The petroleum geology of the West Africa margin: an introduction

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Abstract: The continental margin of West Africa formed as result of the south-to-north rifting of Gondwana and the progressive separation of the South American and African continents. This margin has enjoyed a rich and varied exploration history and, in the 70 years or so since the first significant exploration began in the onshore area, the margin has emerged as a significant hydrocarbon-producing region. The amalgamation of hydrocarbon exploration approaches and imaginative ideas, leveraged with modern technologies, is yielding significant scientific and economic successes.

The main objective of this Special Publication is to provide an overview of the advances in our understanding of the crustal structure, tectonic evolution and Mesozoic to Cenozoic stratigraphy of the West Africa margin both onshore and offshore, with a particular focus on the petroleum geology. The papers contained in this Special Publication represent a selection from the 37 abstracts presented at the original conference in March 2014, which covered the entirety of the margin from South Africa to Morocco as well as stratigraphy from the crystalline basement to the most recent strata. The original abstracts from the conference are available through the Geological Society of London website at: http://www.geolsoc.org.uk/pgresources

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The West Africa continental margin is defined as the coastal area extending from Morocco in the north to the Cape of Good Hope in South Africa in the south (Fig. 1). Twenty-three countries share the coastline along the West Africa margin, and although some of these countries have vast continental interiors (e.g. Democratic Republic of Congo), the coastline and territorial waters of the countries are actively explored for hydrocarbons and have been found to possess large economic resources, capturing academic and industrial interest. Presently, nine of these 23 countries in Africa are oil exporters: Nigeria, Angola, Equatorial Guinea, Congo (Brazzaville), Gabon, Cameroon, Ivory Coast, Democratic Republic of Congo (DRC) and Mauritania (US Energy Information Administration (EIA), http://www.eia.gov/).

The West Africa margin is one component of continental Africa, which formed as a direct result of the rifting of Gondwana and the progressive separation of the South American and African continents.

The South Atlantic can be divided into four segments (Moulin et al. 2005) from south to north: the ‘Falkland Segment’ (not covered in this volume), the ‘South Segment’, the ‘Central Segment’ and the ‘Equatorial Segment’ (Fig. 1), all of which are characterized by different tectonic, crustal and volcanic features. The South Segment, bounded to the south by the Agulhas–Falkland fracture zone and to the north by the Florianopolis Fracture Zone and the Walvis Ridge, is characterized by significant volcanic features identified in surface and subsurface data, such as extensive seaward-dipping reflectors. Evaporitic material, including the precipitation of a large volume of halite, filled the Central Segment during the Aptian, which is separated from the South Segment by the Florianopolis Fracture Zone and bounded to the north by the Romanche Fracture Zone. The Equatorial segment, separated from the Central Segment by the Romanche Fracture Zone and limited to the north at about the 10°N parallel near the Vema Fracture Zone, corresponds to a broad zone of lateral shearing in a transform margin setting (Torsvik et al. 2009).

These various tectonic domains along the West Africa margin are discussed the papers compiled in this volume.
The most widely accepted model for the opening of the Atlantic Ocean corresponds to the classic rift-to-drift transition. Rifting starts initially in the south during the Late Jurassic and propagates northwards, in effect ‘unzipping’ the palaeocontinent of Gondwana. Therefore, rifting in the Equatorial Segment is indicated in the map, along with the South Segment, and the Namibian and South African coast corresponds to the area where seismic reflection data display clear evidence for the presence of seaward-dipping reflectors (SDRs). Stars indicate the papers included in this volume, and purple diamonds show the published abstracts related to the original conference, available online from the Geological Society of London website (http://www.geolsoc.org.uk/pgresources; (Note: only the surname of the first author is used for each symbol).
segment of the margin only initiated in the Late Cretaceous (Rabinowitz & LaBrecque 1979; Emery & Uchupi 1984).

In spite of the general agreement around this empirical model, the early stages of continental rifting, as well as the pre-drift positions of the major tectonic blocks forming the margin, remain a matter of debate. In the various models proposed in the literature, the locations and magnitudes of the gaps and overlaps between the reconstructed continental blocks differ greatly (Karner & Driscoll 1999; Karner et al. 2003; Aslanian et al. 2009; Moulin et al. 2010).

The quest for an integrated global model is economically as important for Africa and the world as it is scientifically. The locations and volumes of possible hydrocarbon reserves are underpinned by the tectonostratigraphic evolution of the margin. According to independent volumetric estimates, the West Africa margin holds the majority of the liquid hydrocarbon in sub-Saharan Africa (US EIA).

The synergy between academic studies and hydrocarbon exploration of the West Africa margin has led to the establishment of one of the most complete and varied datasets available in Earth sciences, and has brought together a large pool of experts in many fields. As a result, the wealth of data currently available to interpreters and modellers alike has considerably changed our understanding of the geometry, evolution, structure and depositional patterns of the margin and related sedimentary basins at all scales (Fig. 1). The interpretation of satellite-derived gravity data, for example, is enabling the development of basin- or margin-scale models that permit the characterization of the general structure and development of the margin (see Péron-Pinvidic et al. 2015; Cowie et al. 2016; Paton et al. 2016). In the meantime, the interpretation of high-resolution 2D and 3D seismic data provides a detailed view of the stratigraphy, structures and volcanic bodies comprising these basins (see Brown et al. 2015; Dalton et al. 2016; Lawrence et al. 2016; Paton et al. 2016; Sabato Ceraldi & Green 2016).

Finally, the wealth of drilling-related and outcrop data for the onshore region allow the characterization of the timing and amplitude of tectonic changes along the West Africa margin (see Green & Machado 2015; Martín-Monge et al. 2016).

The timing of the conference was also coincident with the beginning of the exploration of the pre-salt stratigraphy in Angola. The industry focus on this new promising play had a strong bearing on the content of this volume.

This Special Publication is also characterized by an equal share of papers submitted by authors from both academic and industry backgrounds. This is certainly one of the key achievements of the conference, which enabled a high level of participation of colleagues from both academia and industry.

Between the conference in 2014 and the time of publication of the present volume, the petroleum industry has endured a period of drastic changes with the drive-down in the oil price by over 75% (from c. US$105 per barrel to c. US$35 per barrel in February 2016). These changes, principally implemented to install efficiencies into the industry to cope with a low-price environment, had a significant impact on the submission, review and final publication of the ten selected manuscripts. The editors would especially like to acknowledge the authors and the reviewers for their time and efforts. Without their support in these tough times for the industry, this volume would simply never have been published.

Summary of the selected papers

The original rationale for the Geological Society of London conference on the Petroleum Geoscience of the West Africa Margin in April 2014 was to exhibit some of the recent geoscientific work that had been undertaken along the margin. Previous publications from the Geological Society that focused on the West Africa margin, such as Cameron et al. (1999) and Arthur et al. (2003), established the general tectonic, stratigraphic and petroleum systems fabric of the margin. In the years following the latest Special Publication on the topic, significant progress and step-changes in the understanding of the margin plainly justified the organization of a new meeting. The conference highlighted the advances in the application of remote sensing technologies and 3D seismic data, which have allowed geoscientists to further interrogate the structural definition of the West Africa margin. Developing an understanding of the timing and characterization of the tectonostratigraphic variations both along strike, and between the conjugate components of the Atlantic margins, has proven to be a major step forwards since the millennium, with the Brazilian pre-salt discoveries being used as direct analogues for the Angolan sub-salt prospectivity. It was also shown that the geoscientific understanding of the margin is increasingly drawing on changes in climate as a contributing factor to prospectivity. Although perhaps a product of the post-millennium Zeitgeist, climate effects are directly interpreted to contribute not only in term of variations in the sediment flux along the margin through time, but also to the composition and diageneric characteristics upon burial.

The selection of papers included in this volume is a product of the conference, drawing on these developments over the last 15 years. The papers
show that as a geoscientific community, we are progressing with our overall understanding of the geological aspects of the margin and in many cases – through the synthesis of various data – are able to decipher and unlock the hydrocarbon potential of the West Africa margin.

The papers are organized as a north–south transect through the different tectonic domains along the margin. The following section presents the highlights of each manuscript in this order.

The paper by Martín-Monge et al. (2016) is the only one that focuses on an intracratonic basin, describing the hydrocarbon potential of the Taoudeni Basin (Mauritania) – the largest sedimentary basin in Africa. The basin is also a largely unexplored region; however, a well drilled in 1974 (Abolag-1) tested both a gas and a liquid hydrocarbon phase. This paper evaluates the source–reservoir pair potential of the basin and provides a link between the occurrence of petroleum and the potential sources via geochemical analysis. The play potential is also described for some of the oldest carbonate rocks on Earth that have a complex thermal history and large uncertainties on timing of generation, trap formation and preservation.

Brown et al. (2015) examine an unusual deep-water lithofacies from the West Africa transform margin. Based on well and seismic data, the paper describes aspects of the petrophysical analysis of a quartz-prone clastic interval with good porosity, which differs from drilling results that recorded a c. 200 m ‘claystone’ interval. The combination of the physical observation and wireline interpretation for the single exploration well was subsequently recognized as a regional lithofacies type based on data from a number of wells across several sub-basins along the margin. The consistency in the lithofacies, irrespective of the differing basins and differing sediment source provinces, creates a challenge in formulating a model for the deposition of this lithofacies into a deep-water palaeoenvironment. Through the application of a variety of modern laboratory-based techniques used to characterize the rock, and research into palaeoclimates and modern day analogues, the authors interpret the lithofacies to be derived from far-field aeolian processes. Far-field events, such as this arid dusting of the West Africa transform margin during the Campanian, show that sedimentation in this region is not just a localized process, and that consideration must be given to the hinterland setting and processes acting thereupon during the exploration phase.

Lawrence et al. (2016) present evidence from the interpretation of seismic data for compressional deformation of intraplate oceanic crust in the eastern Gulf of Guinea, a region occupied by the Douala-Rio Muni Basin and the Cameroon Volcanic Line. The Cameroon Volcanic Line is usually attributed to a mantle (‘hotspot’) origin but the interpretation given here indicates that strike-slip and/or compressional tectonics and the reactivation of the oceanic crustal fabric have played important roles in its evolution. A regional tectonic model that associates the deformation in the eastern Gulf of Guinea with regional ‘Alpine far-field’ compressive stress is also presented. The authors suggest that the evolution of the Cameroon Volcanic Line and the continent–ocean transition link has imparted a unique tectonostratigraphic history to the Douala-Rio Muni Basin, which has influenced its petroleum endowment – particularly in the different trapping mechanisms found.

Péron-Pinvidic et al. (2015) summarize observations from the South Atlantic Angola–Gabon rifted margin based on the interpretation of depth-migrated seismic reflection profiles. The mapping and characterization of these domains at the margin scale permit the along-strike structural and stratigraphic variability of the margin to be illustrated. The authors also identified key sections that can be considered as type examples of upper-plate and lower-plate margins and discuss some of the characteristics of these settings.

Cowie et al. (2016) offer a model for the accumulation of salt during the Aptian, a time of South Atlantic rifting. The methodology includes a quantitative analysis of deep seismic reflection and gravity anomaly data together with reverse post-break-up subsidence modelling. Inversion of gravity data is used to infer the Moho depth and crustal thickness, and residual depth anomalies (a technique usually used for the interpretation of oceanic crust) are applied to identify departures from oceanic bathymetry on hyperextended continental crust. In their paper, they propose that the Aptian salt was deposited approximately 0.2 (proximal) and 0.6 km (distal) below global sea-level and that the inner proximal salt subsided by post-rift (post-tectonic) thermal subsidence alone, whereas the outer distal salt formed during the synrift phase, prior to the break-up, resulting in additional tectonic subsidence.

Sabato Ceraldi & Green (2016) present a paper on the pre-salt lacustrine carbonates in both Brazil and Angola. They describe the pre-salt tectonostratigraphy with three significant events: the first is the development of synrift lakes (Valanginian–Hauterivian) during continental break-up and the formation of synrift graben. The formation of several deep basins is interpreted as leading to overfilling of freshwater lakes. The second event (Sag 1) in the Barremian–Aptian caused widespread subsidence through syn-kinematic stretching of the continental crust and/or continuous rifting. Lacustrine sediments comprising coarse coquina grainstones in fresh-to-brackish, balanced-filled interconnected
lakes. The third event (Sag 2) in the Aptian is interpreted to have taken place during continuous subsidence and led to the isolation of the lakes. The base levels fell below sea-level, resulting in underfilled, hypersaline lakes with widespread microbialite growth. On the basis of integrated seismic data, well data, biostratigraphy, stable isotope analysis and tectonic models they develop a regional predictive model for reservoirs in Sag 2 and 3.

Green & Machado (2015) used apatite fission-track data from Cretaceous sediments and Precambrian crystalline basement from outcrop in the Namibe basin, Angola to describe the exhumation history of the region. They recognize Late Carboniferous–Early Permian and Jurassic exhumation events that preceded Early Cretaceous rifting. The most recent event occurred during the Cenozoic and resulted in uplift and erosion between 35 and 20 Ma. This timing is consistent with published analyses of river profiles that suggest that uplift of the margin began at c. 30 Ma. They recognize similar timing in uplift all along the West Africa margin and interpret this as the result of a continent-scale response to stresses related to tectonic plate movement.

In the paper by Mohammed et al. (2016) the pre-rift basement geometries have been characterized and then compared with the geometries of Cretaceous rift basin structures and the subsequent architectural elements of the post-rift margin. Half-graben depocentres migrate westwards through time within the continental synrift phase, at the same time as hard-linked arrays of basin-bounding faults become established, with lengths of approximately 100 km. The authors use the Southern Namibian margin as an example to demonstrate that the rift evolution and subsequent passive margin architecture are the products of lithospheric-thinning processes and crustal heterogeneity. They recognize that crustal heterogeneities play a role in influencing the dimensions and styles of fault evolution and in establishing the position of cross-cutting structures, and go on to highlight the role of pre-rift granitic bodies in influencing the location of deformation.

Dalton et al. (2016) present a large catalogue of gravity-driven structures across the Orange Basin in Namibia and South Africa. The structures documented here illustrate the role of multiple detachment levels, their activation timings and the related timings of fault activation within the gravity-driven system. These observations led Dalton et al. to propose an evolutionary model for the development of these gravity-driven systems that allows the role of the deposition of sediments in controlling the geometry of the structures to be established once placed within a well-defined stratigraphic framework.

The paper by Paton et al. (2016) addresses two previously unanswered questions: the location and continuation of the regionally extensive Gondwanian orogenic belt in the Orange Basin, offshore South Africa; and the reason that the east–west-trending Argentinian Colorado rift is perpendicular to the conjugate Orange Basin and the trend of the Atlantic Ocean spreading. This paper presents a new structural model for the southern South Atlantic by identifying the South African fold belt in the offshore domain for the first time. The trend of the fold belt changes from north–south to east–west offshore, correlating directly with the restored Colorado Basin. The authors suggest that the Colorado and Orange rifts form a tripartite system with the Namibian Gariep belt. All three rift branches were active during the rifting as Gondwana broke up, but during the Atlantic rift phase the Colorado Basin became an aulacogen while the other two branches developed in the present-day location of the South Atlantic.

The editors would like to acknowledge the contribution of the authors who devoted time and effort in the drafting and revision of the papers and the figures of this Special Publication. The editors would also like to extend their acknowledgement to the co-convenors of the conference, Matt Warner and Hannah Suttil, and the numerous named and anonymous reviewers who have contributed time and expertise to provide thorough and constructive reviews, which have considerably improved the quality of the present Special Publication: Anthony Bourne, Rob Crossley, Brian Cullen, Green Darryl, Tim Goodwin, Christian Heine, Richard Hodgkinson, Simon Holford, Sarah Houldsworth, Stephen Jones, Juliette Lamarche, Jean Malan, Webster Mohriak, Chris Morley, Alexis Anastas Nexis, Francisco Pangaro, Marta Perez-Gussinye, Nicholas Richardson, Donna Shillington, Taury Smith, Christina von Nicolai and Robert (Woody) Wilson.

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