosphere and its consequences on sediment maturity.

This case study also highlighted new processes to understand and consider, and software limitations inherent to this specific margin type when assessing petroleum systems.

NOTES:

Session Four
Insights from Numerical Modelling

Numerical models of heat flow and subsidence evolution during rifted margin formation

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German Research Centre for Geosciences GFZ

Hyper-extended continental margins are one of the most promising frontier exploration provinces, but their evolution is still poorly understood in both, industry and academia. The key to assess prospectivity at deep-water, hyper-extended margins is to understand the temperature/pressure environment of the petroleum system by quantifying the evolution of heat flow, paleowaterdepth and sedimentary overburden. These parameters directly link the oil window to the geodynamics of faulting, ductile shear zones and mantle upwelling.

Here I build on recent advances in understanding crustal hyper-extension (Brune et al. 2014, Nature Communications) and rift velocity evolution (Brune et al. 2016, Nature) in order to quantify heat flow and subsidence evolution using the geodynamic modeling code SLIM3D. The code combines thermal processes operating within the lithosphere (heat transport, radiogenic heat generation, shear heating) and the three fundamental processes of rock deformation (brittle failure, elastic straining, viscous flow) in a joint thermo-mechanical solution. Its formulation intrinsically accounts for depth-dependent extension and the associated surface subsidence, while providing a geodynamic framework to compute rifting and passive margin formation with realistic rheology formulations and at high resolution.

The models highlight rift migration as a key process during hyper-extended margin formation. This process where the rift center migrates for many million years is maintained by sequential faulting in the brittle crust and balanced by lower crustal flow. Maximum heat flow follows the migrating rift center so that the distal margin may experience peak heat 10 to 20 My after the proximal margin with profound implication for the petroleum system. This process is of direct relevance to the asymmetric South and North Atlantic conjugates, but also to major Australian margins.

NOTES:

Margin architecture, sediment structure and heat flow at rifted margins

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Sediments at rifted margins host enormous energy resources, whose formation significantly depends on the thermal and deformation history of the margin. However, the relationship between basement deformation, sediment architecture, thermal and subsidence history is not yet understood. The wide range of margin and sediment architectural styles, as well as climatic and geographic conditions during and after rifting makes it difficult to disentangle this relationship. Additionally, age control on sedimentary layers observed in seismic sections is often sparse, the interpretation of the geometrical relationships between syn- and postkinematic sediments and the underlying basement structure is often ambiguous, and subsidence analysis is often based on simplistic assumptions on rifting dynamics. Here we use numerical models which couple tectonic and surface processes to understand the interactions between both, with the purpose of assisting the interpretation of seismic sections and the analysis of subsidence data.

Our models simultaneously recover basement deformation, sedimentation, heat-flow and subsidence history. Furthermore, we are able to track depositional time-lines that can be converted into stratigraphic sections. This allows us to contrast sedimentation patterns, unconformities, subsidence and heat-flow histories for varying margin architectures. We simulate these architectures by changing the initial strength of the lower crust, from very strong, to intermediate, to the weak end member. The extension of the strongest strength case results in narrow symmetric margins and rapid breakup. Syn-kinematic sediments are separated from post-kinematic sediments by an unconformity that dates the breakup and sediment age distribution is symmetric across the rift axis. Heat flow is also symmetric on both margins, with an abrupt peak at the basin center. An intermediate strength crust showcases rift migration by sequential faulting, resulting in strong asymmetry with a wide margin (∼200 km) where the crust thins smoothly and a narrow conjugate (∼50 km) where crust thins abruptly. In this case, the distribution of sediment ages is also asymmetric across the rift axis. In the wide margin, syn- and post-kinematic sediment ages, and the unconformity that separates them young oceanwards as extension migrates in this direction. Likewise, peak heat-flow migrates towards the basin center, as the more distal areas are subsiding. In the weakest case, we observe an initial long phase of wide rifting with different faulting episodes, followed by a final, short phase where deformation localizes leading to crustal breakup. The syn-kinematic sediments contain unconformities separating the different faulting episodes that take place within the wide rifting phase. Away from the final breakup location, unconformities separating syn- and post-rift pre-date breakup. Heat flow is distributed over the two conjugate wide margins and does not present abrupt increases towards the basin center as in the previous two models. In summary, using numerical models we find that the spatial and temporal distribution of sedimentation, subsidence and heat flow strongly depends on rifting styles, and that major unconformities separating syn- from post-kinematic sediments generally date migration of the main locus of deformation but rarely date breakup.

NOTES:

The Highs and Lows of Continental Break-Up

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For the last 40 years, McKenzie's stretching-cooling model has been used as the foundation for studying the subsidence history and thermal evolution of rifted basins. Nonetheless, a problem has long been recognized when the model is applied to passive margins such as those in the South Atlantic. In fact the issues of too little sub-rift, too much early post-rift (or "sag") seem to apply to most rifted margins, including the shelf containing much of the world's oil - the Arabian Platform. The subsidence paradox is not only manifested in unpredictable thicknesses but also in water depths, with sub-aerial to shallow water conditions at the time of break-up rather than the oceanic depths expected from isostatic considerations of thinned plate. Furthermore, in regions conducive to evaporite or carbonate sedimentation, surprisingly thick shelfal strata are often found on top of the break-up unconformity, more accommodation space created than can be explained by thermal contraction.

Using an iterative finite element routine (TecMod), we have tested the thermal-tectonostratigraphic effects of all the many explanations which have been offered for the puzzling subsidence patterns at rifted margins. We show that none of the published models explain the departure from the traditional McKenzie-type model. We therefore turn to a new idea: that the continental plate is made buoyant in proportion to the amount it stretches by increasing amounts of melt trapped in upwelling asthenosphere prior to break-up. The melt is rapidly released when the lithosphere separates, causing rapid subsidence thereafter. We successfully model this effect by adapting the TecMod software to account for the heatflow and density changes associated with melt retention and loss at the plate scale. We show that it is indeed possible for the lithosphere to remain elevated during rifting and then to subside remarkably quickly after an oceanic spreading centre is formed.

A number of implications result from the model, particularly for the maturity of petroleum source rocks and the significance of magmatic versus non-magmatic rifted margins which we illustrate with models from the South Atlantic and the Arabian Platform.

NOTES:

Improved Temperature Models for Petroleum System Analysis

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The results of petroleum system models (PSM) critically depend on the computed evolution of the temperature field. Because PSMs typically only resolve the sedimentary basin and not the entire lithosphere, it is necessary to apply heat-flow boundary conditions inferred from well data, surface–heat-flow measurements, and an assumed tectonic scenario. In this contribution, we demonstrate how temperature models for sedimentary basins can be improved.

First, we assess the use of surface–heat-flow measurements to calibrate basin models. We show that a simple relationship between surface and basement heat flow only exists in thermal steady state and that transient processes such as rifting and sediment deposition will lead to a decoupling. We study this relationship in extensional sedimentary basins with a one-dimensional, lithosphere-scale finite element model. The numerical model was built to capture the large-scale dynamic evolution of the lithosphere and simultaneously solve for transient thermal processes in basin evolution such as sedimentation, compaction-driven fluid flow and seafloor temperature variations. Our analysis shows that several corrections need to be applied when using surface–heat-flow information for the calibration of basement heat flow in PSM. Not doing so can lead to significant errors of up to 30°C–50°C at typical petroleum-reservoir and source-rock depths. We further show that resolving sediment-blanketing effects in basin modeling is crucial, with the thermal impact of sediment deposition being at least as important as rifting-induced basement–heat-flow variations.

Second, having established the importance of the sediment-blanketing effect, we focus on the observation that post-rift sequences are often considerably thicker than the syn-rift deposits. In fact, even synextensional uplift and/or erosion are widely documented in nature (e.g. the Base Cretaceous unconformity of the NE Atlantic). Previous explanations either involve differential thinning, where the mantle thins more than the crust, thereby increasing average temperature of the lithosphere, or focus on the effect of metamorphic reactions showing that such reactions decrease the density of lithospheric rocks. Both approaches result in less synrift subsidence and increased postrift subsidence. The synextensional uplift in these two approaches happens only for special cases that is for a case of initially thin crust, specific mineral assemblage of the lithospheric mantle or extensive differential thinning of the lithosphere. Here, we analyse the effects of shear heating and tectonic underpressure on the evolution of sedimentary basins. In simple 1D models, we test the implications of various mechanisms in regard to uplift, subsidence, density variations and thermal history. Our numerical experiments show that tectonic underpressure during lithospheric thinning combined with pressure-dependent density is a widely applicable mechanism for synextensional uplift. Mineral phase transitions in the subcrustal lithosphere amplify the effect of underpressure and may result in more than 1 km of synextensional erosion. Additional heat from shear heating, especially combined with mineral phase transitions and differential thinning of the lithosphere, greatly decreases the amount of synrift deposits.

Third, we analyse the effect of the formation of new oceanic crust on the thermal and maturity of the adjacent continental crust. Continental breakup along transform margins produces a sequence of (1) continent-continent, (2) continent-oceanic, (3) continent-ridge and (4) continent-oceanic juxtapositions. Spreading ridges are the main sources of heat, which is then distributed by diffusion and advection. Previous work focused on the thermal evolution of transform margins built on 2D numerical models. Here we use a 3D FEM model to obtain the first order evolution of temperature, uplift/subsidence, and thermal maturity of potential source rocks. Snapshots for all four transform phases are provided by 2D sections across the margin. Our 3D approach yields thermal values that lie in between the previously established 2D end-member models. Additionally, the 3D model shows heat transfer into the continental lithosphere across the transform margin during the continental-continental transform stage ignored in previous studies. The largest values for all investigated quantities in the continental area are found along the transform segment between the two ridges, with the maximum values occurring near the transform-ridge corner of the trailing continental edge. This boundary segment records the maximum thermal effect up to 100 km distance from the transform. We also compare the impact of spreading rates on the thermal distribution within the lithosphere. The extent of the perturbation into the continental areas is reduced in the faster models due to the reduced exposure times. The overall pattern is similar and the maximum values next to the transform margin is essentially unchanged. Varying material properties in the upper crust of the continental areas has only a minor influence.

NOTES:

Poster Presentation Abstracts (Presentation order)

Poster Abstracts
Day One

The Thermal Regime of African Plate Margins

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MacGeology Ltd

The African plate provides an ideal laboratory for testing relationships between heat flow and the age and type of continental margins, as break-up on different parts of the margin ranges from Triassic to Pliocene. A database of some 2500 geothermal gradient calculations from deep wells has been assembled across the African plate, which are used in preference to the high error bar shallow core measurements which are normally used. Selected well geothermal gradients are then being corrected wherever possible for drilling effects and then converted to heat flow through a standardised method for estimating thermal conductivity. The use of vastly different thermal conductivity models and assumptions has been found to be a major error in comparing previous heat flow estimates between different authors. The model applied here, based on published Moroccan thermal conductivity, porosity and depth relationships (Rimi and Lucazeau, 1987) enables consistent estimates between basins. In other words, differences observed in heat flows between basins are more credible than actual numbers.

Such estimated heat flows are compared against the models of McKenzie (1978) and Hantschel and Kauerauf (2009) to assess the validity of the thermal decay models of these authors. Essentially the margins studied can be considered in four groups.

1. Those on very young margins that, as expected, show very high heat flows. The Red Sea is the clear example of this, with one Eritrean well showing a heat flow of 215 mWm^{-2}. (Figure 1) This implies a risk that other African margins may have been as hot at the time of their break-up.
2. Those which broke-up in the Triassic to Cretaceous and have now decayed over a considerable amount of time to a background low heat flow, thus also now showing expected behaviour. An example is the deepwater Levantine Basin, which has been cooling since the Triassic and now seems to show a consistent heat flow of around 50 mWm^{-2}. Much of the NW African margin, which spread in the early Jurassic, has also now cooled to 50-60 mWm^{-2} .
3. Those showing what could be considered as unusually low heat flow, though this can be readily tied to the nature of the Basement. The Mozambique plains show average heat flow below 50 mWm^{-2} (Figure 2), which compares to heat flows of above 70 mWm^{-2} in the non-volcanic Rovuma Basin to the north. This could be related to a lack of radiogenic thermal support from underlying transitional crust (heavily intruded by basic igneous material) on this volcanic margin.
4. Those on old margins which show high thermal anomalies up to 300km wide, well above what a thermal decay model based on rift and drift would predict. Geothermal gradients in excess of 40 ^{o}C/km and heat flows in excess of 75 mWm^{-2} are surprisingly common on the eastern and western margins of the continent, amid backgrounds of around 50-60 mWm^{-2} (e.g. Figure 3). The anomalies further south from Senegal on the west Africa margin, in regions such as Ghana, Gabon and the Lower Congo Basin, are poorly data controlled but seem to be reflected in similar anomalies on the Brazilian conjugate (Hamza, 2018). One explanation for these anomalies is relatively young intrusion of hot igneous rocks, as demonstrated by the anomaly associated with Late Cretaceous-Quaternary intrusions and volcanics associated with the Dakar hot spot of Senegal (Figure 3). This is supported by looking at the distribution of ages of African volcanics, which indicate a buildup from the Oligocene to a maximum in the Quaternary. Deep igneous intrusion models have also been proposed for the Brazilian anomalies, which form a belt 100-300km wide close to the continental-ocean transition zone (Hamza, 2018).

These anomalies discussed in 4) above help to explain recent petroleum discovery trends, including several basins which turned out to be oil bearing where immaturity had once been predicted and others where more gas has been found than the predicted oil. The data assembled here indicates that wider and generally higher ranges of heat flow should be applied in basin models across most African basins and petroleum systems, not only at Present Day but also during the times of break-up or other peaks of igneous activity.

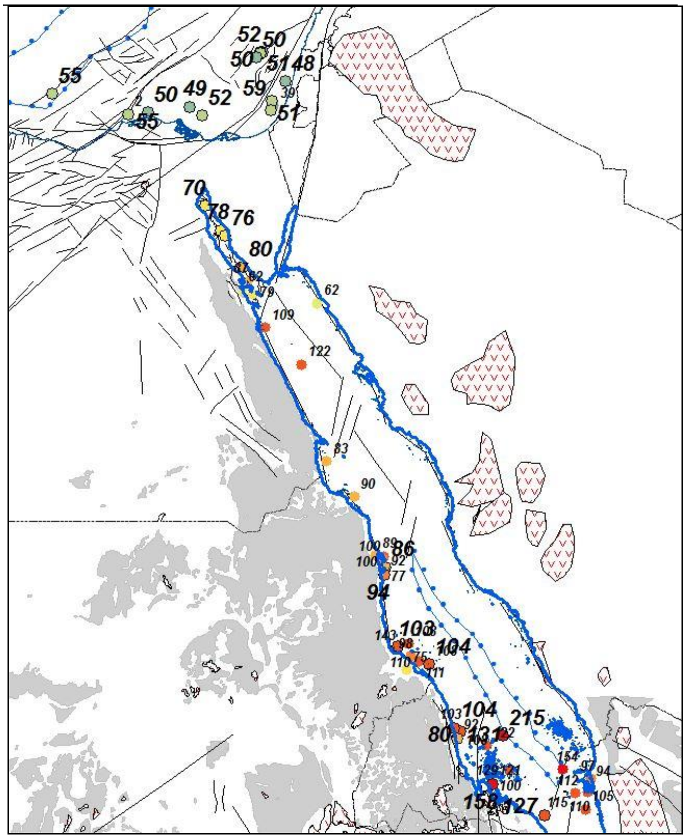
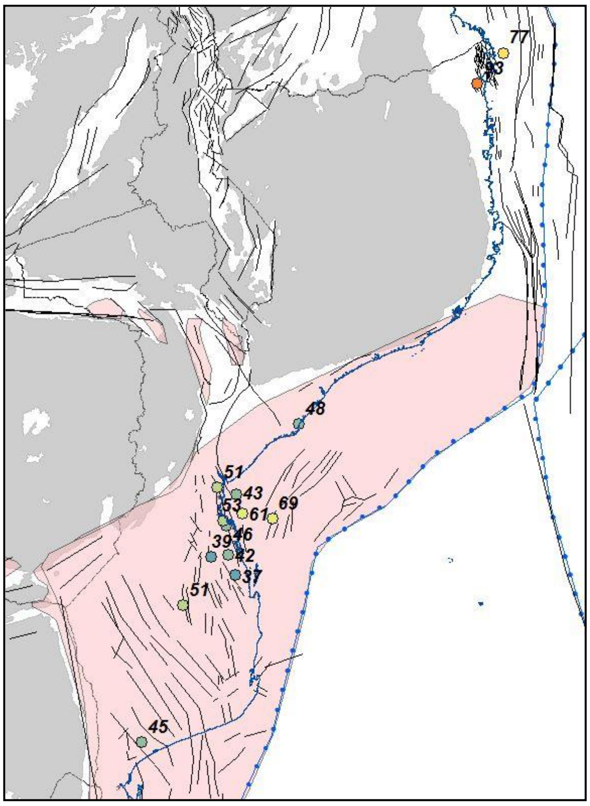


Fig 1 : Levantine Basin and Red Sea heat flow map. Authors heat flows in mWm^{-2} in bold, others in smaller font, Pink Vs are volcanics. Blue dotted line is COB



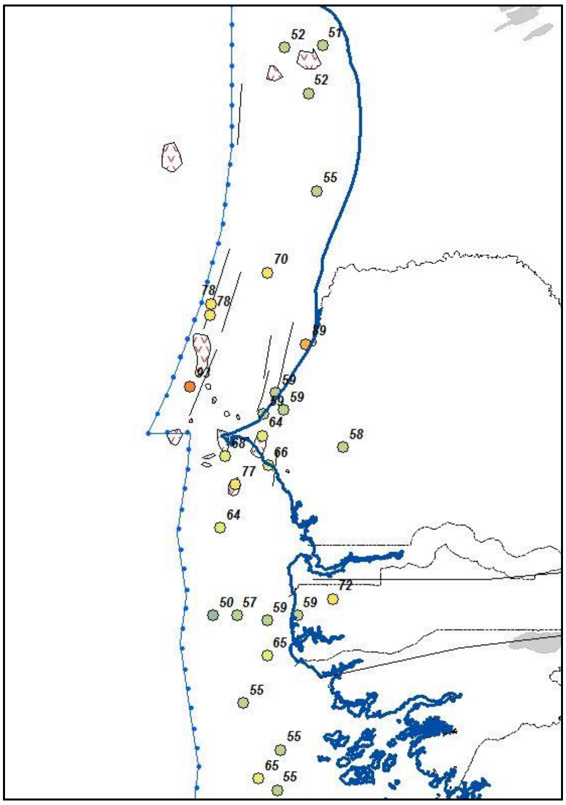


Fig 2 :Mozambique heat flow map
Pink=interpreted transitional crust

Fig 3 : Mauritania-Senegal heat flow map
Pink Vs are volcanics/intrusions (late K-Qy)

Thermal histories during Subsidence and Uplift, and Kinetic Modelling of Petroleum Generation, as controlled by Mechanics and Thermodynamics; Case Studies from the UK Central Graben and Uinta Basin USA

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The presence of producible petroleum in geological basins is due to the interplay between a number of factors including source rock and reservoir quality, and thermal history. The thermal histories of basins can be derived using tectonic and kinetic models calibrated using present day corrected well temperature records (Harris and Peters, 2012). The current models for predicting subsurface temperatures derive the temperatures at different depths using the amounts of thermal energy supplied by conduction and convection from the surrounding rocks, plus any heat generated by thermogenic decay of radioactive isotopes.

As the lithosphere moves during subsidence and uplift, this movement involves mechanical work. Mechanical work is the change in potential and/or kinetic energy of a rock as it changes its position in the potential (gravitational) field, and heat (thermal energy) is always produced during mechanical work. This mechanically produced heat arises mainly due to friction inside and between moving rock systems. Subsidence results in the conversion of potential, via kinetic energy into thermal energy (heat). The conversion between mechanical work and thermal energy during subsidence is required by the conservation of energy (1st law of thermodynamics), as opposed to the current tectonic and kinetic models that only conserve thermal energy. This means that part of the thermal energy currently attributed to convection, etc. from the surrounding rocks ignores a potential thermal energy source in geological basins. As rocks subside they produce between 8 and 12 $^{o}C/m^{3}/km$ of additional temperature compared with that predicted by the conduction-convection-radiogenic models, depending on the distance moved and the specific heat capacities of the rocks (and fluids) being moved. Strictly not all the potential energy is converted into thermal energy during subsidence, as very small amounts of mechanical work will be converted into sound and, in cases of extremely rapid movement, e.g. faulting, some of the converted energy will be converted into shock energy (seismicity). The thermal energy produced from the mechanical work conversion can then be stored or conducted to surrounding rocks depending on the thermal properties of the surrounding rocks. An example of this conversion occurs in the HP-HT area of Central Graben, North Sea, with the high temperatures partly arising from the rapid Plio-Pleistocene subsidence in this area.

Rocks subside because the upward force provided by the lithosphere beneath the basin is lower than the downward force of the basin. As the upward force is decreased and subsidence occurs, then the heat flow from the basement into the basin must also be reduced, since decreasing the upward force reduces the amount of mechanical work (and Heat) associated with the upward force. Heat flow from the basement (including any heat generated by mechanical work in the basement) must therefore decrease during subsidence, with the reduction including the heat produced from mechanical work in the basement and crust. There is always an imbalance between the heat flow supply into the geological basin and that generated within the basin; the conversion between potential-kinetic and thermal energy during subsidence is instantaneous, whereas the reduction in heat flow supply from the basement is slower due to thermal reserve in the basement, crust, etc. Constant heat flows or geothermal gradients as used in many petroleum system modelling publications to calibrate the well temperature and palaeothermal parameters are incorrect, and therefore give false indications for the timing of chemical processes, e.g. petroleum generation, diagenesis, etc. Effectively, in these constant heat flow/geothermal gradient models for predicting temperatures and palaeogeothermal indicators, the laws of kinetics are being used to overrule the laws of thermodynamics, whereas geologists should recognise that a kinetic model that does not obey the laws of thermodynamics is never going to produce the 'correct predictions'.

Uplift in contrast involves an increase in the upward force from the basement-crust-mantle beneath the basin, and as a result of this mechanical work the conducted heat flow into the basin must increase during the uplift. The increase in heat flow arises from the increased mechanical work being done by the basement. Without increased heat flow sufficient to prevent temperature reductions in rocks below the cooling effect of the upper boundary surface, uplifted rocks would see negative entropy changes, something that does not occur in natural systems (2nd law of thermodynamics). Currently most predictions for petroleum generation in basins that contain some period of uplift assume that the temperatures are reduced in the entire uplifted column during the period of upward vertical movement. The effect of maintaining the temperatures achieved before uplift commenced is that more petroleum generation occurs during uplift than predicted by current thermal models. The increased heat flow during uplift means that more maturation and petroleum generation occur during uplift than hitherto considered, and less petroleum generation occurs during subsidence than currently modelled, so as to enable the predicted and observed maturation parameters in wells to be calibrated. The Uinta Basin, USA is a classical example in which the deeper present-day temperatures, i.e. those unaffected by the cooling effect of the earth's surface, have remained largely unchanged during Tertiary uplift.

In the current kinetic models for predicting maturation and petroleum generation histories it is assumed that pressure has no effect on the reaction rates. The first part of chemical reaction involves the generation of a transition state or free radicals (TST-FR), and there is a pseudo-equilibrium between the generation of reactant (immature kerogen) and TST-FR. Ignoring pressure means that the current models do not conserve energy, since all current kinetic models have low values for mechanical (pV) work undertaken during reactions. In geological basins kerogens are surrounded by largely incompressible materials (rocks and pore fluids), and as the pressure of the pore fluid increases, so the reaction pV work increases, thereby increasing the activation energy (Ea). As the pV work increases, so the temperature required to overcome the thermal (Ea) barrier increases. New kinetic models will be shown that are designed to work under basin temperatures and pressures, given the changes to the thermal histories required by the 1st and 2nd laws of thermodynamics. Thermal histories predicted by the energy conservation model predict that petroleum generation starts earlier (due to the higher temperatures and lower pore pressures) but continues for extended periods due to the slower rate of petroleum generation caused by the pressure induced pV work. This extended generation period will extend into periods of uplift.

The challenges faced by petroleum system analysts when applying models to real data have arisen because of the flaws within the thermal history and kinetic models. The general confidence of petroleum system analysts is based on the observations that the current kinetic models work well when used in petroleum system studies in which thermal histories were based on kinetic calibration using palaeothermal history parameters such as vitrinite reflectance. The use of the energy conservation and increased heat flow during uplift models radically reduces the degrees of freedom available to the petroleum system modeller when deriving thermal histories, albeit that the thermal history will still have to produce results that can be calibrated with the available palaeo-geothermal parameters.

The value of deep seismic data: An example from North Western Australia that exposes ancient in-place oceanic lithosphere

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

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

These results demonstrate how the availability of new, deep seismic data have materially impacted the interpretation of the margin and will also have implications for the expected heat-flow history of the basin which may impact models for hydrocarbon generation in the area.

Seismic images of the Opal A/CT transition as a geo-thermometer: Post-rift geotherm in Rockall Trough strongly modified by pore-fluid convection above igneous sills

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Seismic reflections from diagenetic transitions between the opal-A, opal-CT and quartz forms of silica are quite commonly observed within shallow siliceous sedimentary successions. Because these reactions are principally controlled by heating rate, the seismic observations ought to provide a thermochronological tool to map regional low temperature evolution of shallow siliceous basin fill. This potential has not yet been fully realized because there is no agreement on a kinetic model for the reactions. Existing models are based on two laboratory studies, both of which fail to match in-situ opal-quartz transition depths within sedimentary sections, and no kinetic model has ever been derived for transitions developed during natural burial heating. We have assembled a comprehensive dataset of laboratory measurements and naturally occurring in-situ opal A-CT-quartz transitions from around the world, which we have jointly inverted to generate the first globally applicable kinetic model for the opal-quartz reactions.
We have applied the new kinetic model to reconstruct spatio-temporal changes to the post-rift geotherm in the Rockall Trough. Previously unreported reflections from a fossilized opal-A/CT transition are visible on 2D and 3D seismic data in the eastern UK sector. 3D mapping shows a topography of interlocking swells that does not resemble published examples of fossilized opal-A/CT transitions. We interpret that North Atlantic Igneous Province sills intruded the post-rift succession during the Paleocene-Eocene and drove strong hydrothermal convection. We show that multiple sills must have intruded close enough in time to act as a laterally extensive, hot basal layer that drove layer-bound convection within the poorly consolidated surmounting sedimentary succession. We obtain a model of the pore-fluid convection-dominated heat flow immediately after intrusion of the sills layer, and show how the geotherm subsequently cooled, eventually leading to fossilization of the opal-A/CT transition. Finally, we quantify the significant impact of these fluctuations in the geotherm on Cenozoic hydrocarbon generation.

Magma-rich breakup without plume control; lessons from compared W and E Indian margins

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[2]*EGI Laboratory at SAV*
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[4]*Inst. Ang. Geowiss., Technische Universität Darmstadt*
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[8]*ION Geophysical*

There are two end-member types of passive margins at opposite sides of India. The eastern, magma-poor margin, resulted from the crust first/mantle second breakup scenario. Its breakup was not controlled by the plume. The western magma-rich margin resulted from a mantle first/crust second breakup scenario. Neither was this breakup plume-assisted.

The structural architecture of both margins consists of stretched proximal and thinned distal margins. Their main differences include oceanward-dipping listric normal faults accommodating thinning in the distal margin with a zone of the exhumed mantle separating continental and oceanic crusts in the magma-poor case, versus landward-dipping listric faults accommodating magma-assisted thinning in the distal margin and no exhumed mantle in the magma-rich case.

The final breakup takes place in the lithospheric mantle layer in the first case and the crustal layer in the second case. Although the temperature-dependent rheologies of the last unbroken layers are different, the reflection seismic data indicate that they are both broken by an upward-convex normal fault, which succeeded the development of listric faults.

The upward-convex normal fault appears to be the first spontaneously formed fault in the breakup process, although its nucleation may be magma-assisted. It is anticipated to develop with increasing heat flow and extension rate as the last thinning layer reaches its critical thickness.

Poster Abstracts
Day Two

Effect of mantle buoyancy on tectonics and subsidence during rifting. Insights from long-term 2-D geodynamic modelling

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Here we use observations from the central South Atlantic conjugate margins to constrain the role of mantle buoyancy and its effect on paleo-bathymetry using geodynamic modelling. The ultra wide margins of the central South Atlantic are characterized by a lack of magmatism and large subsidence anomalies during the syn-rift. Isostasy should match the difference in elevation between continents and mid oceanic ridges (not considering dynamic topography). On average ridges are at -3000 m below sea level and continents at 300 m above sea level. The isostatic equilibrium between the ridge and the continent is for a large part a function of the density distribution inside the mantle. In most geodynamics models, density is a function of temperature only. However, the ridge depth is incorrectly predicted when using the effect of thermal expansion only.

Here we use the pressure (P), temperature (T), and composition (X) dependent thermodynamic solutions for fertile mantle providing a petrologic consistent density distribution for the mantle (Simon and Podladchikok, 2008). This approach intrinsically includes phase changes and changes in physical properties with pressure and temperature. Simple 1-D thermo-isostatic and complex 2-D forward models using the P-T-X dependent density distribution predict the correct elevation difference between average Phanerozoic continental lithosphere and mid oceanic ridge. These models are subsequently used to consistently address the role of mantle buoyancy on subsidence during the formation of distal rifted margins.

Enigmatic thermal pulse and subsidence retardation during early stages of lithosphere thinning explained by asynchronous depth-dependent necking

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On the one hand, field observations from the European Alps and several seismic data from present-day rifted margins testify for the existence of sedimentary unconformities in the so-called "necking domain" (i.e. the region where the crust thins rapidly from about 30 km to 10 km). On the other hand, recent thermo-chronological studies show that lower crustal rocks from the former necking domain of the Alpine Tethys rifted margins recorded an intense thermal pulse during the so-called "necking stage" of rifting.

Yet, the origin of both the thermal pulse and sedimentary unconformities remains enigmatic. Using results from two-dimensional thermo-mechanical numerical simulations, we show that both features can be explained by asynchronous lithospheric necking of first the upper mantle, and subsequently the crust. When the upper crust is mechanically decoupled from the upper mantle by a weak ductile lower crust and in the absence of a pervasive rheological heterogeneity, upper mantle necking occurs before crustal necking because of the larger effective viscosity and associated stresses in the upper mantle. As extension progresses, strain localization within the crust leads to the formation of necking zones on both sides of a little deformed block, referred to as the (crustal) keystone. The earlier necking of the upper mantle causes a local high geothermal gradient at the base of the future keystone. This thermal support beneath a region of little thinned crust causes the keystone to remain topographically higher than adjacent domains during the early stages of its formation. The peculiar isostatic evolution of the keystone during lithosphere necking, namely its local subsidence retardation with respect to adjacent domains followed by a rapid deepening, may explain the diagnostic unconformity observed in the necking domain of several present-day and fossil hyperextended rifted margins.

A Bayesian approach to inverse thermal history modelling in sedimentary basins and the inference of erosion

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Thermal history modelling (THM) is a key component in basin modelling. Its main objective is to constrain the thermal state of sediments through geological time. This is of particular importance for hydrocarbon exploration and resource assessment, as hydrocarbon generation (maturation) in sedimentary basins depends strongly on the temperature history of the source rock.

Under the assumptions of 1-D heat transfer, the problem can be reduced to the estimation of the heat flow history at the base of the sediment pile. In this case, different approaches have been adopted to infer the thermal history of sedimentary basins, from forward modelling approaches to inverse modelling techniques. In all cases, thermal calibration data such as vitrinite reflectance (VR) or apatite fission track (AFT) are used to constrain the final model(s). However, uplift and erosion in sedimentary basin can strongly affect the thermal state of the sediments. This complicates the modelling by adding extra parameters in the problem, such as amount of erosion and timing of the erosional event. In addition, erosion estimates derived from VR and AFT data are subject to a strong trade-off between the burial and thermal history components of basin models and may increase the uncertainty of model results.

In this work, we adopt a Bayesian approach to address this problem in THM. We use a trans-dimensional Markov chain Monte Carlo algorithm to sample from the unknown posterior distribution in a joint inversion scheme. Thermal indicator and porosity data from well logs are coupled in the inversion to effectively reduce the trade-off between amount of erosion and heat flow. Our proposed methodology offers several advantages over classical approaches: i) quantification of uncertainties on the final solution and correlation between model parameters, ii) multiple data types can be inverted jointly in a straightforward manner, iii) uncertainties on data and on predictive models are effectively propagated in the solution. The algorithm is tested against synthetic data to show the benefits of including compaction data in the inversion. Results are presented and discussed for further developments.

The structure and nature of the basement at magma-poor rifted and hyper-extended margins

Tim Reston[1], Ken McDermott[2]
[1]*University of Birmingham*
[2]*ION*

The nature of the basement underlying rifted margins is crucial for margin prospectivity, but often surprisingly poorly constrained. The various models for the formation of such margins predict during the rifting process quite different distributions of upper and lower crust, and of lithospheric and asthenospheric mantles, but the thick postrift sedimentary cover makes actual determination of basement type problematic. Proposed mechanisms for crustal thinning include sequential faulting, and polyphase faulting; the key differences being whether late faults cut early faults (polyphase) as extension focuses more or less symmetrically in the centre of the rift or whether extension migrated asymmetrically into little extended regions with time (sequential). These two models predict very different distributions of basement types. Sequential faulting is strongly asymmetric, and predicts that the upper crust and associated sedimentary sequences dominate the thin crust of hyperextended margins, whereas polyphase faulting predicts more symmetric extension and the exhumation of lower crustal and mantle rocks.

Synthetic seismic sections reveal the key identifiers of polyphase faulting, all of which can be seen on depth sections across rifted margins but which are far harder to detect on time sections. All can be identified on deep seismic profile SCREECH 3 across the Newfoundland Basin. On this and the conjugate Iberian margin, crustal thinning appears to have focused roughly symmetrically, becoming locally asymmetric once the entire crust had become brittle, and was followed by the symmetrical exhumation of mantle rocks as divergence continued to focus into amagmatic seafloor spreading. As spreading rate and magmatism increased, the system evolved into normal slow seafloor spreading.

In contrast, the margins of the S Atlantic salt basins are wider and of more constant apparent crustal thickness; numerical models suggest that such margins may have formed by asymmetric sequential faulting. However, the common assumption that the present of salt implies that the underlying basement is continental crust needs to be challenged in the light of paleoceanographic constraints on the opening of the South Atlantic.

Dynamic Topography and Rifting: A Global Model

N. Hodgson and K Rodriguez.
Spectrum Geo Ltd

The key physical characteristics of the Atlantic passive margins are being revealed by modern long offset, long record length seismic. These include the width of the continental to oceanic crust transition zones, the abundance of volcanic Seaward Dipping Reflectors (SDR) and conjugate margin asymmetry.

Whilst some passive margins have narrow, rifted transitions from continental to oceanic crust, (<50km wide) others display wide zones of thinned extended continental crust (>150km wide), the latter often terminated by exhumed mantle. Additionally conjugate margins are observed to be asymmetric in structure, with variation in the syn-rift geometries and geologies, and the post-drift thickness and presence of SDRs. We propose that the structure and character of both syn-rift and post-drift domain is controlled by the fabric of the underlying convecting mantle as revealed by dynamic topographic analysis. This is now represented globally, comprising numerous small scale mantle convection cells. (Hoggard et al 2016). This fabric provides topology laterally along a rift, controlling the development of either so called “magma-rich” or “magma-poor” domains, which are an expression of spreading centre elevation relative to sea level.

A model relating mantle topography to observed asymmetry and rift characteristics is proposed, and tested against observations of basin shelf stability back through time in the context of plate tectonic movement. This allows some constraints to be placed on the stability of mantle convection cells and their interaction with the overlying crust. Implications for hydrocarbon exploration are explored and the importance of interaction with deep mantle plumes is also discussed in the context of end-members to the structural expression and the creation of restricted salt basins.

To conclude, a simple model is introduced that seeks to provide a mechanism for both the formation and development of the key structural characteristics observed on passive margins that allows extension to a global synthesis.

Integrated Modelling of the Northeast Rockall Basin: A prelude to Heat flow studies

Bennett Haworth[1], Stephen Rippington[2]
[1]ARK CLS
[2]Astute Geoscience, University of Leicester

This study aims to provide a consistent and robust interpretation of the Northeast Rockall Basin and adjacent areas that can form the foundation of exploration activities in the area.
Integrating the seismic and well data released by the OGA in 2016 with potential field data has allowed us to reduce the interpretational ambiguity in this region, where poor seismic resolution beneath basalts mean interpreting seismic lines in isolation is almost futile.
2D Modelling in XField, to match the gravity response with a set of bodies that were consistent with wells, seismic and a condition of isostasy, was followed by map view interpolation to produce structure maps, and interpolation to produce horizon depth maps, and subsequently thickness maps.

The next stage of this project will be to use the depth maps to calculate subsidence in map view, and combine this with heatflow modelling to produce a map view of when each unit entered and exited the oil window. This will outline a full workflow to integrate all data types commonly available and generate the information needed for the petroleum systems analysis stage.

Burlington House
Fire Safety Information

If you hear the Alarm

Alarm Bells are situated throughout the building and will ring continuously for an evacuation. Do not stop to collect your personal belongings.

Leave the building via the nearest and safest exit or the exit that you are advised to by the Fire Marshal on that floor.

Fire Exits from the Geological Society Conference Rooms

Lower Library:
Exit via main reception onto Piccadilly, or via staff entrance onto the courtyard.
Lecture Theatre
Exit at front of theatre (by screen) onto Courtyard or via side door out to Piccadilly entrance or via the doors that link to the Lower Library and to the staff entrance.
Main Piccadilly Entrance
Straight out door and walk around to the Courtyard.

Close the doors when leaving a room. **DO NOT SWITCH OFF THE LIGHTS**.

Assemble in the Courtyard in front of the Royal Academy, outside the Royal Astronomical Society. Event organizers should report as soon as possible to the nearest Fire Marshal on whether all event participants have been safely evacuated.

Please do not re-enter the building except when you are advised that it is safe to do so by the Fire Brigade.

First Aid

All accidents should be reported to Reception and First Aid assistance will be provided if necessary.

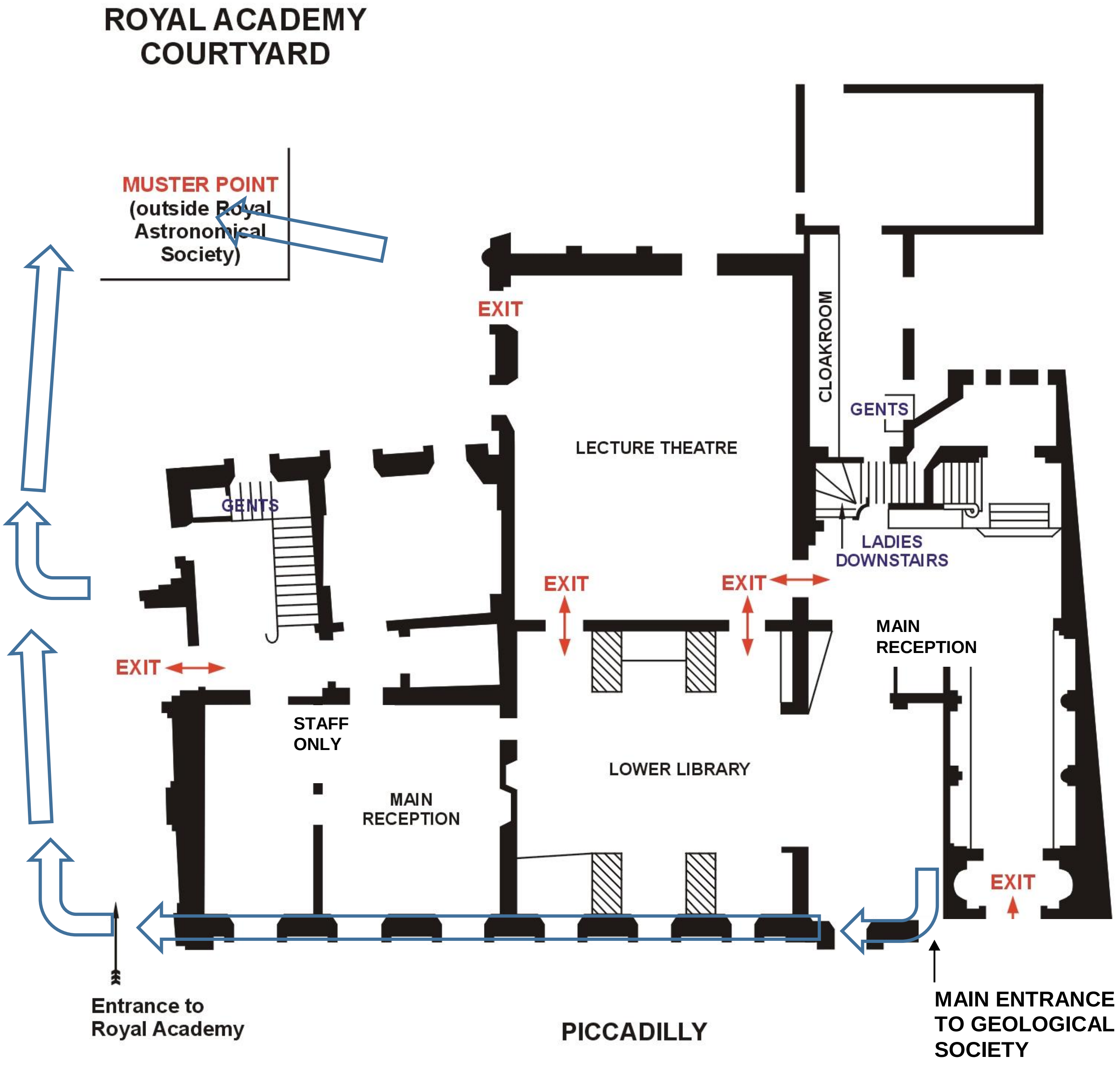
Facilities

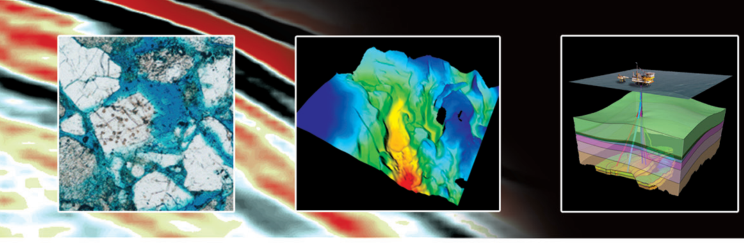
The ladies toilets are situated in the basement at the bottom of the staircase outside the Lecture Theatre.

The Gents toilets are situated on the ground floor in the corridor leading to the Arthur Holmes Room.

The cloakroom is located along the corridor to the Arthur Holmes Room.

Ground Floor Plan of the Geological Society, Burlington House, Piccadilly





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Registration now open

Operations Geoscience Adding Value

7-8 November 2018

The Geological Society, Burlington House, Piccadilly, London

The main focus will be on the value operations geoscientists deliver and the pivotal role they play via the following topics:

- **The value of learning lessons well** – what is a lesson?; how are lessons learned and managed (e.g. avoiding non productive/invisible lost time)?; practical examples of lessons with demonstrable change; personal willingness to share failure/sub optimal performance
- **Risks and safety of operations** – identifying, managing, communicating risks and planning contingencies effectively
- **Formation pressure and geomechanics** – sharing good practice, techniques and knowledge, prediction and detection methods
- **The value of managing and interpreting data** – effective data management for field life, examples of cross company collaboration

Overarching themes:

- Value of these themes to **well life cycle**
- Sharing real world **examples and case studies**
- Importance of **personal behavioural skills** throughout (leadership, communication, relationship building and influencing others)
- Share good practice, showcasing **innovative approaches and technologies**

We look forward to active participation from our colleagues across subsurface, drilling and engineering disciplines to significantly broaden the main conference themes.

There will be a parallel poster session in the library.

For further information and registration please contact:

Sarah Woodcock, The Geological Society, Burlington House, Piccadilly, London W1J 0BG.
T: +44 (0)20 7434 9944 or email: sarah.woodcock@geolsoc.org.uk

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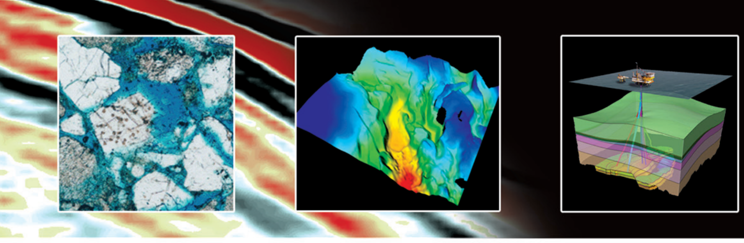

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Call for Abstracts – Deadline: 1 December 2018

Hydrocarbons in Space and Time

9-11 April 2019

The Geological Society, Burlington House, Piccadilly, London

Convenors:

Owen Sutcliffe
Halliburton

Frans van Buchem
Halliburton

Mark Houchen
Shell

Bruce Levell
Oxford University

Hannah Steaggles
BP

Mike Simmons
Halliburton

Keynote Speakers:

A diverse set of keynote speakers are being solicited from across the community

The global endowment of hydrocarbons is markedly uneven both spatially and temporally. In the 1990s, several key papers recognised that distinct stratigraphic and paleogeographic trends exist and that this knowledge was an important guide to successful exploration. So, what has changed in 30 years?

The industry has moved into new frontiers and basins, drilled deeper, found new plays and gone through a revolution that has brought unconventional resources to the fore. It is therefore timely to consider how our knowledge of the distribution of hydrocarbons in time and space has changed. What new insights have we gained? Can this new understanding be used to be better at predicting new hydrocarbon discoveries?

This 3-day conference will seek to share recent advances and case studies and will be built around four main themes:

- The known global heterogeneity of hydrocarbon resources – including source rocks
- The controls on heterogeneity – including palaeoclimates and geodynamics
- The geological and data science tools to aid prediction
- What our present understanding means for future exploration

Event to be accompanied by a post-conference field trip to the Wessex Basin.

For further information please contact:

Sarah Woodcock, The Geological Society, Burlington House, Piccadilly, London W1J 0BG.
Tel: +44 (0)20 7434 9944 or email: sarah.woodcock@geolsoc.org.uk

For Abstract Guidelines, please download a copy from the website:
https://www.geolsoc.org.uk/PG-Hydrocarbons-in-Space-and-Time

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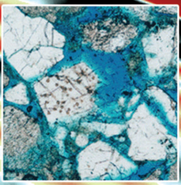
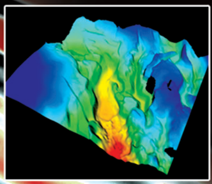
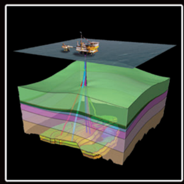

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RPS Energy

Mark Groves Gidney
Energetical

Richard Bray
Subsurface Resource Consulting

John Argent
Sound Energy

Mark Osborne
BP

Call for Abstracts: Extended Deadline

Celebrating the life of Chris Cornford (1948-2017)

Petroleum Systems Analysis 'Science or Art?'

24-25 April 2019

The Geological Society, Burlington House, London

Approaches to tackling the scientific and practical questions in the fields of Petroleum Geochemistry and Petroleum Systems Analysis range from the entirely theoretical to the empirical. Chris Cornford embraced both in his working life. The integrated approach he espoused will form the basis of the technical programme for the Conference covering two themes:

- Recent developments in the use of data including integration of models and (big) data; use of visualisation and data exploration or mining techniques.
- Topical issues & controversies ranging from mass balance approaches, petroleum migration to specific modelling studies and practical applications.

The Conference will be inspired by Chris' ethos of innovation, encouragement of youth and challenging received wisdom.

Call for Abstracts:

Please submit abstracts for oral and poster contributions that cover any of the above themes to sarah.woodcock@geolsoc.org.uk

For further information please contact:

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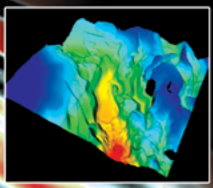

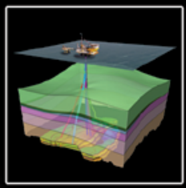

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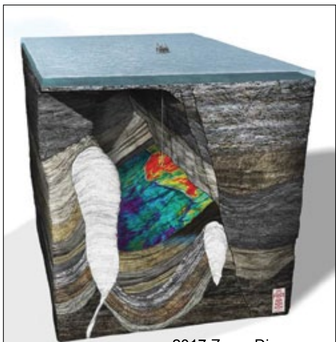
Call for Abstracts – Deadline: 30 November 2018

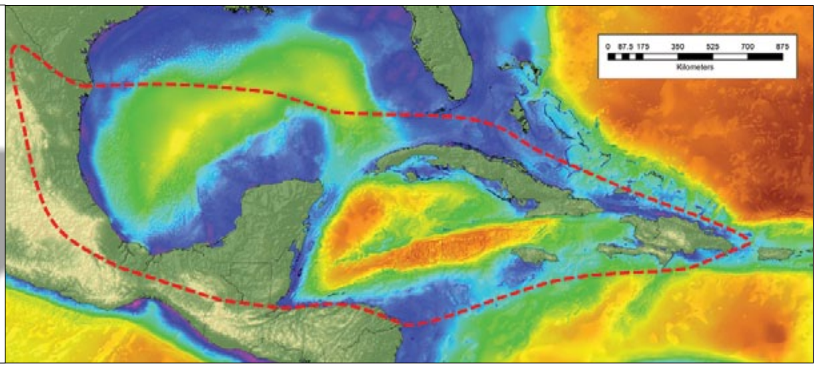
Petroleum Geology of Mexico and the Northern Caribbean

14-16 May 2019

The Geological Society, Burlington House, Piccadilly, London



2017 Zama Discovery



The Gulf of Mexico is a world class prolific hydrocarbon system. As a result of recent energy reform the Mexican sector of this basin has been open to international companies for the first time through a series of competitive licence rounds. The first phase of drilling on these newly awarded permits has resulted in the discovery of giant hydrocarbon accumulations in the Mexican offshore sector. Geologically, the offshore and onshore basins of Mexico offer a diverse range of play types with multiple source / reservoir pairs and are characterised by complex tectonic evolution with associated halokinesis and shale tectonics.

More widely within the Northern Caribbean region, exploration activities are ongoing in several countries targeting both proven and frontier petroleum systems. Some of these play elements are potential extensions of the proven systems in Mexico. While geologically complex, these areas have the potential to emerge as major hydrocarbon basins.

This regional conference aims to bring together both academic and industry geoscientists together to discuss the current state of understanding of the geology and petroleum systems in these geologically complex, but prolific hydrocarbon basins.

The committee now invite submissions of abstracts along the following themes

- Regional Plate Tectonic Evolution
- Basins of Mexico and the Northern Caribbean
- Onshore Basins and the Laramide and Chiapas Fold Belt effects
- Petroleum Systems
- Exploration & Production History
- Neogene Clastic Depositional Systems
- Carbonate Depositional Systems
- Salt Tectonics
- Controls on hydrocarbon habitat – seal capacity
- Relevant GOM Analogues

Call for Abstracts:

Please submit talk or poster abstract to sarah.woodcock@geolsoc.org.uk by 30 November 2018.

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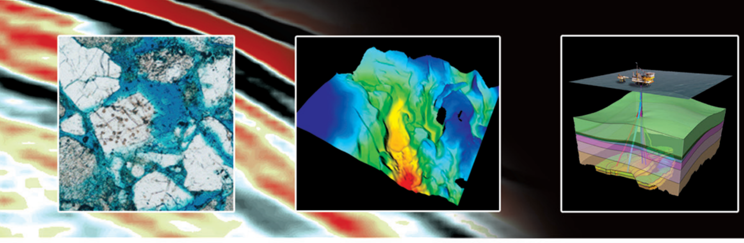

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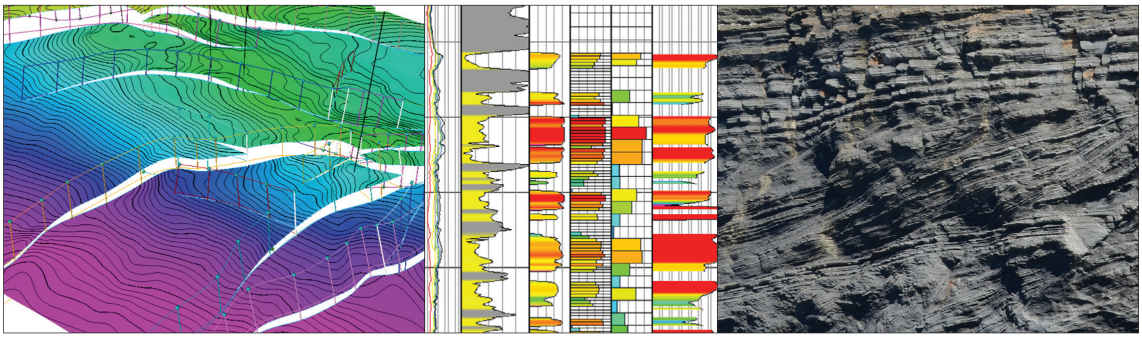
Call for Abstracts – Deadline: 29 March 2019

Capturing Geoscience in Geomodels

26-27 June 2019

Robert Gordon University, Aberdeen



Over recent years the construction of 3D static and dynamic reservoir models has become increasingly complex. With the availability of extensive tools and technology it is important not to forget the objective of the modelling process.

As we develop our hydrocarbon fields it is essential that 3D Static Models be built with fit-for-purpose Geological models, honouring the geological, geophysical and petrophysical data that they are created from.

This two-day conference will explore how Geoscience information should be used to best, effect and to identify when Geoscience data may no longer add value. Sessions will include the following themes:

- Data Integration: Seismic, Well Log, Sedimentological, Core Dynamic data integration and beyond
- Capturing Conceptual Geology in Reservoir modelling for different settings and depositional environments
- Scale: Geology vs Model Scale vs Data
- Uncertainty: Dealing with Geological Uncertainty in Modelling and understanding its benefits & limitations
- Embracing New Modelling Technology and Approaches.

Call for Abstracts:

Please submit talk or poster abstract to sarah.woodcock@geolsoc.org.uk by 29 March 2019.

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