Session: Passive Margins

Passive margins: overview

B. LEVELL,[1] J. ARGENT,[2] A. G. DORÉ[3] and S. FRASER[4]

[1]*Shell International E and P bv., Kessler Park 1, Rijswijk, 2280AB, The Netherlands (e-mail: bruce.levell@Shell.com)*
[2]*BG Group plc, Thames Valley Park, Reading, Berkshire RG6 1PT, UK*
[3]*Statoil USA E&P, 2103 CityWest Boulevard, Suite 800, Houston, TX 77042, USA*
[4]*BHP Billiton Petroleum Inc, 1360 Post Oak Boulevard, Suite 150, Houston, TX 77056, USA*

Abstract: Passive margins have been the reliable, accessible mainstay of exploration success worldwide for the last 25 years, and have hosted the spectacularly fast exploitation of deepwater resources (Angola, Nigeria, Brazil, Trinidad, USA Gulf of Mexico, Egypt, Australia and India). Despite, or perhaps because of this, there is still much to learn about the variety of hydrocarbon habitats they present.

For example: (1) deep seismic observations and deep sea drilling have revealed more of the diversity of passive margins geodynamics. This liberates explorationists from simple geodynamic models, with consequences not only for new views of thermal history but also for the whole tectonic and stratigraphic evolution. For example, the time significance assigned to the geometries traditionally labelled 'pre-rift, syn-rift and sag' may be misleading. This has implications for correlations, the significance assigned to unconformities and sequence boundaries, heat flow and structural history. (2) New deep imaging of the sedimentary sections has revealed mistaken assumptions about the importance of 'mobile substrate' in major deltas and allowed the detailed unravelling of salt and shale movement and its implications for reservoir and trap. (3) Depositional models for deepwater reservoirs have increased in predictive capability and modern seismic imaging supports new models for shallow water sequences. (4) Discoveries of very large amounts of dry bacterial methane in stratigraphic traps have challenged old assumptions about prospectivity based on thermally matured source rocks. (5) New engineering and development technologies are opening up the commercialization of remote frontiers. As a consequence there is legitimate scope to re-visit old 'dogmas' and to propose that each passive margin segment is best regarded as unique, with analysis and interpretation rooted in observation rather than models (at least while the newly proposed models evolve to stability). Many of these themes were visited in the Passive Margins session of the Seventh Petroleum Geology Conference, held in London in 2009. This paper outlines some of these ideas, and considers how exploration along passive margins in the next decade can use new geoscience thinking.

Keywords: passive margins, exploration technology, petroleum systems, rifting, continental breakup, deepwater plays

Despite more than 70 years of active exploration, modern passive continental margins still remain an exploration frontier. With a current aggregate length of 105 000 km (for a recent review see Bradley 2008), they represent a substantial exploration domain, and also a long-lived one: mean Phanerozoic passive margin preservational lifetime, including the modern passive margins, is about 135 Ma (Bradley 2008). Present day passive margins have a mean (incomplete) life span of 104 Ma. The passive margin sequences (post rift) are estimated to host approximately 35% of all giant field discoveries (Mann *et al.* 2003), which in turn represent 67% of discovered conventional hydrocarbons.

Deep sea drilling, a wide variety of geophysical methods (e.g. SCREECH, Funck *et al.* 2003; Van Avendonk *et al.* 2008; ISIMM, White *et al.* 2008, 2010) and geological studies have demonstrated that there is substantial variety in the history of passive margins. In this paper we set out to identify some new thoughts which can trigger critical re-examination of already partly explored areas, and add to the effectiveness of exploration in new frontiers in this basin type.

A snapshot of industry activity shows the diversity of plays currently being pursued including:

(1) major deltaic depocentres (e.g. Cenozoic of US Gulf of Mexico; Venezuela, Orinoco; Brazil Campos, Santos; Niger, Congo and Baram Deltas);
(2) smaller deltaic depocentres (e.g. Alaska, Beaufort Sea; Cameroon, Isongo; Equatorial Guinea; India, Mahanadi, Cauvery; Guyana, Essequibo; South Africa, Orange; Mozambique, Rovuma; Tanzania, Rufiji; Kenya, Lomu);
(3) slope by-pass systems (Ghana; Equatorial Guinea; India, Krishna-Godavari);
(4) carbonate platforms and their margins (Pakistan, Indus; Senegal; Mauritania; Morocco);
(5) deepwater fold belts (Mozambique, Rovuma; Nigeria, São Tomé and Príncipe);
(6) lightly explored frontier Arctic margins (USA Beaufort Sea; Canada, deepwater Mackenzie Delta);
(7) deepwater far-outboard areas with a wide variety of reservoirs and tectonic settings (Norway Outboard Voring; Brazil Santos; Australia, Outer Exmouth);
(8) syn-rift sections (Gabon sub-salt; India Krishna-Godavari; Norway, Voring Nordland);
(9) pre-rift sections on many margins.

Passive margin evolution and its implications

Better understanding of passive margins is demonstrated by the observation that it is now surprisingly hard to find an example of a 'classical' model of margin evolution (e.g. Allen & Allen 2005). Perhaps the best is the Labrador margin (Chalmers &

VINING, B. A. & PICKERING, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*, 823–830. DOI: 10.1144/0070823 © Petroleum Geology Conferences Ltd. Published by the Geological Society, London.

Pulvertaft 2001). The exciting new information on deeper structure of continental margins generated by large-scale refraction and reflection experiments as well as direct drilling supports a wide spectrum of plausible passive margin evolutionary mechanisms. This variety has triggered a wave of model-based inferences, in particular on post-rift evolution of continental margins. These insights have, to some extent at least, liberated the exploration geologist, struggling to interpret the deeper data on industry reflection seismic lines from simple models of the rift, thermal sag, rift/drift unconformity and drift phases. They include:

(1) The common occurrence of multiple rifting events with an irregular relationship to the line of final breakup (Doré *et al.* 1999; Ren *et al.* 2003). A recently identified potential example is described by Scotchman *et al.* (2010), who postulate a pre-breakup rift, oblique to the continental margin, in the Santos Basin, offshore Brazil, thought to have proceeded almost to oceanic status.
(2) The possibility of polyphase faulting in any given rift event. Redfern *et al.* (2010) suggest multiple rift events in the Permo-Triassic sequences of the North Atlantic margins, more varied than the overlying Jurassic and younger basins.
(3) A better understanding of magmatic addition to passive margins. Reynisson *et al.* (2010) systematically describe high-velocity, high-density lower crustal bodies on the mid-Norwegian margin and infer that, contrary to the common view that these bodies constitute magmatic additions to the base of the crust, many such features may be better explained as high-grade metamorphics remaining from the Caledonian orogeny, or as serpentinized mantle. In a similar vein, White *et al.* (2010) show from deep penetration and wide-angle seismic data on the Faroes–Hatton margin the probable existence of massive lower crustal intrusion, confined to the margin and with a sharp landward boundary. This again calls into question the concept of a widespread underplate, and the many phenomena assumed to result from it.
(4) The occurrence of very wide sag-type basins, relative to the syn-rift phase, possibly related to differential lower to mid-crustal stretching rather than a thermal sag related to pure shear rifting. The importance of this structural regime is attested to by recent discoveries on São Paulo Plateau of the Santos Basin (Machado *et al.* 2009).
(5) The possibilities of either hot/wet spot rifting with intra-crustal and supra-crustal magmatic addition or cold/dry-spot or otherwise amagmatic rifting margin. For a summary of magma-poor margins see Reston (2008). Hyperextension and mantle exhumation are currently the source of prolific literature and more examples of hyperextension are regularly being proposed. Blaich *et al.* (2010) discuss the nature of the conjugate magma-poor Camamu–Almada (Brazil) and Gabon margins, and in particular the nature of a prominent deep detachment surface, the M-Reflector. It is uncertain whether the reflector is underlain by exhumed mantle, but it appears to be an intraplate decoupling surface that accommodated significant pre-breakup extension.

As well as the obvious and ubiquitous thermal maturation implications, these insights also potentially impact other issues important to explorers, for example:

(1) the 3D isostatic behaviour of margins, and their consequent palaeobathymetric evolution;
(2) the correlation of poorly dated 'syn-rift units', possibly representing multiple rift phases, and the interpretation of basement penetrations or reflections as non-conformities v. rotated fault planes (and hence the significance to be attached to 'basement' penetrations in terms of completely testing a play);
(3) the nature and significance of unconformities, in particular the presence, significance and age of the 'rift-drift' unconformity (Tucholke *et al.* 2007) – other considerations include local footwall uplifts v. regional changes in crustal stretching and thinning and, again, unconformities due to poly-phase rifting rather than the single rift event of classic passive margin evolution.

Two-dimensional views of margin evolution are clearly only partial. Segmentation of margins can relate to pre-existing geomechanical interfaces in the basement. Many margin geometries are typically attributed to the breaking of continental crust along old lines of structural weakness. Ebbing & Olesen (2010) follow this line in documenting basement thickness variations and structural segmentation along the mid-Norwegian margin. These variations are correlated with Caledonian and Precambrian basement domains, and also with later basement detachments and normal faults mapped close to shore or onshore, and prolongated oceanwards. This paper also provides a valuable compilation of Moho depth and basement thickness for the entire mid-Norwegian shelf and western Barents Sea. It is worth noting, however, that only about 50% of the entire Gondwana supercontinent's rifted margins are even sub-parallel to pre-existing structure, based at least on the structural level of the current Gondwana surface geological map. Hence old structures are not necessarily parallel to either rift/drift tectonic strike or depositional strike. Together with intracontinental deformation, these factors can cause significant trend complexity and segmentation along margins. This can be obscured, particularly in restoring early rift units by generalized continental fits, especially those that do not accommodate intracontinental deformation (De Wit *et al.* 2008).

Hydrocarbon charge and maturation

Major marine source rocks and oceanic anoxic events

The explored passive margin source rocks have typically been the few, major, regionally extensive source rock-bearing intervals characteristic of whole sets of basins and seemingly preponderant in the Atlantic Oceans (e.g. Toarcian, Aptian Turonian and Lower Eocene).

In this respect passive margins are of course no different from other hydrocarbon provinces. For the world as a whole, almost 60% of discovered conventional hydrocarbons were sourced from the major source rocks of the Jurassic and Cretaceous and 75% if the Cenozoic is included (Klemme & Ulmishek 1991). Plays associated with these source rocks have largely been proven, or at least defined. Future potential in these known petroleum systems will arise from changing political/environmental or commercial circumstances. Examples of such 'political' openings include: Guyana (Upper Cretaceous petroleum system); potentially Mexico (Jurassic and Cretaceous); the Eastern seaboard of the USA; Georges Bank off Canada; east Greenland; and Nordland, off northern Norway (Upper Jurassic/Lower Cretaceous).

Local source rocks

Excitingly, much future passive margin exploration may rely on currently unknown, missed or more local or marginal source rocks. For example, driving the Niger Delta play into still deeper water will require an Oligocene or older charge system. In margins where the Middle or Upper Jurassic source is absent or too deep, and the Upper Cretaceous is immature due to lack of a depositional overburden, the Lower Cretaceous is often in the present-day maturity window. The often-marginal source rocks of the Lower Cretaceous will, however, need to deliver! Future large passive margin plays which would benefit from a prolific Lower Cretaceous source rock facies include: west Greenland; much of Africa – NW Africa from Morocco and the Canaries to Liberia, southern Africa, and east Africa; the Great Australian Bight; the South Atlantic, Uruguay and Argentina; and the Lord Howe Rise. Interestingly the geochemistry of the early Aptian oceanic anoxic event suggests that it is a deeper water anoxic event than, for example, the Toarcian, which was characterized by photic zone euxinia (Jenkyns 2003). The specific organic and inorganic geochemistry of source rock pods, reflecting their palaeo-ecology, may enable extrapolation from known occurrences into shallower sections and predict onlap or dilution.

Important clues to missed source rocks are provided by modern geochemical methods. Examples include diamondoid and C isotope analysis (Sassen & Post 2008), which when carried out on minor condensate in the Baltimore Canyon Trough on the eastern North American passive margin (Prather 1991) possibly point to extreme thermal cracking of oils from a Lower–Middle Jurassic source rock. Elsewhere dilution of a minor but effective charge system by a prolific one may obscure a secondary play. Detailed biomarker geochemistry can tease out the secondary charge system.

Hydrates and biogenic gas

In addition to conventional source rocks, biogenic gas has proven in the Nile, Krishna Godavari and Mahanadi deltas to be able to source major fields. A better understanding of biogenic gas, even a predictive understanding, may unlock many new plays.

In the Krishna Godavari (K-G) Basin a detailed model of gas generation, charge focusing and migration has been developed by workers from Reliance, following the discovery of the multi Tcf-Dhirubbai Field and its satellites (Bastia 2006; Kundu *et al.* 2008). The K-G play is believed to be biogenic based on uniformly high negative $\delta^{13}C > 90$ per mil in the gas. The impingement of an oxygen minimum zone on the slope has resulted in preservation of a steady 1–2% total organic carbon (TOC) through the Mio-Pleistocene section. In areas with too rapid accumulation (perhaps >1200 m/Ma) the source rock is too dispersed. In areas with too slow deposition (perhaps <500 m/Ma) there is insufficient organic preservation, or sulphate is not dispersed, or the methane itself can be oxidized. However, in zones with the right sedimentation rate, bacteria generate methane from the organic matter in the shallow subsurface. As the sedimentary section accumulates, this methanogenic zone rises, gas migrates upwards until it reaches the hydrate stability zone where it first forms hydrate, then pools beneath the impermeable layer. This layer itself rises through the sediment column as fresh insulating sediments are deposited and deeper layers dissociate releasing biogenic gas.

The hydrate layer, following the conical sea bottom of the delta, has focused migration updip and broadly towards the delta axis into the ponded slope turbidites of a terrace formed by a linked extensional/compressional fault system.

Biogenic gas systems can be driven not only by organic material in the sediment hosting the methanogenic bacteria, but also by supply of other substrates from thermally maturing source rocks. Known biogenic gas systems also provide a basis for chasing new plays.

Heat flow models

For conventional charge systems thermal maturation is clearly important. In the case of the K-G Basin biogenic system the cooling of the seafloor along the continental slope due to changes in oceanic circulation driven ultimately by glaciations, critically extended the hydrate stability field updip. More usually, heating from below and insulation by sediment are regarded as the major issues. Classical basin models rely on a relationship between observable, if local, sedimentation histories, through regional unloaded crustal subsidence, to a model of isostatically balanced crustal thinning which has heat flow consequences. The 'McKenzie' pure shear stretching model for rifts (McKenzie 1978) has stood the test of time as a robust basis for modelling in various different software suites. It provides, for example, a simple explanation of the occurrence of oil and gas in the passive margin off Congo and Angola related to the Cenomanian–Turonian Iabe Formation, as well as rift basins such as the Kimmeridge Clay of the North Sea. This may in part be due to its general nature which, despite the rigour of back-stripping, still allows matching of temperature histories with loosely constrained crustal and conductivity parameters. Recent observations however challenge the validity of classical pure shear rift models for the later stages of passive margin geodynamics (e.g. Kusznir & Karner 2007). It is plausible that thermal basin models have in some cases been right for the wrong reasons, or alternatively that thermal histories (when calibrated for example to recent temperature data) can be somewhat insensitive to the precise mechanisms of lithospheric deformation.

In addition there has been re-assessment of some of the 'constants', for example the heat-generating capacity and thermal structure of the continental crust itself (Jackson *et al.* 2008) and kinetic parameters used in hydrocarbon modelling (Stainforth 2009).

Seismic observations of shallow or even exposed mantle in the outer parts of passive margins, and direct drilling evidence, cannot be reconciled with pure shear extension, and imply depth-variable extension (so called 'depth-dependent'), which can be logically related to lithospheric mechanics (Reston & Perez-Gussinye 2007).

For hydrocarbon prospectivity in passive margins this has the following implications:

(1) Accommodation space creation, both in the early rift and in the late rift to drift phases, may not follow models based on pure shear. Specifically, the empirical observations are that accommodation space is lower than predicted in the early rifting phase, leading to sustained shallow water depositional environments. This is typically followed by subsidence so rapid that it may not be balanced by sediment supply leading to rapid deepening.
(2) In inboard areas, the brittle extension of the rift phase ends well prior to the onset of drifting, or may even relate to a previous phase of rifting, leading to a rift-drift transition which is younger than the level of 'top extensional faulting', sometimes picked as the rift-drift unconformity. This can lead in frontier settings to erroneous jump correlations, with implications for reservoir and source rock prediction. It may also lead to an erroneous understanding of the regional context of the older rift faulting.
(3) Conversely in outboard areas, rifting, even to an extreme degree, can continue well after true seafloor spreading has commenced (Tucholke *et al.* 2007).
(4) The heat flow models related to pure shear, and the attendant mantle upwelling, may not be relevant to mantle which although uplifted is apparently not uplifted on a 'normal' mantle adiabat, and moreover undergoes extensive serpentinization (Blaich *et al.* 2010; Reynisson *et al.* 2010).

These effects are currently being assessed. The ability to confidently model temperature history based on geodynamics awaits clarity on the physical mechanisms for lithospheric mantle and lower crustal extension.

New thermal history algorithms will probably fall into two domains:

(1) 'pick-and-mix' forward models which can deal with varying margin evolution scenarios and are used to classify margins into genetic types (e.g. magma-rich v. magma-poor, depth-dependent stretching or pure shear);
(2) use of observed geometric attributes (sedimentary backstripping, whatever crustal profiling data are available) and boundary temperature assumptions without explicit choice of a geodynamic model to invert to a crustal profile, followed by a forward temperature model.

An interesting approach to the latter is the 2D inversion of strain rate as defined by stratigraphic geometries (e.g. Bellingham & White 2002; White *et al.* 2004; Crosby *et al.* 2008). In its first exposition this approach was simplified, but it illustrates well the potential of inversion based on observation, rather than forward models based on a sometimes arbitrary choice of geodynamic model.

Exploration on oceanic crust

Exploration is already being pursued onto oceanic crust in areas where sedimentary overburden is thick enough for thermal blanketing to compensate for lower crustal heat production. Typically such plays are sourced by rocks related to major oceanic anoxic events. Examples include the Gulf of Mexico, the outer Niger Delta, the outer Congo Delta and the Ganges–Brahmaputra deep sea fan off Eastern India. There are suggestions that some thick passive margin sequences, such as the anomalously unstructured simple prograding wedges offshore Mozambique, may also be underlain by transitional oceanic crust (Watts 2001).

Reservoirs

Clearly a wide range of reservoir types have proven productive on passive margins: aeolian sandstones (Kudu, Namibia); hydrothermal dolomites (Deep Panuke; Wierzbicki *et al.* 2006); the full range of carbonate facies (Campos and Santos Basin lacustrine coquinas and microbial carbonates, reef and fore-reef limestones in Mexico–Campeche, platform sequences such as the India–Bombay High and salt-rafted limestones in Angola and Congo); shallow marine clastics (NW Australia, Gabon); deltaics (Niger, Cameroon, the Canadian Mackenzie, Nile); and last but not least slope and basin-floor turbidites (all the above deltas, Gulf of Mexico, Norway and UK Atlantic Margin, Angola, Congo, Equatorial Guinea, NW Australia).

It is probably fair to say, however, that turbidite reservoirs have stolen the show as exploration has moved into ever-deeper water. Approximately 125×10^9 BOE have been discovered in water depths of more than 400 m in the last 30 years, and with 30 plus BBOE in the last 4 years, this global play is not yet creamed. The great majority of these volumes have been from passive margins (the major exceptions being the south Caspian and NW Borneo). Reasonable estimates, based on play analysis, creamed field size distribution curves for each province or simply basin creaming curve analysis, are for a further 150–200 BBOE from passive margin deepwater plays via new discoveries and reserve growth.

Notably, recent major exploration discoveries in the deepwater Brazilian Santos Basin have taken the spotlight from turbidite reservoirs (Scotchman *et al.* 2010). These resources are hosted in Late Barremian and Aptian non-marine microbial carbonates in the late syn-rift and sag sequences prior to deposition of the South Atlantic salt basin (Machado *et al.* 2009; Wright & Racey 2009). Reservoir quality is strongly facies-controlled overprinted by a multiphase diagenetic history, culminating in late-stage corrosion enhancing the remnant primary porosity and sequent reservoir deliverability. Predicting reservoir distribution across these giant fields poses an unique challenge for development. However, these discoveries raise the question of whether similar pre-salt petroleum systems are yet to be discovered along the conjugate margins in the South Atlantic (Jones *et al.* 2009).

Reservoirs on outer margins

Outboard portions of passive margins have typically been dominated by exploration for deepwater reservoirs. A number of processes can result in shallow water deposits being drowned in the deep waters of the outer margins and yet still be at economically drillable depths:

(1) sediment starvation, outboard due for example to an active inboard rift-related basin, perhaps in its thermal sag phase;
(2) depth-dependent mid-crustal stretching (Kusznir & Karner 2007), for example on the outboard Exmouth Plateau;
(3) severe crustal thinning and mantle exhumation (e.g. review in Reston 2009);
(4) micro-continent isolation by rift jumping (e.g. São Paulo High, Scotchman *et al.* 2010).

Reservoirs and 'basement' in multi-phase rifts

Much older industry seismic data shot with 4 km streamers warrants re-analysis in the light of the realization that a classical rift then drift model of passive margin evolution is probably too simple. Apart from simply correct imaging of basement, the picking of top basement reflections and an understanding of possibly rotated early fault planes which appear to be top basement is one point to check. A second is the significance and age of 'syn-rift' or 'pre-rift' sequences. Syn- which rift? Pre- which rift? Proximal alluvial sequences may well have been dated by inference from an assumed tectonostratigraphic scheme rather than by biostratigraphic data.

Large drainage basin systems

Some 50 major river drainage systems drain most of the land surface of the present-day continents and of these about half drain to modern passive margins, giving the thermal blanketing, reservoir and seal for recent hydrocarbon generation and preservation. As exploration shifts away from the current major river deltas and/or into deeper sections, it is worth questioning past palaeogeographies to see if drainage basins differed. The widespread development, for example, of Upper and 'Middle' Cretaceous inland (epeiric) seas on all continents suggests that major drainages were busy infilling these essentially foreland basin domains, with relatively minor drainages feeding the then young (Atlantic) passive margins. Earth systems, thinking about interactions between erosion, sedimentation, palaeoclimate and palaeo-oceanography, may also be a stimulating source of new ideas about reservoirs in older sequences (e.g. for the Cretaceous; Skelton *et al.* 2003). Notable Upper Cretaceous discoveries along the equatorial African margin in the Rio Muni Basin, Equatorial Guinea and the West Tano Basin, Ghana have shown that these earlier drainage systems can provide high-quality turbidite reservoirs.

Shelf edge deltas and plays

The compelling outcrop evidence that sediment supply drives deltas to the shelf edge during high stands (e.g. Uroza & Steel 2008), demonstrates that rigorous application of 'standard' sequence stratigraphic models (which for didactic purposes have underplayed the role of variable sediment supply) may have left the possibilities of these depositional systems unexplored. High stand shelf edge deltas can be expected to be characterized by thicker progradational parasequences, in general more linear and wave-dominated shorefaces, and more hyperpycnal flow direct from river mouths. The realization that interactions between palaeoclimate and changing atmospheric conditions may have caused peaks of sediment input allows explorers to investigate these controls for specific time intervals of higher weathering.

The importance of small, localized but high volume, sediment inputs controlled by drainage systems was highlighted by Martinsen *et al.* (2010). They describe a holistic 'source-to-sink' approach relating onshore drainage and geomorphology to subsurface clastic reservoirs, using the Norwegian Sea Paleocene play as an example. New geomorphological insights and data highlighting old river capture patterns are another source of inspiration for undiscovered reservoir sequences. Studies of mantle-related dynamic topography imply a variability in sediment supply due to erosion of regional uplifts, which is in contrast with the often implicit assumption of uniform sediment supply rates in some sequence stratigraphic models.

Improved techniques for establishing provenance enhance precision in this regard. For example, Redfern *et al.* (2010) and Tyrrell *et al.* (2010) describe an approach based on Pb isotope analysis of detrital feldspars that has helped to identify quite surprising and diverse basement origins for the sediments in the Rockall Basin and its margins.

Remaining deepwater plays

It can be expected that deep-marine turbidite plays will continue to be important in passive margins – not only sub-salt as in Angola and the Gulf of Mexico but also in unexplored frontier deepwater areas (e.g. the outboard Mackenzie Delta). Smaller river systems, some driven to the shelf edge as described above, and older drainage systems such as those in Cretaceous depocentres are all currently being pursued (e.g. east Greenland draining to the Norwegian outer Vøring Basin, Morocco–Canaries, Casamance Delta off Senegal). Based on improved seismic imaging, Larsen *et al.* (2010) also proposes that the Cretaceous syn-rift play of the Faroe–Shetland Basin is worth revisiting. Their interpretation revisits the source-to-sink theme, and the concept of rift segmentation, alluded to in this paper and elsewhere in this volume.

It is also possible that, in the thickest deepwater fans with massive slope by-pass of sand such as the Congo and the Ganges–Brahmaputra, largely unstructured compactional fan lobe and channel plays may be possible even on oceanic crust (Anka *et al.* 2009), given of course source rocks and a thick enough thermal blanket of sediment.

Retention

Subtle migration paths

Offshore Equatorial Guinea discoveries in Miocene slope channels spectacularly demonstrate the ability of thin (10–20 m) slope and basin floor sands to form stratigraphic traps in largely unstructured sections (Stephens *et al.* 1996), as well as the ability of oil and gas condensate to migrate vertically through thick mudstone packages from relatively deep Upper Cretaceous source rocks. This impressive feat of migration is mediated by compactional faults related to the seafloor rugosity along transform faults at the top of the oceanic crust, but which have very limited offsets. Much remains unknown about the fault-related focusing of migration flux in such systems.

Late structural evolution

Anderson (2007) argues on the basis of the lack of strength of rocks in tension that a tectonic plate can be seen as a unit of lithosphere in a state of compressive stress: part of a self-organized system essentially held in that state by plate boundary forces. It is therefore not surprising that passive margins that are born and die at plate margins but spend their middle years in plate interiors record mid-life crises, expressed as a fair amount of compressive tectonic structuring. As is well known, the World Stress Map (Heidbach *et al.* 2008) shows that the current orientation of principal horizontal stress is less related to the direction of rifting than to the current direction of plate motion, giving present-day and presumably therefore palaeocompressive stresses at oblique angles to the margins. The relationship of such plate motion-induced stresses, or body-force stresses associated with plate boundaries, to observed strain phenomena is discussed in the paper by Doré *et al.* (2008). Broad compression-related folds in the Cretaceous–Cenozoic cover successions are observed over a wide area between the Mid-Norwegian shelf and the Rockall–Faroes area. The folds appear to be episodic and to have multiple origins, and are interesting as potential late-formed hydrocarbon traps.

Late uplift, unrelated or connected only indirectly to the actual formation of a passive margin, is now well documented from many margins (e.g. Nielsen *et al.* 2008). In west Greenland, Japsen *et al.* (2006) describe three separate phases of uplift: broadly Oligocene (36–30 Ma), Miocene (11 Ma) and Pliocene (7–2 Ma), all clearly post-dating the classical rift shoulder-related uplift in the Eocene. Such events/features may have local or regional causes (Doré *et al.* 2008; Cloetingh *et al.* 2008; Holford *et al.* 2008). There is also clear evidence for substantial transient rapid uplift (Rudge *et al.* 2008; Shaw-Champion *et al.* 2008). Dynamic topography related to mantle phenomena appears to be implicated. The impacts on exploration are potentially profound, with the cessation of active maturation and possibly expulsion of hydrocarbons, embrittlement of seals, creation or destruction of overpressures, and expansion of gas caps being among the more obvious on older uplifted sequences. Furthermore the new input of sediment from erosional products may trigger very recent maturation and expulsion and far-field compressive stresses and fault reactivation may trigger new trapping possibilities. Japsen *et al.* (2010) provide comprehensive documentation of Cenozoic uplift around the North Atlantic, including timing and implications for sedimentation and petroleum systems. They suggest that uplift may be an implicit tendency of passive margin borderlands, speculatively a function of changes in crust and lithosphere thickness over short distances.

Around Africa late continental uplift, associated by many with dynamic topography, has generated seaward dips which bedevil exploration by tilting out the traps. This late uplift is sometimes obscured by salt movement or other forms of gravitational collapse, and is often multi-phase. For example in the apparently simple and 'classical' Orange River Basin margin of NW South Africa, two phases of later-than-rift uplift (Upper Cretaceous and Mid Cenozoic), are revealed (Paton *et al.* 2008).

Technology

New development concepts

The full globalization of LNG is opening up gas exploration in what were previously oil basins (e.g. Vining *et al.* 2010), or in countries or areas without developed gas markets. Furthermore, the ability to process LNG and load tankers offshore will enable development of remote fields, or fields off difficult coastlines, with the benefit also of spreading the burden of LNG plant construction around the world. Floating LNG production is currently considered likely to first be used for developments off NW Australia, but remote passive margins worldwide could follow.

New engineering technologies are also enabling smaller oil accumulations and more difficult fluids to be developed further offshore and in yet deeper water. Recent examples include very deepwater spar developments such as that in the Perdido Fold Belt, Gulf of Mexico, where the Shell group's Great White production well in 2934 m of water holds the current record. This trend too can be expected to continue.

Exploration technology refinement, leading to new exploration models

Improvements to seismic data quality are still occurring at a rapid pace. For example, Hardy *et al.* (2010) describe potential strategies and processing flows for deepwater seismic resolution, with applications for exploration off western Ireland. Wider use of multi-azimuth seismic and pre-stack depth imaging not only for seeing below salt (Ekstrand *et al.* 2010), but also simply for higher-fidelity imaging, has helped in the development of new plays such as the highly successful Gulf of Mexico and South Atlantic sub-salt, and is likely to continue to open up new plays. As costs come down (as, e.g. shooting geometries are optimized), these techniques will become even more widespread. The vastly increased visibility of sub-salt sequences in recent years has been accompanied by significant refinement of salt models, and an increased understanding of how salt and sediment behaves in areas of high sedimentation and multiphase halokinesis. Such models are important offshore Brazil and west Africa, although the key testing ground has been the US Gulf of Mexico. Jackson *et al.* (2010) describe some of these emerging concepts, such as the movement of salt canopies in the subsurface and the transport of exotic sediment rafts over tens of kilometres seaward by migrating canopies. This paper also addresses some of the current enigmas regarding minibasin formation.

Imaging beneath a thick basalt cover is a significant concern and the key to further exploration success in the North Atlantic Faroe–Shetland and Møre Basins. In the few wells that have attempted to test sub-basalt traps, the depth to base basalt has been underestimated and the wells abandoned without reaching their objective. Two studies in this volume address this theme. Davison (2010) describes imaging using deep towed seismic and its results for Cenozoic and Cretaceous trap models, while Ellefsen *et al.* (2010) stress the need for understanding internal volcanic facies at the base of the basalt succession to better resolve the key base basalt reflector.

Use of controlled source electro-magnetic surveying is increasingly becoming routine, and can, for example, usefully distinguish low saturation gas which seismic methods may not be able to separate from higher gas saturation reservoirs. Better basin models based simply on more calibration data as well as new geodynamic insights, more refined geochemical extrapolation of source rock facies based on palaeo-ecological and palaeoclimatic insights, and a clearer understanding of late uplift through fission track geothermometry and satellite-based palaeogeomorphological studies, can all be expected.

Frontiers

In addition to new ideas for already part-explored areas, there are of course still margins which have yet to be explored. Prospective margins which have suffered commercial challenges include the difficult climatic conditions of the Arctic margins and areas subject to border disputes or moratoria, such as much of the western North Atlantic margin.

Arctic

Positions are being taken along the lightly explored margins of the greater Arctic, for example, in the Beaufort Sea–Mackenzie Delta margin, with proven plays in the Paleocene to Miocene, and in west Greenland and Labrador margins. Exploratory survey work is being conducted off east Greenland. Acreage has also been offered recently in the Laptev Sea.

Palaeo-passive margins

Although not the subject of this meeting, it has to be remembered that ancient passive margins also contain oil and gas, the Brookian sequence of Alaska being a major example. In general the conversion of the passive continental margin to an active plate margin, as is currently happening between Timor and Australia, either destroys or overwrites the petroleum system. The significance of palaeo-passive margins as petroleum systems really depends on where the cratonward, updip limit of a passive margin system is placed. Examples where this might be important include the Palaeozoic of the Western Canadian Sedimentary Basin and the Mesozoic of the northeastern (Tethyan) rim of Arabia. In general these sequences are traditionally treated as belonging to continental epeiric sea basins rather than being inboard passive margins. Perhaps new insights into passive margin geodynamics will change this too.

References

Allen, P. A. & Allen, J. R. 2005. *Basin Analysis: Principles and Applications* (2nd edn). Wiley Blackwell, Chichester.

Anderson, D. L. 2007. *New Theory of the Earth*. Cambridge University Press, Cambridge.

Anka, Z., Séranne, M., Lopez, M., Scheck-Wenderoth, M. & Savoye, B. 2009. The long-term evolution of the Congo deep-sea fan: a basin-wide view of the interaction between a giant submarine fan and a mature passive margin (ZaiAngo project). *Tectonophysics*, **470**, 42–56.

Bastia, R. 2006. An overview of Indian sedimentary basins with special focus on emerging East Coast deepwater frontiers. *The Leading Edge*, July, 818–829.

Bellingham, P. & White, N. 2002. A two-dimensional inverse model for extensional sedimentary basins. 2. Applications. *Journal of Geophysical Research*, **107**, 2260; doi: 10.1029/2001JB000174.

Blaich, O. A., Faleide, J. I., Tsikalas, F., Lilletveit, R., Chiossi, D., Brockbank, P. & Cobbold, P. 2010. Structural architecture and nature of the continent–ocean transitional domain at the Camamu and Almada Basins (NE Brazil) within a conjugate margin setting. *In*: Vining, B. A. & Pickering, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, 867–883; doi: 10.1144/070867.

Bradley, D. C. 2008. Passive margins through earth history. *Earth Science Reviews*, **91**, 1–26; doi: 10.1016/j.earscirev.2008.08.001.

Chalmers, J. A. & Pulvertaft, T. C. R. 2001. Development of continental margins of the Labrador Sea: a review. *In*: Wilson, R. C. L., Whitmarsh, R. B., Taylor, B. & Froitzhelm, N. (eds) *Non-volcanic Rifling of Continental Margins: A Comparison of Evidence from Land and Sea*. Geological Society, London, Special Publications, **187**, 77–105.

Cloetingh, S., Beekman, F., Ziegler, P., Van Wees, J.-D. & Sokoutis, D. 2008. Post-rift compressional reactivation of passive margins and extensional basins. *In*: Johnson, H., Doré, A. G., Gatliff, R. W., Holdsworth, R., Lundin, E. R. & Ritchie, J. D. (eds) *The Nature* *and Origin of Compression in Passive Margins*. Geological Society, London, Special Publications, **306**, 27–70; doi: 10.1144/SP306.2.

Crosby, A., White, N., Edwards, G. & Shillington, D. J. 2008. Evolution of the Newfoundland–Iberia conjugate rifted margin. *Earth and Planetary Science Letters*, **273**, 214–226.

Davison, I., Stasiuk, S., Nuttall, P. & Keane, P. 2010. Sub-basalt hydrocarbon prospectivity in the Rockall, Faroe–Shetland and Møre basins, NE Atlantic. *In*: Vining, B. A. & Pickering, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, 1025–1032; doi: 10.1144/0071025.

De Wit, M. J., Stanciewicz, J. & Reeves, C. 2008. Restoring pan African–Brasiliano connections: more Gondwana control, less trans-Atlantic corruption. *In*: Pankhurst, R. J., Trouw, R. A. J., Brito Neves, B. B. & de Wit, M. J. (eds) *West Gondwana Pre-Cenozoic Correlations Across the South Atlantic Region*. Geological Society, London, Special Publications, **294**, 399–412.

Doré, A. G., Lundin, E. R., Jensen, L. N., Birkeland, Ø., Eliassen, P. E. & Fichler, C. 1999. Principal tectonic events in the evolution of the northwest European Atlantic margin. *In*: Fleet, A. J. & Boldy, S. A. R. (eds) *Petroleum Geology of Northwest Europe: Proceedings of the 5th Conference*. Geological Society, London, 41–61; doi: 10.1144/0050041.

Doré, A. G., Lundin, E. R., Kusznir, N. J. & Pascal, C. 2008. Potential mechanisms for the genesis of Cenozoic domal structures on the NE Atlantic margin: pros, cons and some new ideas. *In*: Johnson, H., Doré, A. G., Gatliff, R. W., Holdsworth, R., Lundin, E. R. & Ritchie, J. D. (eds) *The Nature and Origin of Compression in Passive Margins*. Geological Society, London, Special Publications, **306**, 1–26; doi: 10.1144/SP306.1.

Ebbing, J. & Olesen, O. 2010. New compilation of top basement and basement thickness for the Norwegian continental shelf reveals the segmentation of the passive margin system. *In*: Vining, B. A. & Pickering, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, 885–897; doi: 10.1144/0070885.

Ekstrand, E., Hickman, G., Thomas, R., Threadgold, I., Harrison, D., Los, A., Summers, T., Regone, C. & O'Brien, M. 2010. WATS it take to image an oil field subsalt offshore Angola? *In*: Vining, B. A. & Pickering, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, 1013–1024; doi: 10.1144/0071013.

Ellefsen, M., Boldreel, L. O. & Larsen, M. 2010. Intra-basalt units and base of the volcanic succession east of the Faroe Islands exemplified by interpretation of offshore 3D seismic data. *In*: Vining, B. A. & Pickering, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, 1033–1041; doi: 10.1144/0071033.

Funck, T., Hopper, J. R., Larsen, H. C., Louden, K. E., Tucholke, B. E. & Holbrook, W. S. 2003. Crustal structure of the ocean continent transition at Flemish Cap: seismic refraction results. *Journal of Geophysical Research*, **108**, 2531; doi: 10.1029/2003JB002434.

Hardy, R. J. J., Querendez, E., Biancotto, F., Jones, S. M., O'sullivan, J. & White, N. 2010. New methods of improving seismic data to aid understanding of passive margin evolution: a series of case histories from offshore west of Ireland. *In*: Vining, B. A. & Pickering, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, 1005–1012; doi: 10.1144/0071005.

Heidbach, O., Tingay, M., Barth, A., Reinecker, J., Kurfeß, D. & Müller, B. 2008. The 2008 release of the World Stress Map. World Wide Web Address: www.world-stress-map.org.

Holford, S. P., Green, P. F. *et al*. 2008. Evidence for kilometer-scale exhumation driven by compressional deformation in the Irish Sea basin system. *In*: Johnson, H., Doré, A. G., Gatliff, R. W., Holdsworth, R., Lundin, E. R. & Ritchie, J. D. (eds) *The Nature and Origin of Compression in Passive Margins*. Geological Society, London, Special Publications, **306**, 91–119; doi: 10.1144/SP306.4.

Jackson, M. P. A., Hudec, M. R. & Dooley, T. P. 2010. Some emerging concepts in salt tectonics in the deepwater Gulf of Mexico: intrusive plumes, canopy-margin thrusts, minibasin triggers and allochthonous fragments. *In*: Vining, B. A. & Pickering, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, 899–912; doi: 10.1144/0070899.

Jackson, J., McKenzie, D., Priestley, K. & Emmerson, B. 2008. New views on the structure and rheology of the lithosphere. *Journal of the Geological Society, London*, **165**, 453–465.

Japsen, P., Bonow, J. M., Green, P. F., Chalmers, J. A. & Lidmar-Bergstrom, K. 2006. Elevated passive continental margins: long term highs or Neogene uplifts? New evidence from West Greenland. *Earth and Planetary Science Letters*, **248**, 330–339; doi: 10.1016/j.epsl.2006.05.036.

Japsen, P., Green, P. F., Bonow, J. M., Rasmussen, E. S., Chalmers, J. A. & Kjennerud, T. 2010. Episodic uplift and exhumation along North Atlantic passive margins: implications for hydrocarbon prospectivity. *In*: Vining, B. A. & Pickering, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, 979–1004; doi: 10.1144/0070979.

Jenkyns, H. C. 2003. Evidence for rapid climate change in the Mesozoic-Palaeogene greenhouse world. *Philosophical Transactions of the Royal Society, London A*, **361**, 1885–1916.

Jones, W., Guevara, M. *et al*. 2009. The subsalt play in the lower Congo and Kwanza Basins, Angola: a seismic study. Abstract from the *American Association of Petroleum Geologists Annual Convention and Exhibition*, Denver, CO, 7–10 June.

Klemme, H. D. & Ulmishek, G. F. 1991. Effective petroleum source rocks of the world: stratigraphic distribution and controlling depositional factors. *Bulletin of the American Association of Petroleum Geologists*, **75**, 1809–1851.

Kundu, N., Pal, N., Sinha, N. & Budhiraja, I. L. 2008. Do paleo-hydrates play a major role in deepwater biogenic gas reservoirs in Krishna–Godavari Basin? *Methane Hydrate Newsletter, National Energy Technology Laboratory*, Fall 13–15.

Kusznir, N. J. & Karner, G. D. 2007. Continental lithospheric thinning and breakup in response to upwelling divergent mantle flow: application to the Woodlark, Newfoundland and Iberia margins. *In*: Karner, G. D., Manatschal, G. & Pinhero, L. M (eds) *Imaging, Mapping and Modelling Continental Lithosphere Extension and Breakup*. Geological Society, London, Special Publications, **282**, 389–419; doi: 10.1144/SP282.16.

Larsen, M., Rasmussen, T. & Hjelm, L. 2010. Cretaceous revisited: exploring the syn-rift play of the Faroe–Shetland Basin. *In*: Vining, B. A. & Pickering, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, 953–962; doi: 10.1144/0070953.

Machado, M. A. P., Moraes, M. F. B. *et al*. 2009. The pre-salt sequence of ultra-deep water Santos basin: geological aspects and key factors controlling the major oil accumulations. Abstract, *American Association of Petroleum Geologists International Conference and Exhibition*, Rio de Janeiro, 15–18 November.

Mann, P., Gahagan, L. & Gordon, M. B. 2003. *Tectonic Setting of the World's Giant Oil and Gas Fields*. American Association of Petroleum Geologists, Tulsa, OK, Memoirs, **78**, 15–105.

Martinsen, O. J., Sømme, T. O., Thurmond, J. B., Helland-Hansen, W. & Lunt, I. 2010. Source-to-sink systems on passive margins: theory and practice with an example from the Norwegian continental margin. *In*: Vining, B. A. & Pickering, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, 913–920; doi: 10.1144/0070913.

McKenzie, D. P. 1978. Some remarks on the development of sedimentary basins. *Earth and Planetary Science Letters*, **40**, 25–32.

Nielsen, S. B. *et al*. 2008. The evolution of western Scandinavian topography: a review of Neogene uplift versus the ICE (isostasy–climate–erosion) hypothesis. *Journal of Geodynamics*, **47**, 72–95; doi: 10.1016/j.jog.2008.09.001.

Paton, D. A., van der Spuy, D., di Primio, R. & Horsfield, B. 2008. Tectonically induced adjustment of passive-margin accommodation space; influence on the hydrocarbon potential of the Orange Basin, South Africa. *Bulletin of the American Association of Petroleum Geologists*, **92**, 589–609.

Prather, B. E. 1991. Petroleum geology of the Upper Jurassic and Lower Cretaceous, Baltimore Canyon Trough, Western North Atlantic Ocean. *Bulletin of the American Association of Petroleum Geologists*, **75**, 258–277.

Redfern, J. & Shannon, P. M. *et al*. 2010. An integrated study of Permo-Triassic basins along the North Atlantic passive margin: implication for future exploration. *In*: Vining, B. A. & Pickering, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, 921–936; doi: 10.1144/0070921.

Ren, S., Faleide, J. I., Eldholm, O., Skogseid, J. & Gradsetin, F. 2003. Late Cretaceous to Paleocene development of the NW Voring Basin. *Marine and Petroleum Geology*, **20**, 177–206.

Reston, T. J. 2009. The structure, evolution and symmetry of the magma-poor rifted margins of the North and Central Atlantic: a synthesis. *Tectonophysics*, **468**, 6–27.

Reston, T. J. & Perez-Gussinye, M. 2008. Lithospheric extension from rifting to continental breakup at magma-poor margins: rheology, serpentinization and symmetry. *In*: Bernouilli, D., Brun, J.-P. & Burg, J.-P. (eds) Special issue, Continental Extension. *International Journal of Earth Sciences*, **96**, 1033–1046.

Reynisson, R. F., Ebbing, J., Lundin, E. & Osmundsen, P. T. 2010. Properties and distribution of lower crustal bodies on the mid-Norwegian margin. *In*: Vining, B. A. & Pickering, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, 843–854; doi: 10.1144/0070843.

Rudge, J. F., Shaw-Champion, M. E., White, N., McKenzie, D. & Lovell, B. 2008. A plume model of transient diachronous uplift at the Earth's surface. *Earth and Planetary Science Letters*, **267**, 146–160.

Sassen, R. & Post, P. 2008. Enrichment of diamondoids and ^{13}C in condensate from Hudson Canyon, US Atlantic. *Organic Geochemistry*, **39**, 147–151; doi: 10.1016/j.orggeochem.2007.10.004.

Scotchman, I. C., Gilchrist, G., Kusznir, N. J., Roberts, A. M. & Fletcher, R. 2010. The breakup of the South Atlantic Ocean: formation of failed spreading axes and blocks of thinned continental crust in the Santos Basin, Brazil and its consequences for petroleum system development. *In*: Vining, B. A. & Pickering, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, 855–866; doi: 10.1144/0070855.

Shaw-Champion, M. E., White, N. J., Jones, S. M. & Lovell, J. P. B. 2008. Quantifying transient mantle convective uplift: an example from the Faroe Shetland Basin. *Tectonics*, **27**; doi: 10.1029/2007TC002106.

Skelton, P. W., Spicer, R. A., Kelley, S. P. & Gilmour, I. 2003. *In*: Skelton, P. W. (ed.) *The Cretaceous World*. The Open University/Cambridge University Press, Buckingham/Cambridge.

Stainforth, J. G. 2009. Practical kinetic modeling of petroleum generation and expulsion. *Marine and Petroleum Geology*, **26**, 552–572.

Stephens, A. R., Monson, G. D. & Reilly, J. M. 1996. *Seismic Amplitudes: Their Relevance for Hydrocarbon Exploration in the Late Miocene/Early Pliocene Sediments of the Distal Niger Delta: Examples from the Zafiro Field.* Equatorial Guinea: Offshore West Africa Conference, Libreville.

Tucholke, B. E., Sawyer, D. S. & Sibuet, J.-C. 2007. *The Iberia Newfoundland Continental Extension System (Geological and Geophysical Constraints)*. Geological Society, London, Special Publications, **282**, 9–46.

Tyrrell, S., Souders, A. K., Haughton, P. D. W., Daly, J. S. & Shannon, P. M. 2010. Sedimentology, sandstone provenance and palaeodrainage on the eastern Rockall Basin margin: evidence from the Pb isotopic composition of detrital K-feldspar. *In*: Vining, B. A. & Pickering, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, 937–952; doi: 10.1144/0070937.

Uroza, C. A. & Steel, R. J. 2008. A highstand shelf margin delta system from the Eocene of West Spitsbergen, Norway. *Sedimentary Geology*, **203**, 229–245.

van Avendonk, H. J. A., Lavier, L. L., Shillington, D. J. & Manatschal, G. 2008. Extension of continental crust at the margin of the eastern Grand Banks Newfoundland. *Tectonophysics*, **468**, 131–148; doi: 10.1016/j.tecto.2008.05.030.

Watts, A. B. 2001. Gravity anomalies, flexure and crustal structure at the Mozambique rifted margin. *Marine and Petroleum Geology*, **18**, 445–455.

White, R. S., Eccles, J. D. & Roberts, A. W. 2010. Constraints on volcanism, igneous intrusion and stretching on the Rockall–Faroe continental margin. *In*: Vining, B. A. & Pickering, S. C. (eds) *Petroleum Geology: From Mature Basins to New Frontiers – Proceedings of the 7th Petroleum Geology Conference*. Geological Society, London, 831–842; doi: 10.1144/0070831.

White, N., Haines, J. & Hanne, D. 2004. Towards an automated strategy for modelling extensional basins and margins in four dimensions. *In*: Davies, R. J., Cartwright, J. A., Stewart, S. A., Lappin, M. & Underhill, J. R. (eds) *3D Seismic Technology: Applications to the Exploration of Sedimentary Basins*. Geological Society, London, Memoirs, **29**, 321–331.

White, R. S., Smith, L. K., Roberts, A. W., Christie, P. A. F., Kusznir, N. J. & the rest of the ISIMM team. 2008. Lower-crustal intrusion on the North Atlantic continental margin. *Nature*, **452**, 460–464.

Wierzbicki, R., Dravis, J. J., Al-Aasm, I. & Harland, N. 2006. Burial dolomitization and dissolution of Upper Jurassic Abenaki platform carbonates, Deep Panuke reservoir, Nova Scotia, Canada. *Bulletin of the American Association of Petroleum Geologists*, **90**, 1843–1861; doi: 10.1306/03200605074.

Wright, P. V. & Racey, A. 2009. Pre-salt microbial carbonate reservoirs of the Santos Basin, offshore Brazil. Abstract from the *American Association of Petroleum Geologists Annual Convention and Exhibition*, Denver, CO, 7–10 June 2009.