Introduction to the thematic set: Tectonics and petroleum systems of East Africa

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This paper provides an overview of a series of papers to be published within two issues of Petroleum Geoscience in 2018 expressing the theme ‘tectonics and petroleum systems of East Africa’. These papers partly result from the Geological Society of London’s Petroleum Group conference in April 2016 on ‘East Africa; From Research to Reserves’. The theme of this conference highlighted the advances that have been made since a previous East Africa conference as a result of the recent major exploration efforts. This issue (February 2018) concentrates on the regional tectonics and include overviews of our current understanding of Permian to Mesozoic rifting (Macgregor), Tertiary rifting (Purcell), the plate tectonic model (Reeves), and of the development of the East African margin (Davison & Steel). The August 2018 issue is planned to include more basin and regional specific papers on the Kenyan rift system, offshore Somalia, offshore Tanzania and offshore Mozambique.

This first series of papers provides a comprehensive summary of our developing state of knowledge of regional tectonics across East Africa and its influence on petroleum systems. While there were a number of oral papers presented at this and subsequent conferences which provided greater detail on the numerous petroleum discoveries across the region that have been made this century, it would appear that this compilation was too early for operators to release such data in writing and as yet, we are still lacking many peer reviewed papers on East African petroleum systems. Table 1 presents a brief summary of our knowledge of the most significant discoveries in each basin which, in terms of reserve additions, make East Africa the most globally successful region in this century for discoveries in each basin which, in terms of reserve additions, make East Africa the most globally successful region in this century for frontier conventional exploration. In keeping with the tectonic diversity and complexity of the region, these individual fields have little in common with each other, though there is a general theme of complex trapping styles, with the traditional four-way-dip closures, that have comprised the trap types of most of the world’s giant fields, not represented at all on this list. There is also an apparent relationship between the regions of success and those of active Neogene subsidence and likely hydrocarbon generation. Many of these petroleum systems, particularly those within or close to Neogene rifts (including the Kerimbas Graben of the Rovuma Basin) may be dynamic petroleum systems.

In very broad terms, we can split over 100 individual basins in East Africa into Tertiary rifts (Purcell lists over 50 of these basins alone), Cretaceous rifts, Permian to Jurassic rifts, and the marginal basins to the Indian Ocean (Fig. 1). Many basins are composite between these categories, being active in more than one phase. Petroleum prospectivity onshore is generally associated with narrow rifts, within which two new petroleum provinces have been established this century in the Albertine and South Lokichar Basins, as represented by the largest fields listed in each basin on Table 1. This compilation includes two complementary papers on Permain–Mesozoic and Tertiary rift systems, by Macgregor and Purcell, which map out the development of these rifts from the Early Permian to Recent times, presented in a total of 15 maps showing the development of these rift systems through time. Previous authors have attempted to categorize these basins into temporal groups but as Purcell points out, as further data are gathered, there is a trend of increasing complexity in our interpretations that confounds such classifications. It has consequently proven, as recent disappointing well results in frontier rifts have shown, extremely difficult to apply exploration analogues across many rifts. For example, hopes that the Early Miocene Lokone Shale source rock of the South Lokichar Basin would extend into other rifts appear to have been dashed, seemingly because these rifts have emerged as not having entered the main rift phase at this time of source rock deposition. In general we believe, as Macgregor points out, that the younger rifts are more prospective than the older ones and that there remain, nevertheless, many of these still to explore.

The study of plate tectonics is particularly relevant to petroleum geology in East Africa, as the source rocks proposed for nearly all accumulations to date lie within continental rift successions (Table 1) and will clearly not occur on oceanic crust. One of the most relevant interpretations along the East African margin is therefore the location of the ‘continent–ocean boundary’ (COB), a term taken here as tying to the most oceanward limit of hyperextended continental crust. It is now being accepted on margins across the world that wide zones of necking and hyperextension typically occur between undeformed continental crust and true oceanic crust on non-volcanic margins, as best demonstrated by a 250 km wide hyperextended margin off Somalia (Stanca et al. 2016). Volcanic margins are often characterized by wide zones of seaward-dipping reflectors, at least some of which are volcanics flowing over thinned and heavily intruded continental crust. The position of the COB off East Africa remains controversial and there are indeed differing interpretations within the papers in this thematic set (Fig. 2). Reeves provides useful guidelines from plate fits as to what crustal models can and cannot be applied in some specific basins, particularly the Mozambique plains, which have been the subject of considerable controversy in the past. We now appear to be working towards a consensus here that there is an extremely wide continent to oceanic transition zone on this volcanic margin, as in the Antarctic conjugate, underlain by seabed dipping reflectors (Davison & Steel), with the Beira High being a stranded continental fragment. Elsewhere these authors, for the first time, publish some of the deep seismic data that could eventually be used to resolve the COB location: a final answer will follow when more of these become available. The editors of this volume have also added their own interpretation of the COB, which is somewhat of a compromise between the evidence provided by the various contributors, and also considers the distal limits of structural...
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styles normally associated with continental or hyperextended crust, such as half-grabens and inversions (e.g. the inversions that lie >200 km offshore in the Lamu Basin of Kenya (Biancone et al. 2015)).

Such observations lead to considerations of what was the geometry of the original continental fit of Africa within Gondwanaland, and as to the precise timing of breakup of Western Gondwanaland (including Africa) and Eastern Gondwanaland (including Madagascar). A variety of evidence is presented across these papers, though again no unequivocal answer is reached. Reeves, together with many others working at a plate scale, favours a tight fit of Somalia versus northern Madagascar, supported by a correlation of the Karoo rifts of Tanzania with the Sakamena Trough of Madagascar as well as other magnetic lineaments. Reeves acknowledges that large scale hyperextension is required to then move the COB to its current position, though this is somewhat greater than the beta factors calculated on the hyperextended margin of Somalia by Stanca et al. (2016). This tight fit is still problematic offshore Tanzania, as will be discussed in part two of this thematic set, and particularly in offshore Kenya, where the COB may lie outboard of the inversions around the

Fig. 1. Tectonic elements map of East Africa, derived from the papers in this compilation and multiple other sources, including Macgregor (2015).
Kiboko well, 200 km offshore Kenya (Fig. 1, Biancone et al. 2015). As yet, we have no good knowledge of crustal structure below northern Madagascar, which would comprise the ‘missing link’ here, although a seismic line published here by Davison & Steel (with the clearest indications yet seen of salt tectonics) would imply a COB that is also some distance offshore. Macgregor suggests alternative fits of Karoo rifts between Africa and Madagascar that would enable a wider fit, but at this stage the evidence between the models remains inconclusive and further data and analysis, including back-stripping on deep high-quality seismic, is required. More work is also required on onshore seismic data in Tanzania to understand the kinematics and extension directions of the early rifts, which would further help to constrain the plate tectonic models.

There seems also to be no definitive answer to the age of initial breakup between Africa and the eastern Gondwanaland continents, although the papers here seem to restrain this in time to a c. 10 Ma interval between Late Toarcian and Bajocian. Reeves interprets a Late Toarcian age for first oceanic crust between Somalia and Madagascar, although predicts that the age of the first oceanic crust may vary from this in other basins. Macgregor favours a Bajocian break-up offshore Tanzania on stratigraphic evidence. As a transform margin, similar to that on the equatorial West Africa margin, where multiple unconformities are seen corresponding to first oceanic crust and to first complete separation with South America, it may be predicted that there will be no single break-up event or unconformity across the complex East African margin.

Davison & Steel provide a comprehensive overview of our current state of knowledge of the margin between South Africa and Somalia, including the Seychelles and Madagascar. The most valuable new data presented are the numerous maps, seismic lines and cross-sections across the different frontier basins. As in the rifts, as more data are gathered, there is a trend of increased complexity evident with many basins now interpreted to be considerably deeper than once predicted, and filled with thick sediments from rift shoulders of multiple ages and eroded uplifts, such as that of the African superplume. This highlights perhaps the explorers’ prime concern along this margin, that overburdens to the rift-related source rocks will push these into the gas window, and it is notable that recent licence round awards, such as those in the Angoche Basin of Mozambique, have been concentrated in regions of diminished overburden. Davison & Steel highlight other basins, such as those in Somalia, where the overburden to Jurassic (or in some cases Cretaceous) source rocks may be diminished.

Within the second group of papers, to be published in August 2018, reviews are expected to be presented of several basins within the region, one on the effects of volcanic topography on petroleum systems within Kenyan and Ethiopian rifts, and three along the East Africa margin, on Somalia, Tanzania and the Zambezi Basin of Mozambique. In particular, we anticipate the publication of significant new deep-water seismic and well data offshore Tanzania, linking onshore to deep-water offshore areas,
helping to drive a new sequence stratigraphic model for the evolution of this part of the margin from rifting and break-up to the present.

There is thus a pattern through this compilation of increasing tectonic complexity in our interpretations of East Africa basins, which is reflected in the variety and sometimes unusual nature of the petroleum systems recognized to date. The two parts to this thematic set make progress in constraining, but not firmly resolving, some of the key tectonic interpretations, such as the COB location and original continental fit. No doubt improved models will result from further conferences and publications, as is typified by Purcell’s improvements on the East African Rift’s temporal analysis from an earlier paper by Macgregor (2015). There are still many tantalizing aspects of East African petroleum geology yet to document and we look forward to the day when this fascinating geological region becomes as well documented as other key petroleum provinces in the world. These papers represent a significant step in this process.

References