Thematic set:
Rifts III: Catching the wave

PG
Petroleum Geoscience

Published online November 8, 2018

https://doi.org/10.1144/petgeo2018-143 | Vol. 24 | 2018 | pp. 376–378

Introduction to the thematic set: Rifts III: catching the wave

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Received 12 October 2018; **accepted** 12 October 2018

Our understanding of the complex interplay of geodynamic processes that operate during lithospheric extension and results in the formation of magmatic and amagmatic passive margins remains equivocal. The challenge of the third rift conference in the series was, how to better constrain interpretation of those mechanisms, contributing to the surface expression at rifted plate margins. The fundamental observation that not all extensional basins and rifted continental margins involve the development of process-related magmatism continues to court significant debate and controversy (Rifts III: Catching the Wave, Geological Society, London – *this conference*). Consensus remains elusive; however empirical data are providing more informed insights into the boundary conditions for input into more realistic and testable geodynamic numerical models (Lavier *et al.* 2016). Studied margins record their own particular complexities and causally reflect the influence of important crustal and mantle-scale heterogeneities in addition to plume-lithosphere interactions associated with core-mantle boundary hot-spot anomalies (Ryberg *et al.* 2015). The apparent paradoxical juxtaposition of magma-rich and magma-poor continental margin segments is now more widely recognized (e.g. Koopmann *et al.* 2013). By inference, we now conclude that rupture of the lithosphere is less likely to correspond to a continuous, single phase, uniform extension model (*sensu* McKenzie 1978). This simplistic, elegant concept, in which crust and mantle thin by the same factor, is unable to explain the diversity of documented rift margin relationships. Instead, either the crust or lithospheric mantle (or both) are more likely influenced by a combination of complementary regional or local dynamic stresses involving 'passive' tensional far-field plate forces and/or 'active' mantle upwelling. Whichever prevailing 'cold' or 'hot' mechanisms determine the nature of lithospheric rupture, the plate boundary evolution is better understood by highlighting characteristic basin margin morphologies and describing diagnostic structural/stratigraphic architectures.

Of significant interest and debate during the conference was the genesis of the volcanic margin end-members. Less explored and somewhat enigmatic, these margin-types are dominated by characteristic and well-imaged seaward dipping reflector packages. The structure of volcanic rifted margins is believed to be primarily composed of variously intruded stretched continental crust which passes distally into a 'transitional' crustal zone constructed from progressively more asthenosphere-derived intrusive and extrusive magmatic additions (Huismans & Beaumont 2014). The 'transitional' phase of crustal addition and magmatic basin margin evolution is of particular interest to the oil industry given the global extent and prevalence of this relatively under-explored passive margin type. Previous views of a simple monoclinal, unstructured and narrow magmatic margin-archetype are being re-considered and re-classified. The potential to extend prospective hydrocarbon play domains basinward has now gained a firm scientific foundation with new commercial implications recognized (Clark & Fraser 2016; Thompson *et al.* 2016).

In an attempt to capture the essence of the meeting, Tables 1a and 1b below give a representation of the continuum and interplay of variables which likely determine rift basin evolution. These variables will naturally evolve but will provide a basis for forward thinking and the next iteration of the science – Rifts IV?

The series of international technical meetings on Rifts hosted by the Geological Society of London and the Petroleum Group has consistently delivered a strong technical program that has captured the latest science in understanding continental margin evolution. The acquisition of high fidelity seismic datasets and the continuing search for new hydrocarbon resources has provided the technical foundation for the newest observations and paradigm shifts in our comprehension of basin margin types and rifting processes. Rifts I, Return to Rifts (2005) highlighted the range of extensional models and introduced the newest thinking around hyper-extension and potential evidence for depth-related extension mechanisms. Rifts II, (August 2008) 'Rifts Renaissance-Stretching the Crust and Extending Exploration Frontiers' considered the evidence for mantle exhumation processes and the perceived exclusivity between magmatic and amagmatic rifting processes. Rifts III (March 2016), featured a data-rich compilation of basin margin papers that highlighted the imperfections of end-member thinking and, importantly, discussed the exploration implications and significance of fundamental observations rather than on fitting a preconceived model to a margin archetype. The 54 oral papers over six sessions captured the journey from continental margins to production scale observations and highlighted the importance of geodynamic process which determine source to sink relationships. In addition, and for the first time, the oral sessions were augmented by 15 posters giving an overall technical program balance between invited contributions from leading scientists from both academia and industry. The discussions and debate benefitted from this deliberate design.

On reflection, the highlights of the integrated meeting were the milestones recognized in: imaging continent-ocean transitions; understanding extensional processes and regimes; testing models with the benefit of new data and unbiased observations; consideration of heat flow scenarios and the results of exploration (polarizing the potential processes that form wide and narrow margins); subsidence in time and space; and using the empirical data to better constrain numerical models whilst developing exploration forward models to reduce exploration risk.

Table 1. *Summary of (a) phases, forces and processes controlling rifting and (b) the factors involved*

RIFTING - AN EVOLUTION/CONTINUUM OF FORCES AND PROCESSES							
PHASE	1) PASSIVE RIFTING	2) STRETCHING/ THINNING/UNLOADING	3) BOUYANCY FORCES	4) ACTIVE RIFTING	5) STRAIN LOCALISATION	6) OCEANISATION	7) PLATE MARGIN ESTABLISHED
DRIVING FORCES	Far-field lithospheric extension	Localised thinning of the Lithosphere	Changes in bouyancy forces	Mantle upwelling	Asthenospheric flow	Lithospheric rupture	Asthenospheric exhumation
STATE	Surface stress regime established	Orthogonal; oblique; rotational	Rift suction	Asthenospheric dome formation	Lateral propogation and growth	Continuous/organised oceanic ridge	Ridge push; sea floor spreading
FEATURES	CRUSTAL STRETCHING / MECHANICAL RIFTING		MANTLE EXHUMATION MAGMA-RELATED INTRUSIVE AND EXTRUSIVE VOLCANISM / MAGMATIC DIKING				

CONTROLLING PARAMETERS	DRIVING FORCES	RIFT PROCESSES	EXPLORATION IMPLICATIONS
Crustal thickness	Dynamic topography	Active / Passive	Basal heat flow; accommodation space
Lithospheric boundaries	Isostacy	Extension; compression; strike-slip	Structural styles, wavelength, primary traps
Crustal sutures	Subsidence; uplift; erosion	Normal; oblique; rotational	Sediment dispersal patterns; topography; drainage
Lithospheric heterogeneity	Thermal bouyancy	Volcanism - intrusive; extrusive; volume	Volcanic/non-volcanic margins
Lithospheric rheology	Far-field tectonic forces	Continuous, pulsed; aborted	Rift orientaion; controlling basement faults
Thermal anomalies	Asthenospheric flow - upward flow/lateral flow	Rate - fast/slow	Wide margins; narrow margins; hyper-extension
Mantle enrichment/fertility/chemistry	Viscous coupling of Lithosphere to astenosphere	Strain - distributed/localised	Inversion; strike-slip extensional fault block density
Strain evolution/Surface stress patterns	Rift suction	Planar faults; detachment; low angle	Basin geometry, facies patterns
Stress orientation/duration/evolution	Lithospheric cooling	Lithospheric rupture, oceanic spreading	Seal development; SR development post-rift basin

The thematic compilation that follows (this thematic set) represents a cross-section of the conference content. **Lundin *et al.*** discuss the contrast between magma-rich and magma-poor margins and the relationship to anticipated spreading rates. Building on that theme, **Armitage & Collier** introduce their preferred numerical modeling approach for volcanic margins that incorporates many of the original White and McKenzie decompression melting processes (White & Mckenzie 1989) with pure-shear deformation of the lithosphere. They contend that the excess magmatism associated with magmatic margins is due to the interaction of rifting with a thermal anomaly in the asthenosphere**. Drachev *et al.*** combine the interpretation of new regional-scale long-offset 2D seismic with integrated gravity forward models to characterize the crustal architecture of the Laptev Sea Rift System. They contend that upper crust deformation was dominated by brittle stretching whilst the lower crust experienced ductile thinning in the absence of significant heat input from the asthenosphere. Maryam **Khodayar** in her paper on the Northern Rift Zone of Iceland, introduces her observations of complex stress interactions with extensional rift structures in the presence of a transform fracture zone. She demonstrates that displacement of primary rift structures along graben bounding faults is controlled by the interplay with the dextral motion within the transform fault zone. The integrated petroleum system paper on the northern Upper Rhine Graben, SW-Germany by **Perner *et al.*** combines heat flow analyses with maturation models to characterize the hydrocarbon habitat within the extensional rift system. In linking subsidence patterns to reservoir and source rock facies, they present an integrated model which links hydrocarbon potential directly to rift dynamics.

In conclusion we acknowledge the authors of the published papers, our co-conveners of the meeting and the sponsor group of Shell, BP, Equinor, Badley Geoscience Ltd and EGI. In particular we acknowledge the support and involvement of Spectrum ASA who provided live seismic examples from their worldwide seismic data library.

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