The Hydrocarbon Potential of the Ethiopian Tertiary Rift Basins

Peter Purcell[1]

Abstract

Recent oil discoveries in the Uganda's Lake Albert Rift have stimulated widespread interest in the hydrocarbon potential of the East African Rift System. Rift basins contain major oil and gas accumulations in many countries, including Sudan and Yemen.

In Ethiopia, the Tertiary rift system can be divided into three main areas: the Southern Rift Basins, the Main Ethiopian Rift (MER) and Afar. The potential for oil or gas deposits of commercial significance in these rift basins will be determined by the sediments within the rifts and the thermal and magmatic history of the rifting. Potentially prospective sediments could be either the Tertiary syn-rift sequence or older pre-rift units.

The Southern Rift Basins extend into Kenya, where seismic surveys and drilling have shown thick sediments and oil-prone Paleogene lacustrine source rocks. Similar rocks are present in Ethiopia in the rift basins near Jimma. If buried to sufficient depth, these source rocks could generate significant volumes of oil and gas. There is very little information on the subsurface stratigraphy or structure in these basins and it is not known if an effective Tertiary petroleum system is present.

Miocene lacustrine shales are known in the Main Ethiopian Rift and Afar, and Paleogene equivalents can reasonably be expected in the subsurface. The Upper Jurassic Uarandab Formation, a proven oil-prone source unit, is also expected in the subsurface of the northern part of the Main Ethiopia Rift and the Afar. Higher heat flow and burial under the thick Tertiary basalts could have matured the source rocks, with oil migrating into interbedded or juxtaposed reservoirs. The main risk is that the pervasive volcanism and the high geothermal regime will have destroyed any hydrocarbons generated in these rifts. Systematic exploration in the MER and Afar is precluded by the inadequacy of current seismic reflection surveying techniques to map sub-basalt structure, except in local areas.

Considerably more work is needed to determine the petroleum potential of the Tertiary rift basins in Ethiopia. Current work by exploration companies will add greatly to existing knowledge.

Introduction

The proximity to the oil-rich Middle East has stimulated interest in Ethiopia's oil potential for nearly a century. Most of that exploration has been in the Ogaden Basin in southeast Ethiopia, and in the Red Sea, offshore from (now) Eritrea.

In the 1980s, a series of oil discoveries in the Mesozoic/Tertiary rift basins of Sudan and Yemen caused renewed interest in Ethiopia's oil potential. Gravity data confirmed that Sudan's petroliferous Melut Basin extended into the Gambela region in western Ethiopia, with a thick

[1] P & R Geological Consultants Pty Ltd, 141 Hastings Street, Scarborough, WA 6019, Australia.
Email: peterpurcell@tpgi.com.au

sedimentary section. The Yemen rift system was thought to extend across the (reconstructed) Gulf of Aden into Somalia, and possibly into the Ethiopian Ogaden Basin. Efforts in the 1990s to locate Jurassic-Cretaceous rifts in the Ogaden Basin were unsuccessful but exploration is ongoing in Gambela Basin, with two wells drilled.

In 2005, the Australian oil exploration company, Hardman Resources Limited (Hardman) discovered oil in the Lake Albert Rift (LAR) in Uganda. Subsequent discoveries of oil and gas established the LAR as the first East African oil province and stimulated great interest in the possibility of similar discoveries in Tertiary rift basins in Ethiopia and Kenya.

This paper is a brief overview of the possibilities and problems for oil or gas exploration in the sedimentary basins associated with the Ethiopian Tertiary rift system. It is based on a presentation to the 'International Conference on the Geodynamics of Afar and the Ethiopian rifts: Geophysics, Geohazard Challenges and Resources', held in Addis Ababa, Ethiopia in November 2007[2]. The presentation was prepared primarily for geoscientists unfamiliar with petroleum geology and current exploration in Ethiopia.

Regional setting (Figure 1)

Ethiopia is located in a very 'rift-prone' region: deep Permo-Triassic and Jurassic-Cretaceous rifts occur in the subsurface and the Tertiary rifting has created the region's spectacular landscape. In several areas, the younger rifts have cut across the older rift basins, creating locally complex basin structure.

The Permo-Triassic rifting is part of the extensive rifting of Gondwana that led to the separation of the African, Indian and Madagascan plates. This so-called Karroo rifting[3] extends north through Kenya into southeastern Ethiopia, where it forms the Bodle and Shilabo troughs of the Ogaden Basin. Karroo rifting also appears to have developed along the northwest-trending Marda Fault Zone, which may have acted as a transfer zone (Purcell, 1981). Thick pre-Jurassic sediments in the Danakil Alps (Hutchinson and Engels, 1970) suggest that the Karroo basin system extended northward though Afar, where it is now obscured by the Tertiary tectonics and magmatism. It is also probable that a shallow Karroo trough extended northwest towards the Abbay Gorge region of central Ethiopia. The Karroo sediments provide source and reservoir for the Calub and Hilala gas accumulations in the south-central Ogaden Basin (Hunegnaw et al, 1998)

Major northwest-trending Mesozoic/Tertiary rift systems are well developed in Sudan and Kenya to the southwest of Ethiopia, and in Yemen and Somalia, to the northeast. The rifting in Sudan involved Lower Cretaceous, Upper Cretaceous and Lower Tertiary extensional episodes (McHargue et al, 1992), and might have commenced in the Upper Jurassic. The two main rifts in Sudan - the Muglad and Melut basins - are both prolific oil producers. The Muglad Basin lies along trend from the Anza Graben in northern Kenya, but the original connection between these rift segments, if any, has been overprinted by the Tertiary uplift and rifting. The Melut Basin extends into the Gambela region in the extreme west of Ethiopia.

[2] Comments on exploration activity in Ethiopia have been updated to September 2008
[3] The term 'Karroo' is now used widely in Ethiopia to refer to Permo-Triassic sediments and tectonism, replacing the old 'Pre-Adigrat' term.

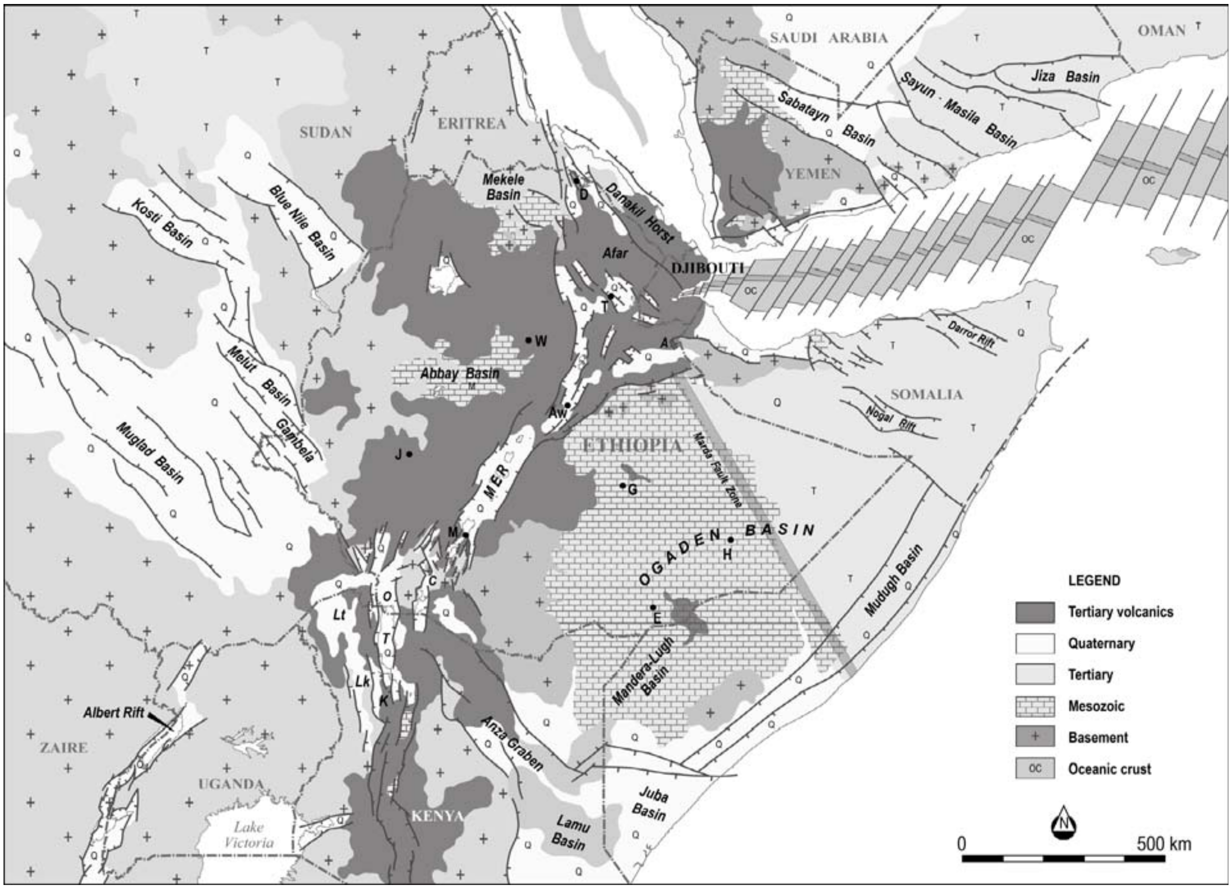

Figure 1. Regional structural setting of the Ethiopian Tertiary rift system. A = Aisha Horst, C = Chew Bahir rift, D = Dallol, E = El Kuran-1, G = Gherbi-1, H = Hilala-1, J = Jimma, ; K = Kerio Basin, Lk = Lokichar Basin, Lt = Lokitipi Basin, O = Omo rift, T = Turkana rift, W = Were Ilu seep,

The northwest-trending Mesozoic rifting in Yemen is relatively well-defined by data from oil exploration projects. The main rift occurred in the Upper Jurassic-Lower Cretaceous. In Somalia, rift episodes in the Jurassic, Cretaceous and Tertiary are recognized but remain poorly defined.

The Tertiary East African Rift System (EARS) extends through Ethiopia from the Southern Rift Basins, near Lake Turkana, to the Afar in the north. The tectonic development of the Tertiary EARS has been summarized by Chorowitz (2005), Ebinger (1989) and others, and is not reviewed in this paper. In Ethiopia and Kenya, the EARS cuts across the old rift trends and is characterized by extensive pre-rift and syn-rift volcanism.

Rift Basin Petroleum Systems

Prolific petroleum systems commonly develop in rift basins, as evidenced by the large volumes of oil and gas discovered in rift basins around the world: over 200 billion barrels by the end of the 20th Century (Morley, 1999a). Despite this, the EARS basins generally have not been considered prospective for hydrocarbons[4] - a view that is now being challenged, or at least reconsidered, by some petroleum explorationists.

[4] This negative perception applies mainly to the Eastern Branch and much less so to the Western Branch where the LAR, in particular, has been a long-standing exception.

Morley (1999a) sub-divided rift basins into three 'tectonic' categories - cratonic rift, cratonic rift with overlying sag basin, and cratonic rift on passive margin - and sub-divided those categories according to their rift-fill sequence (continental versus marine). Figure 2 shows the hydrocarbon resources discovered in these various rift settings.

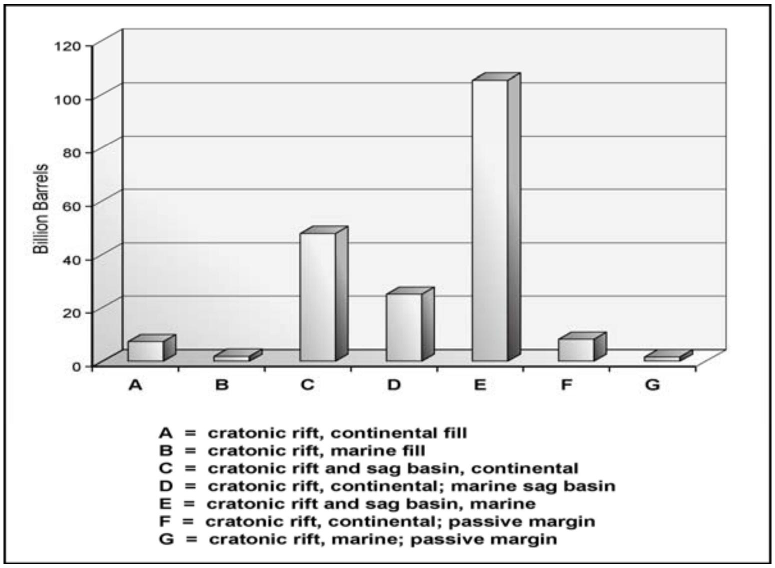

Figure 2. Oil resources discovered in rift basins, to 1999 (Morley, 1999a)

The most petroliferous rift basins are those where the rift basin is overlain by a sag basin, especially when both the rift and sag basins contain marine sediments. This is shown as Category E in Figure 2, with over 100 billion barrels of proven resources. Cratonic rifts filled with continental sediments (A in Figure 2) – the category relevant to the East African/Ethiopian Tertiary rift basins – had proven oil resources as of 2000 of about 8 billion barrels. Though smaller by comparison, this shows that there is also considerable hydrocarbon potential within continental rift basins.

In most rift basins, the critical elements in the petroleum system are the source and seal units; there are usually adequate reservoir units present. In a cratonic rift, the source and seal are provided by the lacustrine shale units that develop in the deeper rift lakes. The reservoir units are primarily fluviatile sandstones that variously underlie, overlie, and inter-finger with, the lacustrine sequences, or turbiditic sandstones within it.

Figure 3 presents a schematic cross-section of a continental rift, with a deep lake system similar to Lake Tanganyika today. There are the basal fanglomerates and sandstones developed on the basin floor and faulted flanks as rifting is initiated; an overlying shale sequence deposited in the deep lakes that commonly form during the main subsidence episodes; and, finally, a sand-dominated sequence, deposited after extension has largely ceased. Two rift pulses are shown, marked by the two lacustrine shale units, with an intervening fluviatile episode. There are also several sediment-input episodes during the first rift phase. The shale sequences grade to sandstones up the basin ramp. Mass flow sand bodies are shown in the deep-water shale sequence; these can be deposited during low stands or periods of increased sediment supply. No pre-rift sediments are shown.

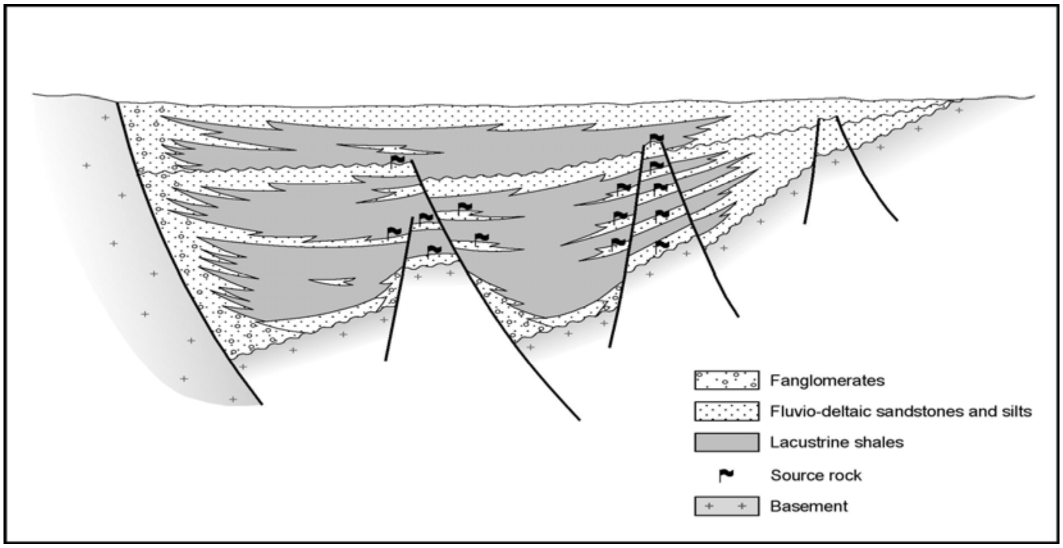

Figure 3. Schematic cross-section of a continental rift basin, showing shale and sandstone distribution, and potential oil accumulations. The lower syn-rift sequence is capped by a basin-wide sandstone unit deposited as the first cycle of extension waned. The upper rift sequence is controlled by reactivation of the main rift faults. Antithetic faults create horsts that provide typical rift basin exploration targets.

The critical element for oil generation in continental rift basins is the formation of carbonaceous muds in the anoxic conditions in the deep rift lakes. Organic material carried by rivers from the rift surrounds is mixed with algal and other microbial material from the lake itself and preserved in the reducing environment of the lake floor. This material commonly forms a Type 1 or Type 2 oil-prone kerogen, with a high wax content reflecting the terrestrial component and the high hydrogen index derived from the algal content (Kelts, 1988). With the right temperature conditions, that kerogen becomes a rich source of oil.[5]

The type and quality of lacustrine source rocks is determined by many factors, with climate, terrestrial sediment-input rate and endogenic organic productivity, among others, very important. Figure 4 shows a schematic cross-section of a deep stratified lake, with organic carbon generated endogenically from algae, zooplankton, plants, fish and other organisms. Bacteria and fecal pellets can be major components of the organic cycle in rift lakes. Detailed information on lacustrine source rocks is available in Fleet et al (1988) and Katz (1990).

Oil generated in the shales can migrate into the adjacent and overlying sandstones and, if there is an impervious sealing layer, can be trapped there. There are many possibilities for trapping, both stratigraphic and structural, and combinations thereof. Two points deserve emphasis. Firstly, there is no way to trap oil in the upper sandstone unit in a simple continental rift, such as depicted in Figure 3; this is the reason that rift basins sealed by an overlying sag-basin contain more oil resources. Secondly, the more pulses of rifting that have occurred, the more interbedded will be the sandstones and shales, and the greater the potential for trapping in stacked reservoirs - as occurs, for instance, in the Sudan rifts.

[5] Major thicknesses of source rock are not required to generate commercial-scale accumulations. A 20 m thick shale in a 200 km^2 mature oil kitchen, with 5% TOC and yield of 20 kg/tonne could generate over 3 billion barrels of oil, of which perhaps 1-5% would be trapped.

The temperature regime in a rift basin is also a critical factor in determining hydrocarbon potential; firstly, for the generation and expulsion of the oil and, secondly, for its preservation. Oil generation peaks in the temperature range 110^{o}C to 150^{o}C; gas, in the range of 150^{o}C to 200^{o}C; and by 200^{o}C, only methane is preserved.

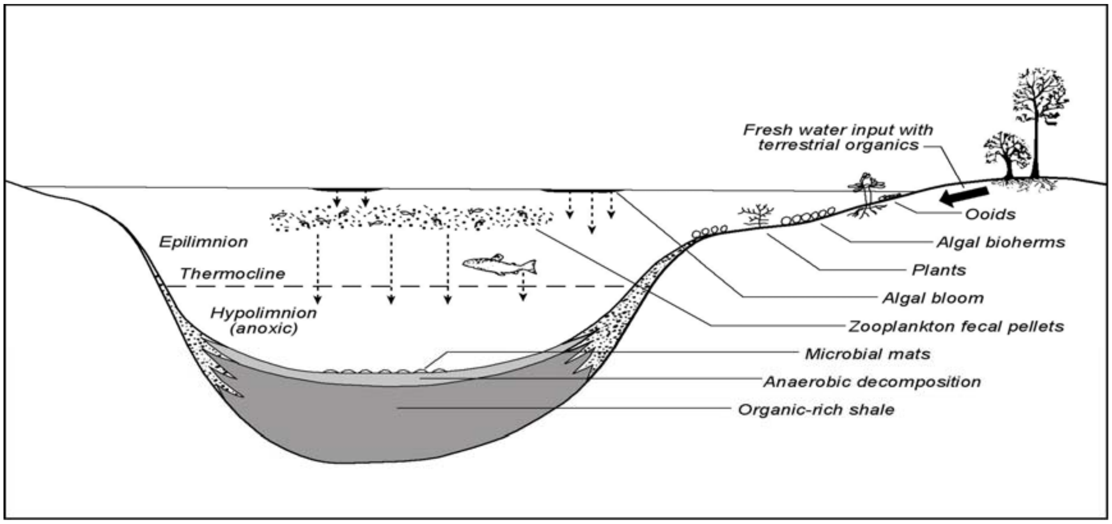

Figure 4. Schematic model of organic depositional system in deep continental rift lake (after Kelts (1988), Figure 7b and De Dekker (1988), Figure 9.)

Petroliferous Rift Basins in East Africa and Yemen

All the significant oil discoveries in East Africa and Yemen are located in rift basins. This contrasts markedly with the worldwide figure of about 6% of oil deposits being located in rift basins, and shows the importance of rift systems in East African petroleum exploration.

Only the Ugandan discoveries are associated with a petroleum system completely within a Tertiary rift sequence. In Sudan, Tertiary syn-rift sandstones and shales are reservoir and seal respectively for oil fields in the Melut Basin but the oil-source is of Lower Cretaceous age. The Yemen rifts are essentially Jurassic-Cretaceous basins and Tertiary rifting occurs only locally onshore.

This section briefly reviews the petroleum geology of the Sudan, Yemen and Uganda rift basins and oil discoveries to identify the main elements of these proven petroleum systems.

Sudan

The Muglad and Melut basins in Sudan are part of the extensive rift system that formed along the Central African Shear Zone in the Early Cretaceous and Tertiary (Binks and Fairhead, 1972). Both basins trend northwest/southeast overall and contain up to 10 km of sediments deposited in three rift episodes: Early Cretaceous, Late Cretaceous and Tertiary. Both basins contain major oil accumulations. The Southern Melut Sub-basin extends into Ethiopia's Gambela region.

The critical element in the petroleum geology of the Sudan rift basins is the Lower Cretaceous deposition of oil-prone shales in deep anoxic rift lakes, with average total organic carbon (TOC) of 2%, mainly Type II kerogen, and an average Hydrogen Index (HI) over 400. In contrast, the Upper Cretaceous and Paleogene rift cycles created only shallow lakes and the shales deposited in them are almost all oxidized, with relatively low TOCs and only limited generating potential (Dou et al, 2006).

In the Muglad Basin, the main reservoirs are Lower Cretaceous sandstones sealed by Upper Cretaceous shales. In the Melut Basin, however, the Upper Cretaceous syn-rift sequence is sand-dominated and does not provide a regional seal. Consequently, oil generated in the Lower Cretaceous shales has migrated up through the Upper Cretaceous sediments and into Paleogene sandstones, where it is trapped below sealing Eocene shales.

There is relatively little magmatism associated with the Sudan rifts. This has been attributed to the shallow depth (2-16 km) of fault detachment at the brittle-ductile boundary (McHargue et al, 1992). In the Melut's Southern Sub-basin, a layer of Senonian basalt and tuffs is well defined on seismic data (Dou et al, 2006) and has been penetrated in Sobat-1 near the Ethiopian border. This layer is reportedly present in the Gambela area.

Yemen

The oil producing rift basins onshore Yemen are essentially of Mesozoic age, with rift episodes in the Kimmeridgian-Berriasian and Hauterivian-Barremian. The main source rock is the Mabdi Formation, a deep-water carbonaceous shale sequence deposited during the Kimmeridgian to Tithonian. Oil is reservoired in pre-rift, syn-rift and post-rift sediments, as well as in fractured basement.

Ray Fairchild (1992), head of the Hunt Oil team who discovered the Yemen rifts, called them 'a gift of the Gods', referring in part to the serendipitous juxtaposition of source, reservoir, seal and trap formation. In the Alif Field, for instance, fluvio-deltaic sands overlie the Mabdi shales and are sealed by salt layers that were precipitated in the hypersaline waters in the isolated rift depression. Cyclic deposition of low-stand sands and high-stand salt layers has provided stacked reservoir-seal pairs (Ellis et al, 1996). In the Masila Rift, the Upper Jurassic salt is missing, allowing the oil to migrate up into thick post-rift Cretaceous sandstones which are sealed by tight limestones (Bosence, 1997). Elsewhere, the renewed rifting in the Hauterivian juxtaposed the Madbi source against pre-rift Lower Jurassic reservoirs.

Tertiary rifting occurred onshore Yemen in association with the development of the Gulf of Aden and the Red Sea, and has been separated into three phases (Ellis et al, 1996). The onshore Balhaf and Ad Dall grabens are Oligo-Miocene reactivations of the Mesozoic rift trends but have not proved to be petroliferous.

The Gulf of Aden and Red Sea basins in Yemen were both initiated as continental rifts, with Mesozoic pre-rift sediments buried under Tertiary syn-rift sediments. Both basins have yielded encouraging oil shows but no commercial discoveries have been made.

Uganda

Long known for its thick sediments and many oil seeps, the Lake Albert rift has been the site of occasional exploration since the 1930s but there had been little activity for decades before this recent success.

Since Hardman's 2005 Mputa-1 oil discovery[6], there have been five discoveries (Figure 5) by Tullow Oil Limited[7] (Tullow) in the Lake Albert basin, or Albertine Graben, as it is commonly known in Uganda. Tullow Oil (2007) estimates proven reserves to be 100-250 MMbbl and, based on the many undrilled leads in their Lake Albert permits, predicts ultimate resources for the basin of the order of 1 billion barrels.

The drilling in Lake Albert has confirmed the presence of interbedded mature oil-prone source rocks and thick sandstone reservoirs. The sandstones are both fluvio-deltaic and turbiditic in origin, with porosities ranging to 30% and permeabilities of 200-8000 millidarcies (mD). The shales are deep-water lacustrine facies, with TOCs of 6-7%, mostly of algal origin, and yielding a low- sulphur, light oil (35^{o} API). A variety of successful plays have been defined (Tullow Oil, 2007): a) structural /stratigraphic traps with cross-fault seals against shales (Nzizi-1) or basement (Waraga-1; Mputa-1), b) fractured basement (Mputa-1) and c) turbidite sands (Mputa-2).

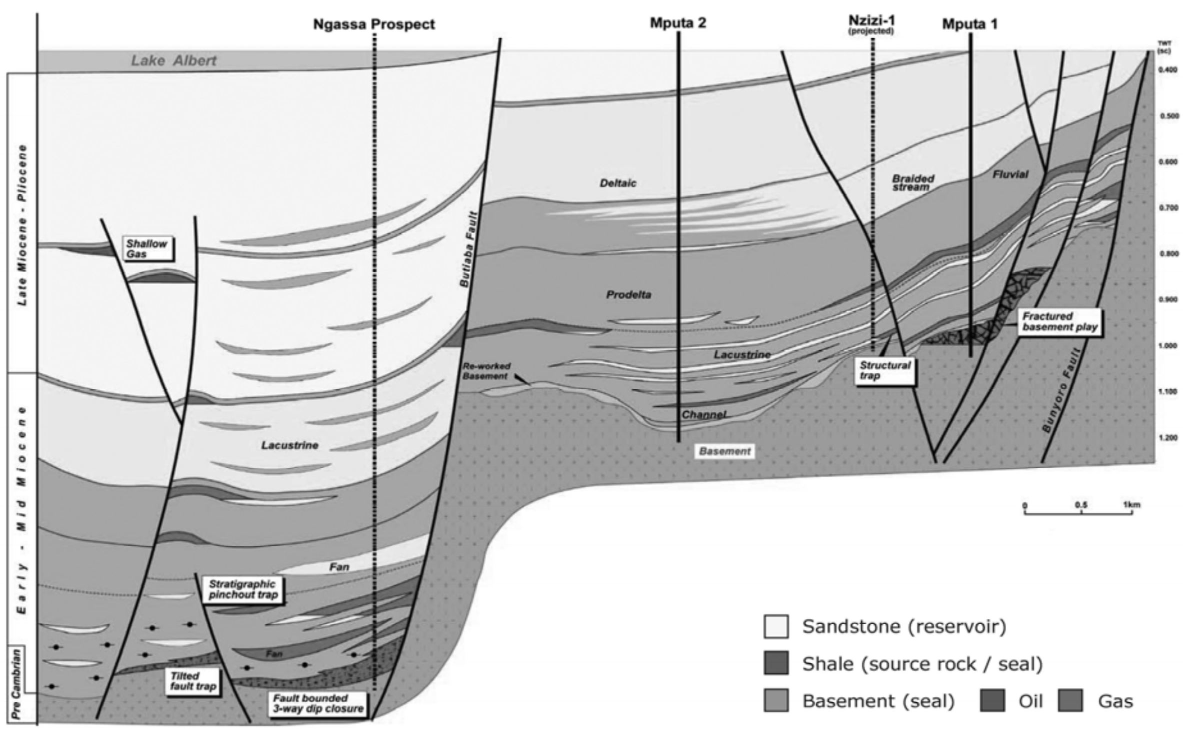

Figure 5. Schematic cross-section, Lake Albert Basin, showing the sedimentary section, oil discoveries and interpreted structural and stratigraphic traps (Tullow Oil, 2007). Note a) the lack of volcanics; b) the very minor basal sandstone layer, suggesting rapid subsidence, with a deep lake forming very early in the rift episode and c) the importance of cross-fault seals against shales and basement in controlling the oil accumulations.

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[6] Heritage had discovered gas in Block 3 in the Albertine Graben in 2003/4, but the very high CO_2 content (80+%) made the deposit uncommercial.
[7] Tullow Oil Limited took-over Hardman Resources in 2007 and became the operator in Block 2

The crude has a pour point of 39^{o}C, and maintaining this temperature during the production, trucking and piping of the oil will be a significant operational challenge. Tullow has announced plans to commence production in 2009 at 4000 bbl/day, with half being trucked to Kampala and the other half used to run a 50 Mw power plant (Tullow Oil, 2007).

Ethiopian Rift Basins

The Tertiary Rift System in Ethiopian extends NNE from the Omo/Turkana region in the south, through the Main Ethiopian Rift segment, then 'opens' into the Afar Depression, with its links to the active spreading centres in the Gulf of Aden and the Red Sea. This provides a natural sub-division of the Ethiopian rift into three segments: the Southern Rift Basins, the Main Ethiopian Rift and the Afar. The Gambela rifting in western Ethiopia is not the main focus of this paper but is also discussed briefly.

An analogy to the Albert Rift is commonly cited as evidencing the hydrocarbon potential of the Ethiopian and Kenyan rifts. Certainly, all are segments of the greater East African Rift System, but significant differences in the tectonic development and volcanism have long been noted between the Eastern Rift, which includes the main Ethiopian and Kenyan rifts, and the Western Rift, of which the Lake Albert graben is an element. Notable among the differences is the apparent localization of volcanism in the Western Rift, mainly at offset zones between rift segments (e.g. the Katwe-Kikorongoro volcanic complex between the Lake Edward and Lake George rifts), in contrast to the extensive pre-rift and syn-rift volcanism characteristic of much of the Ethiopian rift system. Ebinger (1989) noted that the differences between the Western and Kenyan rifts 'largely can be interpreted as differences in the time span of volcanism and stage of development'. Smith (1990) inferred better source rock development in the Western Rift because the lakes there were larger and deeper than in the Eastern Rift where the extensive volcanism had led to smaller drainage basins and shallower lakes.

The presence of volcanics in a basin does not preclude petroleum deposits, of course. There are numerous basins that contain volcanic or intrusive complexes but also have substantial oil production. In some instances the volcanics are even part of the petroleum system: in the Takutu Rift in Guyana, for example, fractured basalts are the producing reservoir, sourced by the overlying lacustrine shales (Webster, 2004). Also, the presence of volcanics in and surrounding the rift can enhance source rock development: chemical influx from alkaline volcanic ash areas creates high salinity and phosphorous levels which support high zooplankton and algal productivity (Kelts, 1988).

Ultimately, the potential for commercial oil or gas deposits in the Ethiopian rift segments will be determined by their respective structural, stratigraphic and thermal histories, as has been noted above for other rift basins in the Horn of Africa region. This history will include not only the syn-rift section but also the pre-rift and post-rift sequences.

Southern Rift Basins

'Southern Rift Basins' is a collective term used in Ethiopia for the Chew Bahir and Omo rifts, and their poorly understood extensions to the north – though not including the shallow coal-bearing rift basins of the Jimma area (Wolela, 2004). The Omo Rift extends into Kenya where it is known as the Turkana Rift. These roughly north/south-trending rifts cut across the NW/SE trend of the Muglad and Anza rifts of Sudan and Kenya respectively. Bouguer gravity data clearly define the Kenya basins (Figure 6) and should be a useful tool for mapping the rift structure and sediment thickness in Ethiopia.

There is no subsurface stratigraphic information available for the Omo and Chew Bahir rift basins in Ethiopia. Predominantly arenaceous sediments in two northwest-trending faulted depressions have been dated as Permian (Davidson and Macgregor, 1976). Other sediments below the Tertiary basalts are reportedly interpreted as Cretaceous in age. Coarse-grained sediments of Late Cretaceous age unconformably overlie basement in the Turkana region in Kenya (Williamson and Savage, 1989) and have been interpreted as signaling the onset of rifting.

The potential for a significant thickness of pre-rift sediments in the Southern Rift Basins is unclear. If the Anza Graben was originally continuous with the Muglad rift system, then the Paleogene rifting might have down-faulted and preserved Cretaceous sediments which were otherwise eroded during the Upper Cretaceous/Lower Tertiary uplift. Alternatively, the Muglad and Anza rifts might have been connected only by a transfer zone, as proposed by Bosworth (1992), with no significant Cretaceous rifting or sedimentation in this area. Ebinger and Ibrahim (1994) inferred from gravity evidence that the Anza Graben extended into the Turkana area, but the anomaly could as easily be explained by Tertiary sediments.

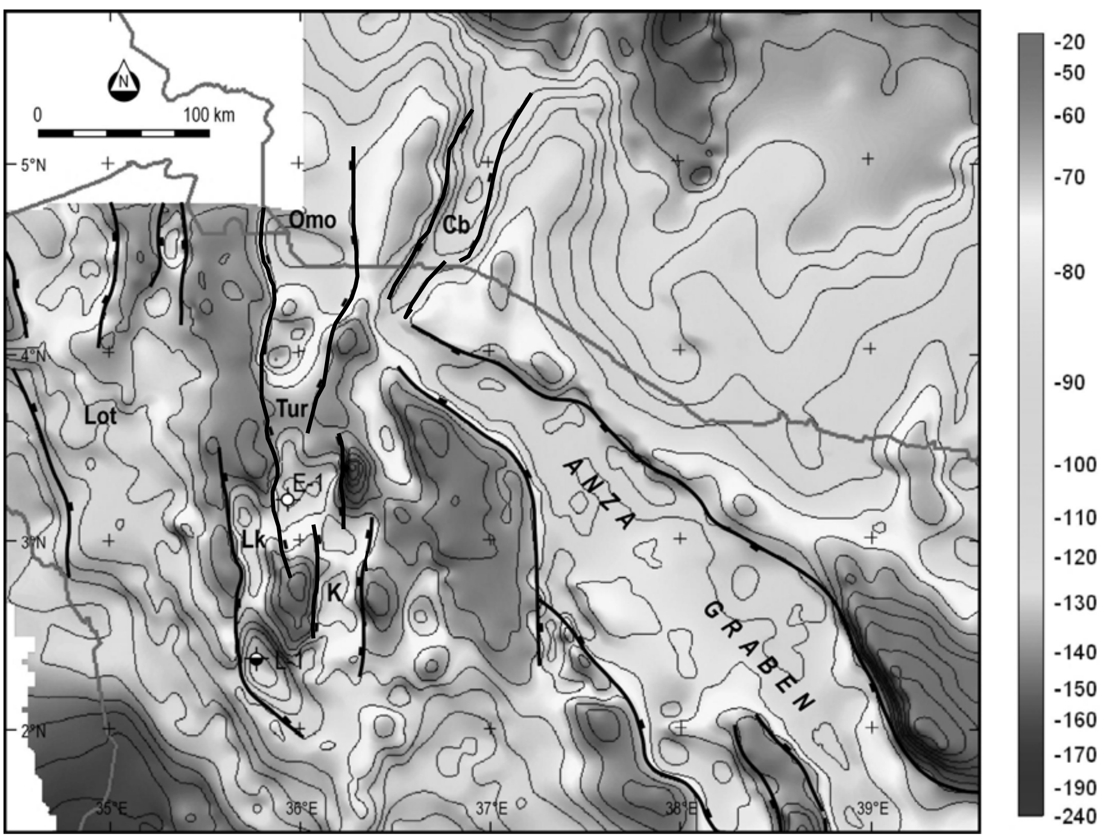

Figure 6. Bouguer gravity map of NW Kenya and SE Ethiopia, showing the Cretaceous (NW/SE) and Tertiary (~N/S) rift defined by gravity minima. Cb= Chew Bahir; Tur = Turkana; K = Kerio; Lk = Lokichar; Lot = Lokitipi; L-1 = Loperot-1; E-1 = Eliye Springs-1.

Some insight into the syn-rift sequence in the Ethiopian basins might be taken from the contiguous Lockichar, Kerio and Turkana basins in Kenya: seismic data, two deep oil wells and outcropping sediments reveal extreme stratigraphic variability, complex internal structure and evidence of major inversion tectonics in the Mid Miocene and latest Pliocene. Significantly, however, mature lacustrine oil-source shales are proven in the southern Lokichar Basin, an east-dipping half-graben containing over 7 km of sediments. Loperot-1, on the basin ramp, encountered Miocene to Eocene sediments, with thermally mature (Ro=1.1%) Oligo-Eocene shales. Testing recovered a small amount of waxy oil and water from Miocene sandstones with limited reservoir potential. (Morley, 1999b). A seismic cross-section of the basin, showing the interpreted stratigraphy and the Loperot-1 well, is presented in Figure 7.

In the North Lokichar Basin, the Oligo-Eocene section, deposited in an east-dipping half graben and inverted in the Miocene, is seen in outcrop to be predominantly interbedded volcanic flows and sediments. In the Turkana Sub-basin, Eliye Springs-1 drilled Pliocene-Upper Miocene sediments (Morley et al, 1999b), with only thin oxidized lacustrine shale beds in the Miocene section. In the Kerio Basin, thick Mio-Pliocene sediments have been interpreted on seismic data and a deeper Paleogene sequence has been inferred from outcrop evidence. Paleogene sediments have also been interpreted on seismic evidence in the narrow north-trending basins below the Lokitipi Plain near the Kenya/Sudan border. (Wescott et al, 1999). The presence of Paleogene shales that formed in deep-water lakes early in the rift development may well be the key to successful oil exploration in these basins.

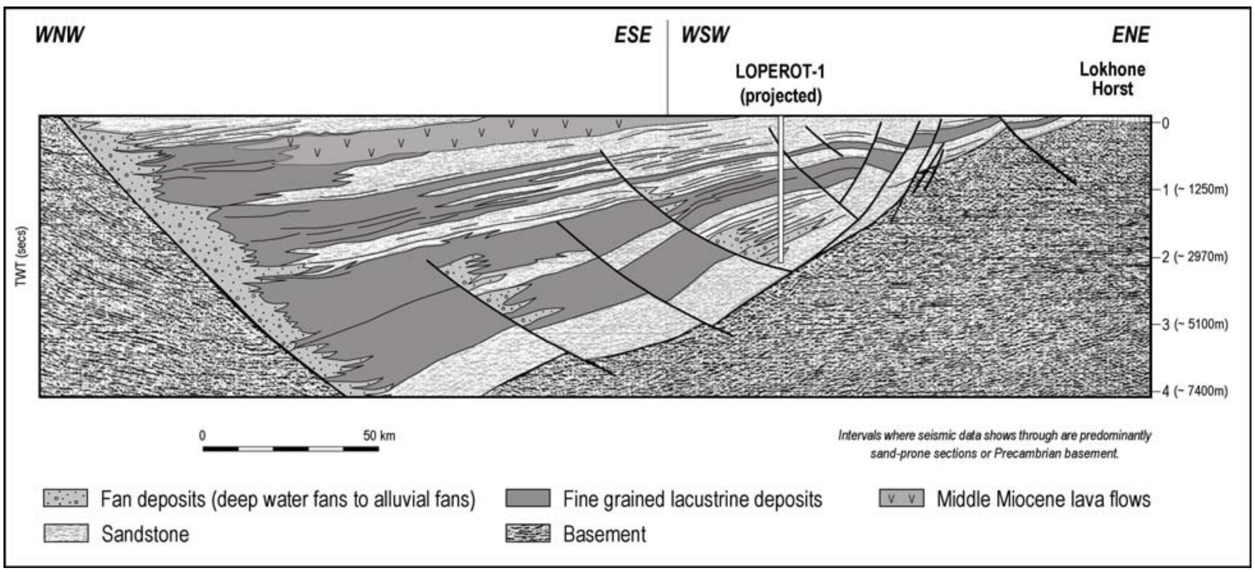

Figure 7. Interpreted seismic cross-section, South Lokichar Basin, showing the Loperot-1 well (Morley, 1999b). The scarcity of structural traps is clear and cross-fault sealing by juxtaposition of sands and shales appears the main trap-type.

Shallow NNW-trending rift basins near Jimma (Wolela, 2004; 2006) may also offer clues to the basin-fill sequence in the Omo and Chew Bahir basins. Significantly, these basins contain oil-prone source rocks that could, if buried deeply enough, generate significant volumes of oil.

In the Delbi-Moye Basin, two sedimentary sequences are present between basalt layers. The lower sedimentary formation is about 280 m thick and contains two layers (60 m and 20 m thick) of dark brown to black oil shale and sapropelic mudstone. The lower oil shales are dated palynologically as Eocene to Miocene (Wolela, 2004) and are equivalent to the Paleogene shales in the Lockichar Basin. Other small oil shale basins occur in this region. All these oil shales were deposited in anoxic conditions in deep stratified lakes. The organic content is dominantly Type I/II kerogen, predominantly liptinite, derived from planktonic algae, and herbaceous material. TOC ranges from 1.4% to 61%, with over 65% of samples having HI>400 and ranging to 1100; yield is estimated at up to 237 kg/ton (Wolela, 2006). These oil shales are thermally immature, generally 0.3-0.5%Ro, ranging to 0.68%, but have the potential to generate large volumes of oil if similar sediments are present at thermally mature levels in the Southern Rift Basins.

The possibility of oil-prone lacustrine Paleogene source units in the Southern Rift Basins is very encouraging. The thermal maturity of any such shales will be determined by the depth of burial and constitutes one of the main risks for exploration in these basins. The limited gravity data available in Ethiopia suggest that the Omo Basin will have basement depths comparable with the Lake Turkana basin in Kenya, where over 4000 m of sediment occur. Hautot et al (2007) reported basement depths of about 4000 m in the southern Omo Basin on the basis of gravity and magnetotellurics surveys, shallowing to 2000 m at the northern end.

The other risks for exploration in the basins will be a) the presence of structural traps capable of holding commercial-size oil accumulations and b) excessive volcanism. Dunkleman et al (1989) suggest that the widespread volcanism of the Turkana Rift in Kenya was related to the thinner, warmer crust there, and constituted a fundamental difference between the Turkana Rift and the Western Branch rifts such as LAR and Lake Tanganyika Rift.

The results of current exploration work in these areas by White Nile and Southwest Energy, discussed below, will be of great interest.

Main Ethiopian Rift

The Main Ethiopian Rift (MER) extends from the Lake Margarita rift segment in the south to near Awash in the north, where the rift 'opens' into Afar. Extensive volcanism preceded and accompanied the rifting which appears to have commenced approximately 35 My ago, contemporaneous with the Paleogene rifting in Kenya, although Ebinger et al (1989) and others now favour a younger age (~20 My) for the onset of rifting in the Main Ethiopian Rift.

There has been no significant exploration for oil or gas deposits in the Main Ethiopian Rift. In fact, the intense associated volcanism, with inferred high temperatures, has been seen historically as detrimental to any hydrocarbon potential. The question of the moment is whether a more optimistic interpretation is now warranted, at least in local areas.

There is the potential for both syn-rift and pre-rift source rocks in the subsurface of the MER. By analogy to the Jimma oil-shale basins, there is potential for Paleogene lacustrine shales in the MER, as well as younger units. The lakes in the MER today are only remnants of more extensive Plio-Pleistocene lakes (Tiercelin and Lezzar, 2000): the Lower Pliocene Chorora Formation, for example, was deposited in a lake covering over 1000 km^2 (Sickenberg and Schonfeld, 1975). It is reasonable to postulate, therefore, that extensive lakes might have been present in the MER during the Paleogene, with deep anoxic waters where algal and other organic matter was preserved. The high heat flow rates associated with the rift valley could have generated oil from any such source rocks.

The MER also contains over 2000 m of pre-rift sediments of Jurassic and Cretaceous age, including high quality Upper Jurassic oil-prone source rocks, at least north of about Lake Langanno. These sediments are exposed on the uplifted and eroded flank of the Ogaden Basin (Figure 1), which forms the southeast shoulder of the MER. Prior to the downwarping and faulting into the rift, the Ogaden Basin sequence was part of a vast Mesozoic basin extending across most of central and northern Ethiopia (Purcell, 1981). Basement refractor (6.0 km/sec)

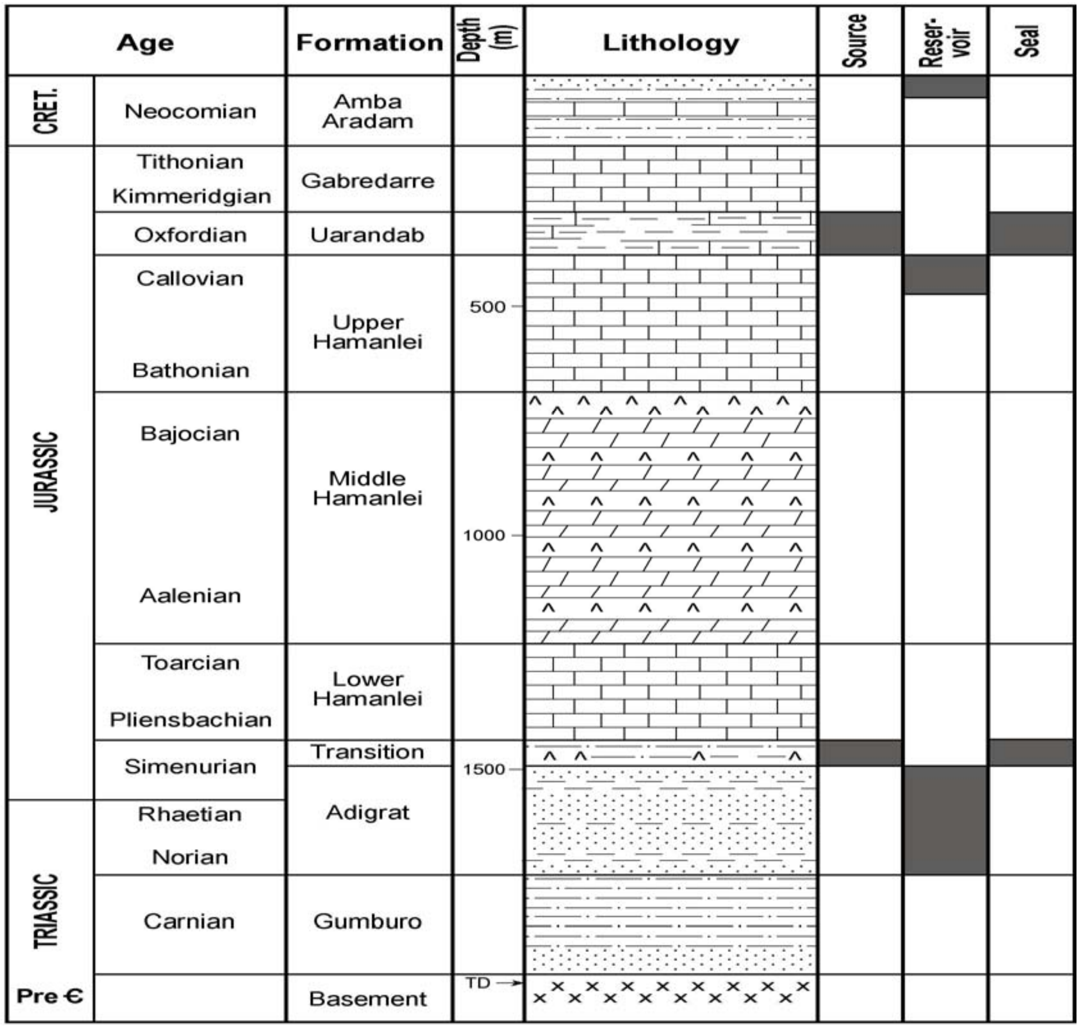

Figure 8. Generalized stratigraphic column for the western Ogaden Basin, based on Gherbi-1 well, drilled by Tenneco in 1974. The location of Gherbi-1 is shown on Figure 1.

depths of 4-6 km in the Awash-Hertale area (Berckhemer et al, 1975) can be interpreted in terms of a thick ‘Ogaden sequence’ buried under the Tertiary volcanic and sedimentary syn-rift units. Figure 8 shows the Ogaden Basin sedimentary sequence encountered in the Gherbi-1 well about 200 km from the MER but, nonetheless, a reasonable analogue for the section likely to be present in the bottom of the rift beneath the thick volcanic layer.

The Uarandab Formation is Oxfordian/Early Kimmeridgian in age and over large areas of the Ogaden is potentially a world-class source rock, with TOCs exceeding 9%, HIs of 800+ and yields of 20 kg/tonne (Hunegnaw,1998). The main oil source facies comprises deeper-water shales and argillaceous limestones. Figure 9 shows the Oxfordian paleogeography during the maximum flooding of eastern Africa and suggests that this source facies may have been deposited over large areas of what is now the MER and Afar.

Oil has been generated from the Uarandab shales in the deeper Ogaden basin axes, as demonstrated by oil recoveries in wells such as Hilala-4 and El Kuran-1, and the oil seeps and shows. Over most of the Ogaden Basin, however, the Uarandab Formation is immature for oil

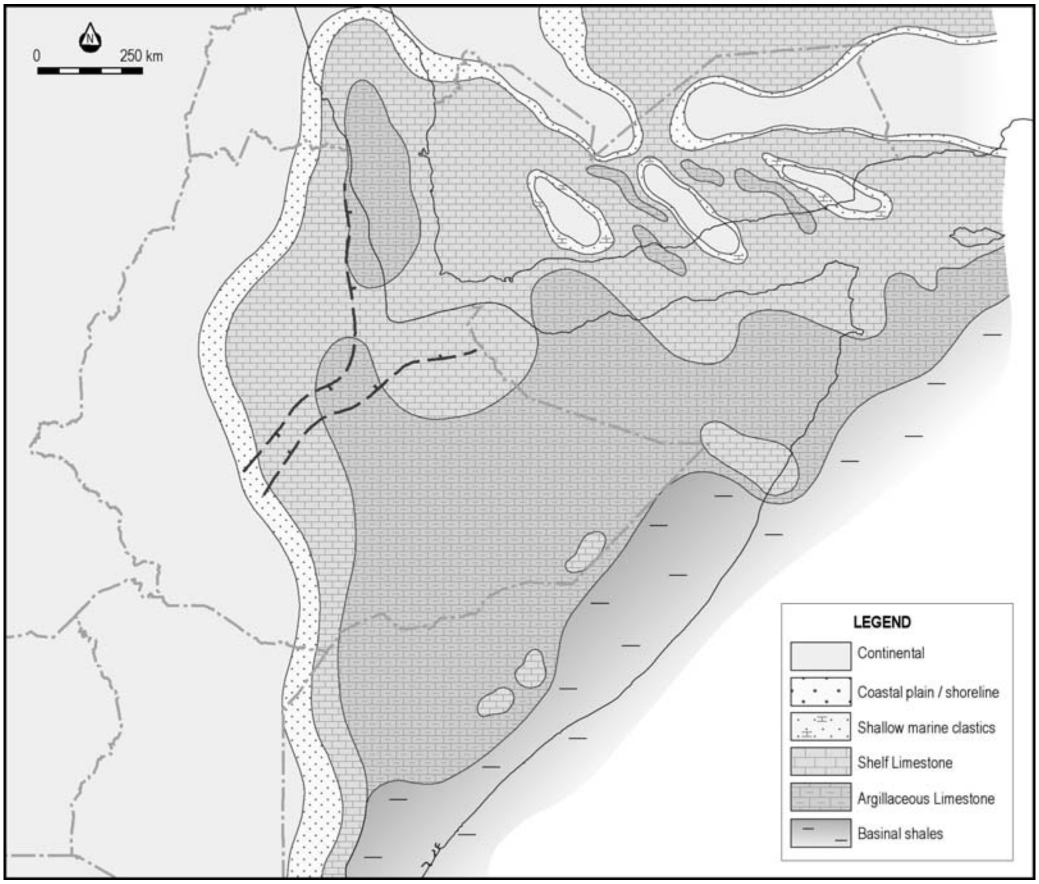

Figure 9. Paleogeography of the Horn of Africa and Yemen region during the Oxfordian flooding. The margins of the MER and Afar are shown schematically. This reconstruction of the Red Sea and Gulf of Aden does not accept any overlap of Precambrian basement outcrops in Yemen and SE Afar and, consequently, is significantly more 'open' than most published reconstructions.

generation and expulsion: it has not been buried deeply enough and has been uplifted during the Cretaceous and Tertiary tectonism.

Figure 10 is a very simplified schematic cross-section of the MER, showing the Mesozoic Ogaden sequence down-warped and faulted into the MER where it is buried under about 2000 m of Lower and Upper Trap volcanics and interbedded fluvio-lacustrine sediments, including oil source shales. Upper Miocene lacustrine sediments are shown below the Pliocene silicics.

Ideally, the extra burial will have matured the Uarandab shales and the expelled oil will have migrated into adjacent or overlying reservoirs. Equally, the higher heat flow and intrusives will have matured the syn-rift Tertiary shales, which could source juxtaposed Mesozoic reservoirs as well as interbedded Tertiary sandstones.

Historically, the consensus view has been far from that ideal: the volcanism and high heat flow have been considered destructive of any oil potential in the MER. Subsurface temperatures measured in the MER reveal 270^{o}C at 1000 m at Aluto/Langanno and 315-335^{o}C at 2200 m at Tendaho in the MER/Afar transition (Tsegaye, 2000). Such temperature levels, if widespread, will have destroyed most of any oil generated as well as any porosity and permeability in sandstone and carbonate units.

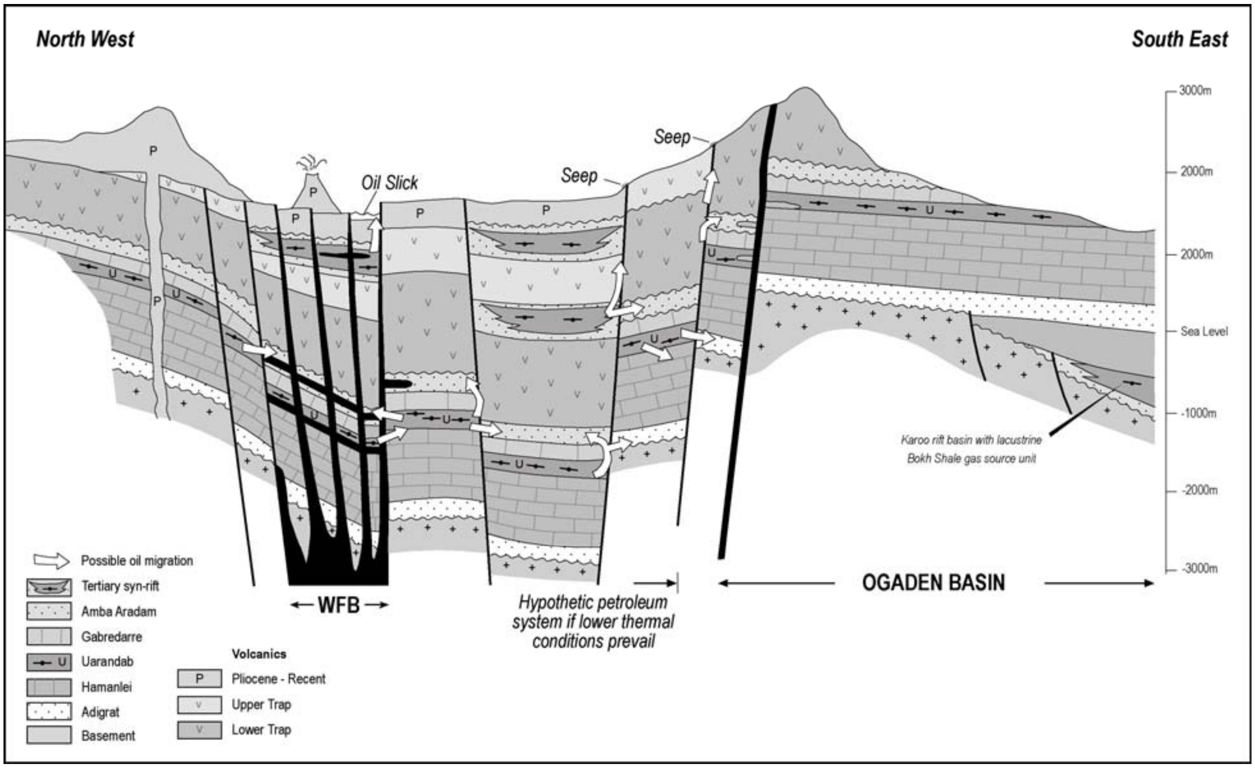

Figure 10. Schematic cross-section of the Main Ethiopian Rift at about 8^{o}N, showing Mesozoic pre-rift section and syn-rift igneous and sedimentary units. Note that the section is idealized to show the main intrusive core restricted to the Wonji Fault Belt (WFB) , here placed on the western side of the rift, with Mesozoic and Tertiary sediments in central and eastern areas generating oil because of depth of burial and higher heat flow, and relatively unaffected by magmatic intrusions. A less optimistic view would show intense magmatic activity across the entire rift and all hydrocarbon potential destroyed by the associated high temperature regime.

However, both these hydrothermal exploration wells targeted known ‘hot-spots’ in the rift, and the high temperatures encountered should not be generalized over the entire rift (Getahun Demissie, personal communication). It may be, for instance, that the higher temperatures and intrusions are concentrated along the Wonji Fault Belt (Mohr, 1967), as shown schematically on Figure 10, and that elsewhere within the rift there are relatively cool, un-intruded areas that have oil potential. Only future investigation of the rift subsurface can address that uncertainty

Unfortunately, geophysical technology does not yet permit economic exploration for oil accumulations beneath the thick volcanics in the MER. There has been considerable progress with seismic exploration below surface basalt in the past decade, especially in the Faroe Island/Shetland basins in the North Atlantic. Long offsets (>10 km), integration of P-wave and S-wave data and high effort processing have given marked improvements in sub-basalt imaging (Fruehn, 2006). However, all significant progress to date involves marine surveying in areas with sediment cover on the basalt; equivalent breakthroughs have not yet been made on land (Ziska, 2006). Magnetotelluric surveying can define basement depths below the volcanics but not with sufficient local detail or accuracy to identify commercially-acceptable drilling prospects.

Afar

The Afar region has not been associated historically with petroleum exploration, being far better known for its volcanism and tectonism.

The Were Ilu oil seep is sometimes cited in general support of the oil potential of Ethiopian rift areas such as Afar. Geochemical analyses have shown that anoxic marine shales are the likely origin of the oil (Harriman, 1992), prompting speculation that the source unit is deeply buried Jurassic shale. It is not clear, however, that the Were Ilu seep, located as it is on the Ethiopian Plateau near the erosional 'Abbay Basin' outcrops (Wolela, 2007), offers any insight into the oil potential of Afar.

Oil 'seeps' consisting of tar-like material and small pools of paraffin were reportedly found along the Afar axial zone near Dallol by BHP Billiton geologists in 2007 (Oil and Gas Journal, 2008) . The results of the sample analyses are not available but, based on the hydrocarbon content of hot springs and fumaroles elsewhere in Africa and other countries, can reasonably be expected to show thermogenic hydrocarbons. Darling (1998) has noted that hydrocarbon gases are 'ubiquitous in the hydrothermal systems of the EARS', based on analyses from Kenya, Ethiopia, Djibouti and Uganda.

Oil seeps were first reported in Afar near Teo hot springs, south of Tendaho in 1888 by an Italian Somaliland official travelling overland through the region. Over subsequent decades, these indications apparently grew into reports of 'asphalt lakes', prompting the Italian national oil company AGIP to mount a major expedition to the area in 1938 (Kalb, 2001). No indications of hydrocarbons were found.

Oil and gas seeps can be generated in volcanic provinces by geothermal processing of organic material in shallow lacustrine sediments, and need not be in any way indicative of commercial oil potential. Oil seeps within the Uzon Caldera in Kamchatka, Russia (Bazhenova et al, 1998), for example, are known to have formed in the past 1000 years by geothermal conversion of Pleistocene lacustrine algal/bacterial detritus (Simoneit et al, 2008). Oil seeps in Afar, if proven, will obviously demonstrate that some hydrocarbons have been generated in those local areas but any inferences regarding the commercial oil potential of the region need to be drawn with caution.

That said, the basic elements of the Afar 'basin' are essentially the same as shown for the MER on Figure 10: a downwarped and faulted Mesozoic basin buried under Tertiary volcanics and sediments, with an extensive intrusive system. Mesozoic sediments are 1500+ m thick on the western Afar margin near Mekele (Martire et al, 1998) and about 3000 m thick in the Danakil Alps[8] on the eastern flank (Hutchinson and Engels, 1970). The presence of source and reservoir units in this pre-rift sequence, while unproven, can reasonably be expected, given the Jurassic facies observed in the Danakil Alps (Sagri et al, 1998). The paleogeographic map of Figure 10 shows a deeper-water trough in the Afar region during the Upper Jurassic, with good potential for deposition of oil-source facies.

One seeming enigma of the Afar area is the widespread occurrence of refractors of 6.0-6.2 km/sec at 2-3 km depth (Berckhemer et al, 1975). This would likely constitute economic basement from an oil exploration perspective and appears anomalously shallow given the thickness of volcanics and Mesozoic sediments that are commonly projected below the Afar surface.

[8] The nearly 1800 m of arenaceous sediments underlying the Jurassic Antalo Formation includes both Adigrat and Karroo units, apparently indistinguishable, and with the basal section possibly of Permian age.

There is also the potential for syn-rift lacustrine shale deposition in the Afar, as discussed for the MER, and the high thermal regime can be expected to rapidly mature any oil-prone source units. As in the MER, the concern is that the thermal conditions associated with the Afar tectonism and magmatism will have destroyed any oil generated in the pre-rift or syn-rift units. The drilling at Tendaho, albeit targeting geothermal maxima, shows that very high subsurface temperatures destructive of oil deposits occur in the Afar region. Conversely, however, there may be local areas that are relatively cooler and un-intruded, and which retain hydrocarbon prospectivity. For instance, Precambrian and Mesozoic sediments outcrop in what is geographically the southeast corner of Afar, in an area commonly referred to as the Aisha Horst (Black et al, 1972). This structural province seems to be the eastern shoulder of the Afar 'rift', analogous to the Danakil Alps to the north, though not a continuation of it. This area is the site of current exploration work by Lundin Petroleum, as discussed below.

Gambela

The Gambela Basin, effectively the southern end of the Southern Sub-basin of the Melut Basin of Sudan (McHargue et al, 1992), is a Cretaceous/Tertiary rift basin. There is little information available regarding the subsurface structure and stratigraphy of the Gambela Basin.

Gravity surveying in the 1980s suggested, by analogy to gravity minima in Sudan, that over 6 km of sediments are present in the Gambela Basin. Petronas Carigali has conducted seismic reflection surveys and drilled two wells since 2003. No significant shows were reported.

The critical factor for the Gambela Basin, as demonstrated elsewhere in the Melut Basin, is the presence of Lower Cretaceous oil-prone lacustrine shales in the basin centres. The main concern with the Gambela Basin is that its location near the southeastern end of the Melut rift system carries a higher risk for predominantly fluviatile and shallow lacustrine facies, with limited source and seal units. However, the depth of the basin, based on the gravity data, encourages cautious optimism that thick lacustrine shales are present. Oil has been found in the Melut Basin in Sudan within 70 km of the border.

Current Exploration Activity in Tertiary Rift Basins

The current worldwide petroleum exploration surge, driven by record high oil prices, includes renewed interest in Ethiopian and East African basins, after many years of inactivity. Several companies are conducting exploration programmes or studies over Tertiary rift basin areas in Ethiopia. In several instances, this exploration is focussed on the Tertiary rift sequence; in other cases, the exploration interest is in underlying Mesozoic sediments. The location of the exploration and study areas are shown on Figure 11.

Results of the surveys and studies in these areas are all confidential but there is some information in the public domain as a result of company press releases, Ethiopian Government statements and a few publications.

White Nile. White Nile Ltd, a publicly-listed British company, signed a Petroleum Production Sharing Agreement (PPSA) over a large area of the Southern Rift Basins in January 2008. White Nile had previously held a two-year Joint Study Agreement (JSA) over this region. Structural mapping and magnetotelluric and gravity surveys were reported to have revealed 'deep basins, potentially containing sedimentary sections similar to that of the petroliferous

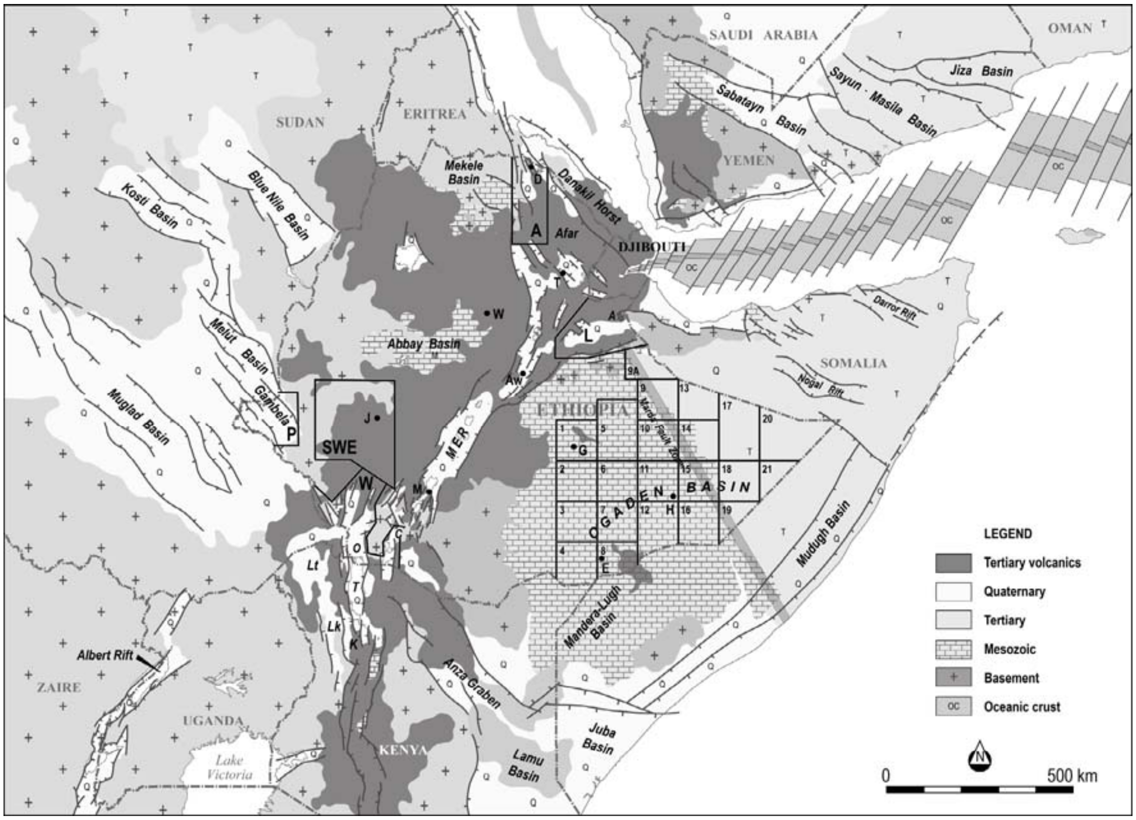

Figure 11. Petroleum exploration permits and study areas in Ethiopia, July 2008. A=Afar Exploration; L=Lundin; P=Petronas Carigali; S=Southwest Energy and W=White Nile

Muglad and Melut Basins of Southern Sudan'. White Nile reportedly plans to conduct seismic operations prior to drilling (gulfoilandgas.com 16/1/08).

Lundin. Lundin was awarded a PPSA in 2007 over the Adigala area in the southeast Afar, between the southern Afar escarpment and the Djibouti border. Regional gravity data, processed to define the Isostatic Residual Gravity field, revealed an east/west-trending system of gravity minima, extending from the Adigala area to the Berbera Basin in Somaliland (Lundin, 2008), where the well-known Daga Shabel oil seep is located. Lundin acquired airborne gravity and magnetic data over the area in late 2007. These higher resolution data show two gravity lows, which have been interpreted as probable Jurassic basins. Cretaceous reservoirs and potential Jurassic source intervals, exposed in the uplifted highlands to the south and east, might be present at prospective depths in the Adigala area (Lundin, 2008).

This area is politically part of the Afar but geologically quite distinct, being continuous with the major basement block extending west from Somaliland. The relationship between the Afar volcano-tectonic province and the Aisha Horst is not understood: the enigmatic Marda Fault Zone (Purcell, 1976) might be the controlling structure. Lundin reportedly plans to conduct seismic surveying in the Adigala block in 2009. The results of this work, when available, will be of great interest for geologists working on the Afar region.

Southwest Energy. Southwest Energy (SWE) signed a Joint Study Agreement in late 2007 covering part of the rift basin system in the Jimma area, with its well known oil shales (Wolela, 2006), as discussed above. SWE have completed photogeological and field studies, as well as gravity and geochemical surveys. The results reportedly confirm Type I/II kerogen and further work is planned to better define the rift structure, oil shale distribution and thermal maturity

(SWE, 2008). The relationship between the Jimma rifting and the Southern Rift Basins and MER is not well defined and the SWE work will be a valuable contribution to the knowledge of the Ethiopia rift basins.

Afar Exploration. A PPSA over the Dallol region of the Afar was granted in March 2006 to Afar Exploration Company, a company owned by American William Athens and which had previously held a 'petroleum exploration agreement' over this area in the mid 1990s (Horn of Africa Bulletin, 1994). This long-standing interest originates with Athens' father, who believed that a well drilled near Lake Dallol by AGIP had blown-out, with both gas and condensate.[9] Afar has conducted an aeromagnetic and gravity survey of the area and announced the 'discovery' of an evaporite basin approximately 4600 m deep, with Miocene and Cretaceous reservoirs at 1500 m and 2700 m respectively (Oil and Gas Journal, 2008)[10]. The main area of interest is said to be the Dallol salt dome where seeps were discovered in 2007. Afar's stated expectation of recoverable oil 'in excess of 6 billion barrels' (op cit) is not based on any subsurface data and must be considered highly speculative. Seismic surveying is planned for early 2009[11]. If completed, these data have the potential to greatly improve understanding of the Dallol area.

Conclusion

Rift basins contain major oil and gas accumulations in many countries. The recent oil discoveries in the Lake Albert rift in Uganda have sponsored renewed speculation about the oil potential of Ethiopia's Tertiary rift system. The structural, stratigraphic and magmatic history of the three main rift segments - the Southern Basins, the Main Ethiopian Rift and Afar will determine that potential

The Southern Rift Basins in the Omo region appear to contain 4-8 km of sediments, possibly including Paleogene shales with oil-source potential. Seismic reflection surveys will be needed to define subsurface structure and develop drilling sites.

The Main Ethiopian Rift is expected to contain Paleogene and Neogene lacustrine sediments interbedded with the thick volcanics. In the northern part, the MER also contains thick Mesozoic pre-rift sediments, including the oil-prone Upper Jurassic Uarandab Formation. Higher heat flow in the rift and burial under 1-2 km of volcanics could mature pre-rift and syn-rift source rocks, with oil migrating into interbedded or juxtaposed reservoirs. Subsurface temperatures in the MER appear, at least locally, too high for oil preservation and it appears likely that exploration potential will be limited to cooler, less intruded areas of the rift. Reflection seismic techniques to successfully map the sub-basalt structure are yet to be developed.

The potential over most of Afar is similar to the MER: pre-rift and syn-rift source rocks are probably present but it is unknown whether the temperature regime has been conducive to the generation and preservation of oil accumulations

[9] The writer has been unable to find any reference to AGIP drilling in the Afar. ENI (c1963) documented AGIP's work in Ethiopia during the Italian Occupation and concluded that there is no oil potential in Afar because of the 'great diffusion of recent volcanic phenomena'. AGIP mounted a major expedition into east central Afar in 1938 to investigate 50-year old reports of oil lakes in the area, but found nothing. The expedition leader wrote to his wife, 'The legend of oil in Dancalia is dead' (Kalb, 2001). Reports of blow-outs or plugged wells are common in oral stories about early oil exploration. What were probably genuine hydrothermally-caused oil occurrences in 1888, had become 'asphalt lakes' by 1938, and the blow-out story may well be just a further embellishment. The geographic setting of the 'lake' and the 'blow-out' are different but accuracy is not usually a constraining requirement in myths about forgotten or hidden oil discoveries.

[10] The reference is to 'Cretaceous Adigrat sandstone' but either the name or age is incorrect, because the Adigrat is Triassic-Jurassic in this area.

[11] The survey was reportedly abandoned after several non-survey people were killed in the area by anti-tank mines in April 2009.

Current petroleum exploration programmes over the Southern Rifts Basins, including the Jimma area, and in the Afar region near Dallol and Aisha, will add considerably to our understanding of the structural framework of these Ethiopian rift basins, and their petroleum potential.

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