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THE ROYAL SOCIETY

Hydrocarbons in rift basins: the role of stratigraphy

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Hydrocarbon occurrence and distribution in rift basins is largely a product of the stratigraphic succession in the syn- and post-rift phases of basin evolution. Most of the known reserves of recoverable hydrocarbons occur in rifts with post-rift sag basins and in those basins that are dominated by marine fill. Simple rifts and passive margins are significantly less prolific. Key factors are the style of post-rift tectonics and whether the basin fill is dominated by non-marine or marine strata.

Tectonically derived topography is the prime control on both sedimentary processes and facies distribution, which results in a consistent geographic, and stratigraphic distribution of hydrocarbon source rocks, reservoirs and seals in syn-rift successions. Potential reservoirs are abundant throughout the syn- and post-rift successions and include a wide variety of sandstone and, less commonly, carbonates. Source rocks occur less frequently and are restricted to specific stratigraphic horizons; their presence or absence is one of the limiting factors in hydrocarbon distribution. Good seals tend to be uncommon in continental syn-rift successions and their absence often prevents the formation of hydrocarbon accumulations. Seals are more common in post-rift successions and widespread in marine syn-rift successions. The reserve distribution is largely controlled by seal distribution, which is best in sag-basin successions and in basins filled with marine strata.

A strategy for the efficient exploration of rift basins can be derived from post-rift basin geometry and the nature of the stratigraphic fill. Plays can be developed that identify the most prospective areas within the syn- and post-rift successions by predicting the distribution of hydrocarbon source rocks, reservoirs and seals from stratigraphic architecture.

Keywords: depositional processes; stratigraphic succession; facies distribution; hydrocarbon prospectivity; controls on sedimentation; hydrocarbon habitat

1. Introduction

Rift basins are well known as prolific hydrocarbon-bearing provinces worldwide, with estimated total recoverable oil reserves of approximately 2×10^{11} barrels (Morley 1999). Although structural development does significantly influence the occurrence and distribution of hydrocarbons within rifts, the character of the basin fill stratigraphy also determines whether or not a basin is hydrocarbon bearing. It is the basin fill that provides the source rocks, reservoirs and seals for rift-basin hydrocarbon accumulations. This is not to claim that the nature of the basin fill is independent of structural development; indeed, an argument central to the objectives of this paper is that rift stratigraphy is highly dependent upon tectonically generated topography.

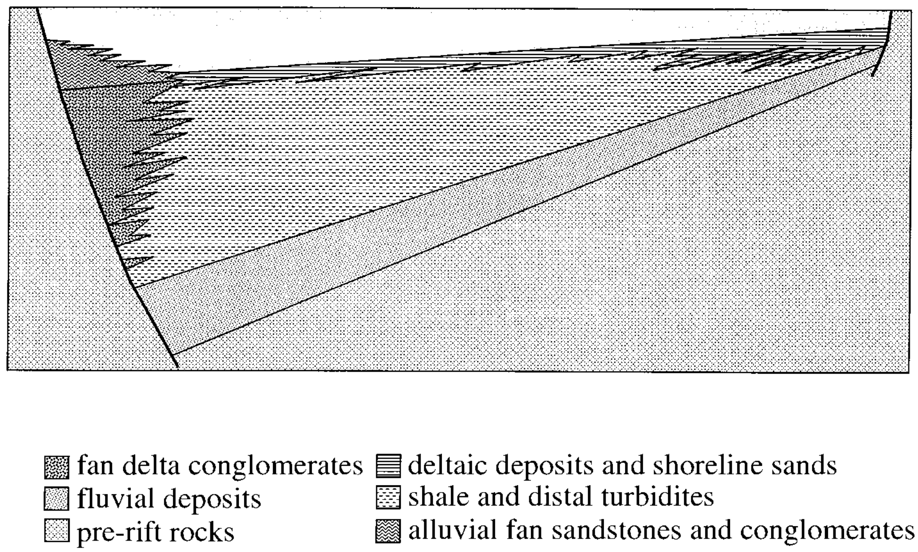

Figure 1. Idealized cross-section of syn-rift facies distribution (not to scale).

It will be shown that the link between tectonics and sedimentation causes the distribution of source rocks, reservoirs and seals to be geographically and stratigraphically consistent, and, therefore, predictable. The occurrences of known hydrocarbon accumulations can then be analysed in terms of the predictive model and an exploration strategy devised.

Two factors that contribute significantly to rift-basin stratigraphy, and hydrocarbon potential, are whether the syn- and post-rift basin fill is dominantly marine or non-marine sediment, and the geometry of the post-rift basin. Following Kingston *et al.* (1983), this paper considers post-rift basins as either sag basins or passive margins; rifts without a post-rift succession are termed simple rifts. The focus of this paper will be non-marine syn-rift successions, and, to a lesser degree, non-marine sag basins and marine syn-rift and sag basins. Hydrocarbon occurrences on passive margins that relate to rift basins will be mentioned only briefly. Although the following discussion is partitioned into marine versus non-marine successions, it is recognized that in many rifts the stratigraphic succession is a combination of marine and non-marine sediments, with marine post-rift successions very commonly associated with non-marine syn-rift successions.

(*a*) *Stratal geometry*

The syn-rift consists of all those strata that were deposited within a fault-bounded rift basin. These sediments generally are recognized to have an asymmetric cross-section because deposition occurs while subsidence continues along the bounding fault of an evolving half-graben (see, for example, Leeder & Gawthorpe 1987). Depositional units thicken toward the bounding fault and thin to the up-dip flexural edge (figure 1). During deposition, the basin floor slopes down toward the bounding fault so that facies change laterally and are progressively more distal (basinal) toward the bounding fault within each unit. Consequently, stratigraphic columns from different

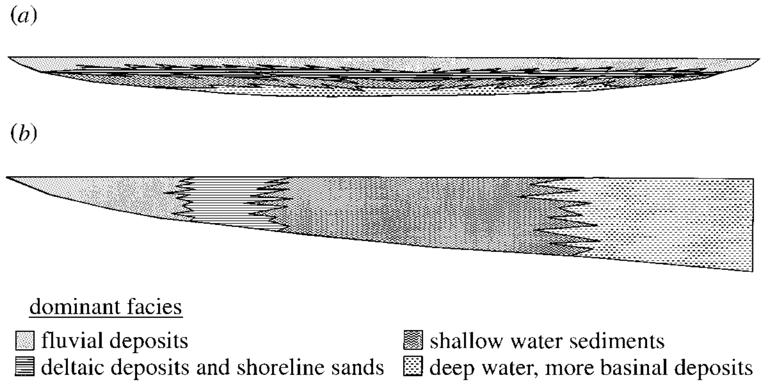

Figure 2. Schematic diagram of general facies distribution (*a*) in a sag basin and (*b*) on a passive margin (not to scale).

sides of a half-graben are significantly different, with thicker more basinal facies near the bounding fault, and thinner more proximal facies toward the flexural margin. Half-graben basins also have a plunge, so that facies change along strike as well.

Post-rift basins either contain strata that are deposited during thermal subsidence following rifting in the case of sag basins, or are broad depressions that extend laterally over a much greater area than the underlying fault-bounded syn-rift basin (Morley 1999). In a sag basin, sediment enters from the margins and slopes are low. The strata thicken gradually toward the basin centre (figure 2*a*). Generally, facies are more distal toward the basin centre and more proximal at the edges. A passive margin develops a wedge-shaped succession that generally has more distal facies in the thicker down-dip basinal side than toward the up-dip shoreward end (figure 2*b*).

(*b*) *Controls on syn-rift sedimentation*

The two most important controls on sedimentation in non-marine rift basins are tectonics and climate, and tectonics and relative sea level in marine rifts. It has been debated whether climate or tectonics is more important; the debate is not simply an academic argument because the ability to predict facies and, therefore, source, reservoir and seal distribution is dependent upon a proper understanding of the controls. Also, different factors, or a different combination of factors, are important in different phases of rift-basin development.

(i) *Tectonics*

Many recent studies of sedimentation in rift basins have concluded that tectonism is the most important control on syn-rift sedimentation, and a model has been proposed that interprets the observed syn-rift stratigraphic succession in non-marine basins as a direct product of tectonically induced basin topography (Lambiase & Bosworth 1995). Climate exerts a strong influence on the facies that comprise the stratigraphic succession, although climatic effects are generally recognized as secondary relative to the tectonic imprint.

Tectonic, or structural, control operates in several ways and at several scales in the syn-rift succession. Of primary importance is the rate of subsidence on the bounding

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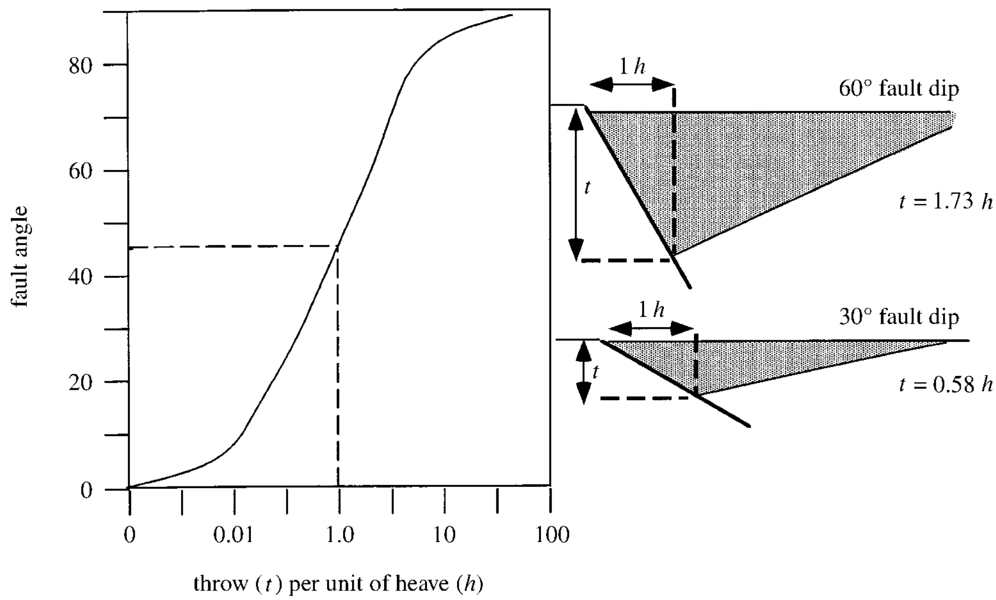

Figure 3. Subsidence as a function of bounding fault angle. The ratio of vertical throw to heave quantifies basin subsidence per unit of extension. High-angle faults (60–70°) have a high throw:heave ratio (1.7–2.7), while low-angle faults (15–30°) have a low ratio (0.26–0.57).

fault and on individual fault blocks compared to the rate of sedimentation (Morley 1989). The hade of major boundary faults significantly affects the amount of hanging wall subsidence. The ratio of vertical throw to heave on a fault is, effectively, a measure of the amount of basin subsidence for a unit of extension. High-angle faults (60–70°) have a high throw-to-heave ratio (1.7–2.7), while low-angle faults (15–30°) have a low ratio (0.26–0.57). Hence, for a given amount of extension, high-angle faults can accommodate much more subsidence than low-angle faults; similarly, for a given strain rate, high-angle faults have considerably faster subsidence rates than low-angle faults (figure 3). This relationship controls the formation of accommodation space for sediments and often the depositional facies.

Another aspect of tectonic control on sedimentation is the evolving topography generated by rift-basin development. Topography controls processes, facies and sediment supply. The overall dip and plunge of a basin determine sediment transport paths and, consequently, facies distribution. Fault blocks create depocentres at the sub-basin scale, and serve as local sediment sources and sinks for a variety of sedimentary environments including alluvial fans, small rivers, swamps and small lakes. At the basin scale, fault scarps source alluvial fans and fan deltas at the basin edge. Uplifted rift shoulders deflect drainage away from the rift and significantly reduce sediment supply to the basin by preventing access to large external drainage systems. Transfer zones can also be local sediment sources and often help to form basin-wide depocentres.

In rifts with marine fill, tectonics control sedimentation in the same manner as in non-marine rifts; however, relative sea level is a more important control on sedimentation than climate. Relative sea level determines many aspects of facies distribution, such as the proportion of deep versus shallow-water environments, and rates of rel-

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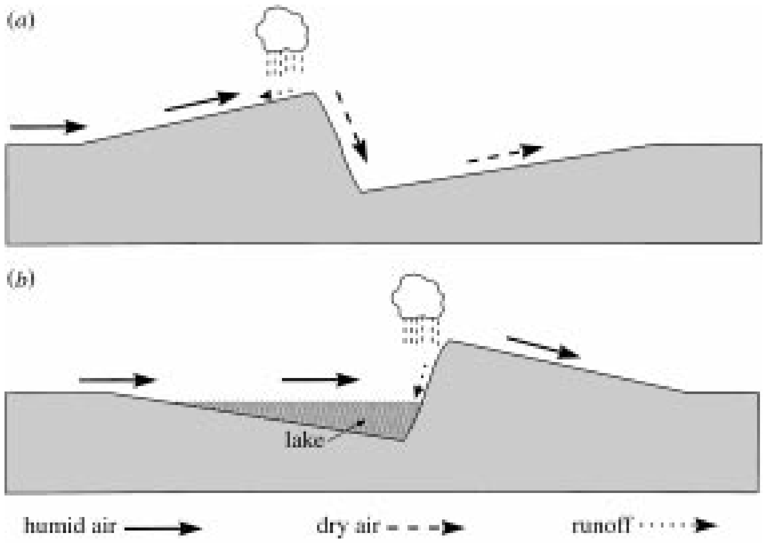

Figure 4. Modification of local climate by half-graben topography showing (*a*) a decrease in humidity caused by wind approach from the footwall side; and (*b*) an increase in humidity caused by winds approaching from the flexural margin. See the text for an explanation.

ative sea level change determine stratigraphic architecture. Combined with climate, relative sea level controls the presence or absence of evaporites and carbonates.

(ii) *Climate*

Climate primarily controls the amount of water available to a non-marine rift, which determines whether lacustrine, fluvial or aeolian sedimentation dominates. In a generally humid climate, the type of lake, lake level changes and sediment supply are also controlled by climatic variations; when there is little water, rivers are small and sediment supply is low, while larger rivers and an increased sediment supply result when conditions are wetter.

Climate operates at both regional and local scales. The effects of regional climate are well illustrated by the Triassic rifts of eastern North America. The system spanned palaeolatitudes of 3° S to 8° N; large lakes filled those basins that formed in a region with a continuously wet climate at one end of the rift system, while shallow lake sediments, evaporites and aeolian sediments were deposited contemporaneously in areas of dry climate at the other end (Olsen 1990). The sedimentary fill of the intermediary basins reflects alternating wet and dry conditions brought about by shifting of the climatic zones with time.

Local climate in rift basins is partly a function of topography. Hay *et al*. (1982) described how adiabatic cooling and heating of winds blowing across a full graben with topographically high rift shoulders can remove moisture from the basin floor. Applying the same principle to half-graben basins demonstrates that basin orientation can strongly influence local climate. Winds that approach an uplifted footwall cool as they move upslope, causing precipitation on the rift shoulder that runs away from the rift (figure 4). The now relatively cool and dry air mass sinks toward the basin floor after it crests the rift shoulder. As it sinks, it heats up, causing the rela-

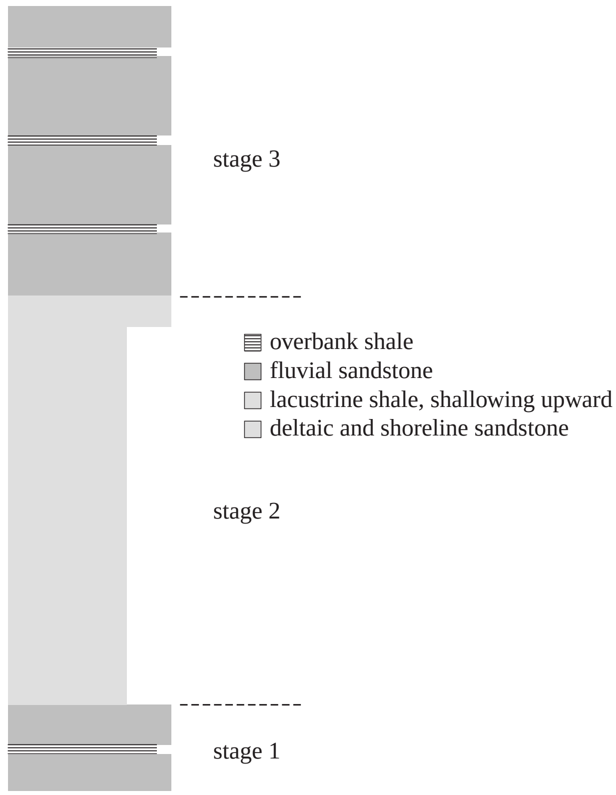

Figure 5. Idealized syn-rift stratigraphic column showing the facies associated with the three stages of stratigraphic development (not to scale).

tive humidity to drop further; the now hot, dry air mass causes evaporation on the basin floor and removal of water from the rift as the air passes out of the basin over the flexural margin. Winds approaching from the opposite direction cross the rift essentially unimpeded and then climb the bounding fault scarp. This again causes cooling and precipitation as the air climbs, but in this case the rain falls into the basin and increases the water in the system. Thus, the orientation of a rift basin relative to wind direction can cause the local climate to be wetter or drier than the regional climate.

(*c*) *Controls on post-rift sedimentation*

In post-rift sag basins, the rate of tectonic subsidence controls the depositional slope and influences the accommodation space available for sediment. Relative sea level determines whether the sag-basin deposits are marine or non-marine, and also affects accommodation space.

Climate can influence the marine facies in a sag basin, and often determines whether clastics, carbonates or evaporites are deposited. Climate also controls whether lacustrine or fluvial strata accumulate in a non-marine sag basin. On passive margins, subsidence rate also controls depositional slope and influences accommodation space, but relative sea level is the most important control on facies distribution.

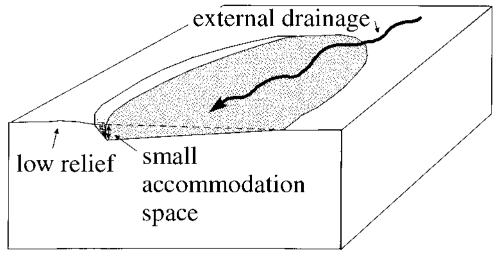

Figure 6. Depositional model for stage 1 fluvial sediments.

2. Non-marine syn- and post-rift sedimentation, facies and hydrocarbon potential

(*a*) *Syn-rift*

It has been recognized that many non-marine rifts have a remarkably similar syn-rift stratigraphy, despite a wide range of age, geographical setting and climate, that forms a three-stage succession (Lambiase 1990). The basal unit is dominantly fluvial sandstones, followed by a rapid transition to deep lacustrine deposits. The lacustrine sediments gradually shallow upward to deltaic and shoreline strata, and the third stage is marked by a return to fluvial deposition (figure 5). Alluvial-fan and fan-delta deposits often occur along the bounding fault. Each of the three stages has a specific combination of sedimentary processes, facies distribution and character, as well as source, reservoir and seal potential. This is largely because each stratigraphic stage is deposited at a different phase of the rift's structural development; the different basin topography associated with each phase causes major differences in the sedimentary processes and facies.

(i) *Stage 1*

Depositional model

During stage 1 deposition, the rift basin is just beginning to form, and the subsidence rate is relatively low compared with the sedimentation rate. Accommodation space is created slowly and is promptly filled because there are no uplifted footwalls, or other barriers, to prevent drainage systems from entering the basin and the subsiding basin is the lowest point in the region so that rivers tend to flow into it, bringing a lot of sediment with them (figure 6). The thickness of stage 1 deposits varies enormously from basin to basin, apparently as a function of subsidence rate. Rapidly subsiding basins have thin, if any, stage 1 strata because they quickly enter stage 2, with its dramatically different sedimentation style (as discussed below), before a significant thickness of stage 1 strata can accumulate. This often occurs in pull-apart basins, where fault planes are steep and minimal extension causes significant subsidence, e.g. the Kyokpo Basin, Korea (Lambiase & Bosworth 1996). Thick basal successions (1–2 km) are found in basins that subsided more slowly, such as the Triassic Newark Basin of eastern North America (Manspeizer & Olsen 1981) and the Morondava Basin, Madagascar (Besairie & Collignon 1972).

Facies and hydrocarbon potential

Fluvial sediments are the most common facies in the first stratigraphic stage. They tend to be coarse grained and have little associated mudstone; they can be either braided or meandering stream deposits, and often both types occur in thicker successions (Besairie & Collignon 1972; Manspeizer & Olsen 1981). Observations of ancient rifts in outcrop suggest that individual channels are relatively small and large streams are rare. Stage 1 fluvial deposits generally cover the entire basin area and are thickest near the basin-bounding fault.

Stage 1 sediments are derived from pre-rift rocks so their composition varies considerably from basin to basin. Textural maturity can also vary, and is a function of original composition plus the distance of transport into the developing rift. Diagenetic alteration can also degrade porosity and permeability (Winn *et al*. 1993). Those sediments that are quartzose and texturally mature can have good reservoir potential, although they are often difficult to charge with hydrocarbons because they usually underlie any potential source rocks and only achieve favourable juxtaposition for migration by faulting. Also, fluvial sandstones are best developed in the deepest parts of the basin, which generally are the most difficult areas to charge with hydrocarbons.

Other stage 1 facies generally are relatively thin and laterally discontinuous. In very dry climates, aeolian sands and playas may develop, but not commonly. Aeolian dunes usually have excellent reservoir potential, although they have the same charging problems as stage 1 fluvial sandstones. Alluvial fans can develop where there is topographic relief on basin-bounding or internal faults; generally, relief remains low so that stage 1 fans are small and thin and have limited reservoir potential. Small lakes and coal swamps may develop in wetter climates; neither normally deposit thick, areally extensive strata that constitute potential source rocks or seals.

(ii) *Stage 2*

Depositional model

The transition from the first to the second stratigraphic stage in non-marine rifts occurs rapidly as a result of a major change in rift topography (Lambiase & Bosworth 1995). As the rift basin develops, the rate of subsidence increases quickly. Most subsidence is along the bounding fault, which generates the asymmetric half-graben morphology, although subsidence along faults on the basin floor also produces significant relief on internal fault blocks. The increased subsidence causes a substantial increase in the rate of accommodation-space increase within the basin.

Other topographic changes accompany the formation of an asymmetric basin. These include footwall uplift and a flexural margin that deflect regional drainage away from the rift basin, and the development of some transfer zones as topographic highs. The development of rift shoulders inhibits external drainage, and sediment, from entering the basin. Consequently, the sedimentation rate is lowered dramatically and is much less than the subsidence rate; the net result is the formation of a deep, closed, sediment-starved basin (figure 7).

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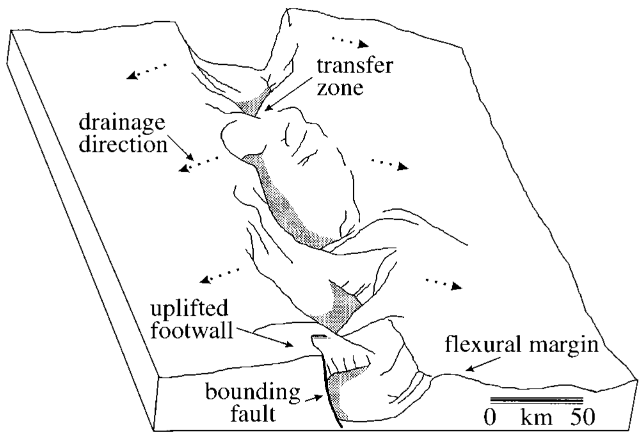

Figure 7. Block diagram illustrating rift-basin topography at the onset of stage 2 stratigraphy. Dimensions are scaled to a seismic interpretation of the East African Rift with a vertical exaggeration of 10.

Facies and hydrocarbon potential

The prime control on facies in the deep basin is the availability of water. This can either be run-off to form lakes, or a marine connection; marine rifts are discussed after non-marine basins. Lakes come in all sizes up to Lake Baikal, with a surface area of *ca.* 6000 km^2 and a depth of 1600 m, and their water chemistries differ tremendously as well. Lake size and chemistry significantly affect sedimentation within lakes; both are determined by the amount of water in the system (i.e. climate) and the lithology of the provenance area of the sediments, which influences dissolved solids. Climate, and, therefore, water in the system, is highly variable with time, and causes significant lake level changes in large lakes, repeatedly changes the character of intermediate sized lakes, and makes small lakes ephemeral on a time-scale of tens of thousands of years (Olsen 1990).

In a very dry basin, alluvial fans (bounding fault and small blocks), aeolian dune deposits and playas can dominate the stage 2 facies, and the dune and fan sandstones can be very good reservoirs. However, most stage 2 sediments are locally derived and tend to be texturally immature. Small streams will form in slightly wetter rifts; these often drain into swamps and/or evaporitic lakes (figure 8*a*).

(iii) *Small lake facies*

Evaporitic lakes become chemically stratified as evaporation concentrates the dissolved minerals in the bottom layers, forming a harsh environment that excludes bottom-dwelling organisms and allows organic matter produced by algae in the fresher surface waters to be preserved, e.g. Lake Magadi, Kenya. Evaporitic lakes have been proposed as a potential source of hydrocarbons (Surdam & Wolfbauer 1975); however, in rift basins, they are generally small, and rapid climate changes make them very ephemeral. If the climate becomes wetter, they are no longer chemically stratified or able to preserve organic matter; if the climate becomes drier, they disappear completely. The limited area, often only a few kilometres square on one

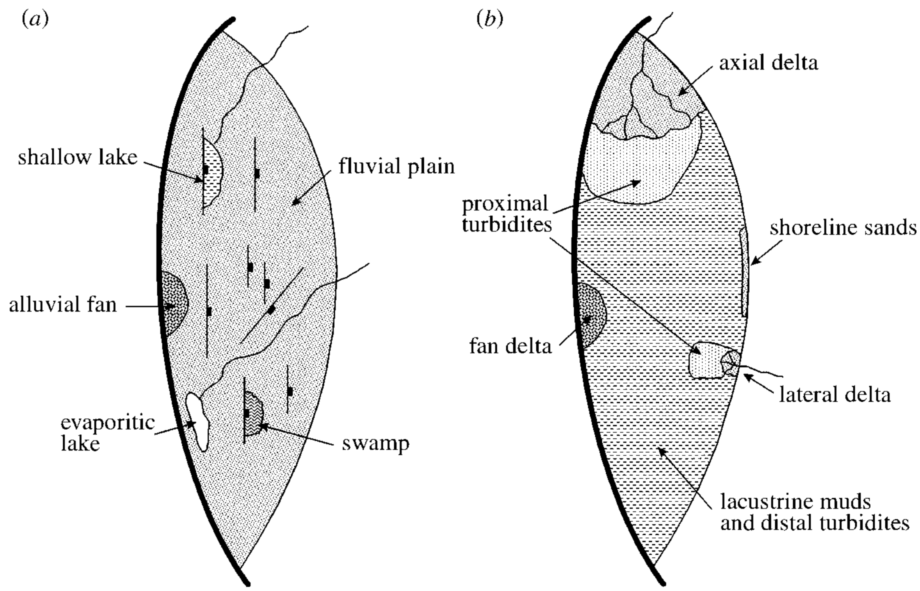

Figure 8. Schematic diagram for general stage 2 facies distribution in (*a*) a relatively dry climate; and (*b*) a wet climate capable of sustaining large lakes.

fault block, and ephemeral character of evaporitic lakes in rift basins, limits their source-rock potential.

A rift basin with a slightly wetter climate establishes larger river systems and permanent shallow lakes that generally occupy the area of one fault block or less. The small surface area severely limits wave size so that shorelines are muddy; the shallow depth means that bottom sediments are oxygenated and, therefore, do not accumulate organic matter. Fluvial sands and overbank muds plus lacustrine muds are the main deposits; there is some reservoir potential in the fluvial sands, but source-rock potential is minimal. There may occasionally be some local seal potential in the mudstones.

(iv) *Large lake facies*

Large, deep lakes are common in rift basins with humid climates. 'Deep' does not specify a minimum water depth; it means that the lake floor is below wave base and sedimentary structures record no wave influence, while 'large' indicates that the lake waters extend across the entire fault-bounded basin, not just one fault block. Worldwide, about 30% of all rift half-grabens contain deposits from large, deep lakes. This is clearly demonstrated by the distribution of modern lakes in the East African Rift and the occurrence of thick, deep lacustrine shales in the Triassic rifts of the eastern US (figure 9). Large, deep lakes are the most important type for hydrocarbon generation and accumulation, mainly because of their source-rock potential (as discussed below). Their basin-wide areal extent, plus the ability to accumulate shale with thicknesses that commonly reach several hundred metres, also makes the seal potential of these deposits obvious.

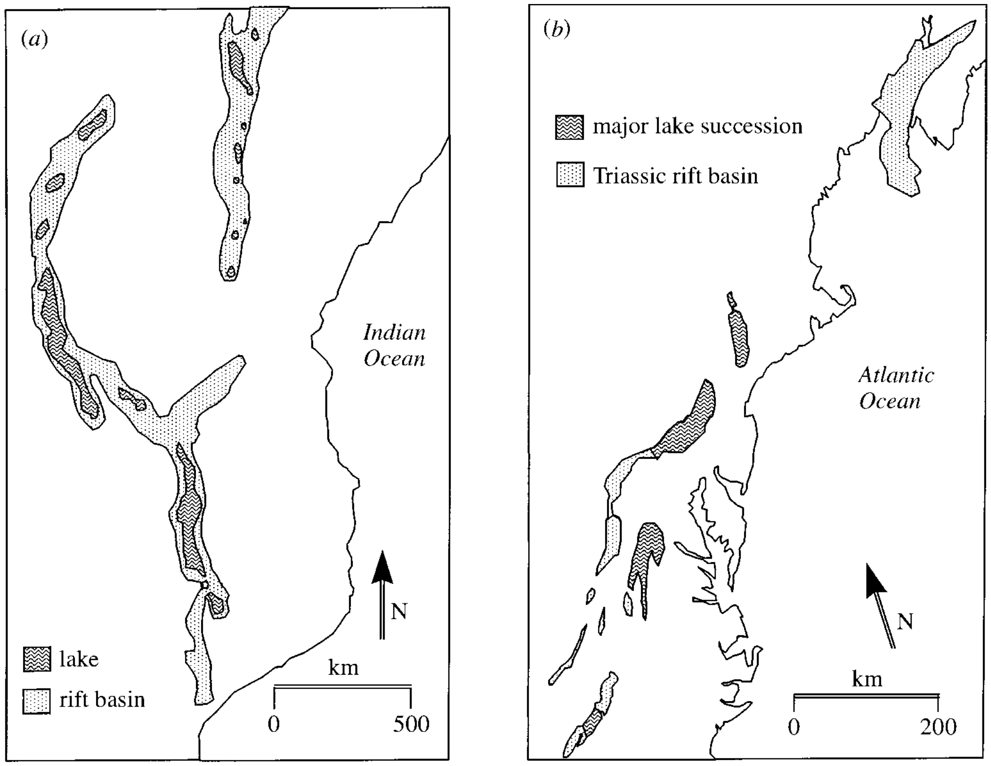

Figure 9. The distribution of (*a*) lakes in the modern East African Rift; and (*b*) major lacustrine successions in the Triassic rifts of the eastern US (modified from Olsen 1990).

There are also a number of associated sandy facies that are often underrated as potential reservoirs. Sands accumulate in several facies along the margins of, and in, large, deep rift lakes (figure 8*b*). The wet climate that generates the large lakes often generates rivers that are large enough to deposit sandy deltas. Generally, rivers do not enter the lakes along the bounding fault and deltas are restricted to the flexural side of the basin, at either end from axial drainage and along transfer zones. The size, thickness and reservoir quality of the deltaic sandstones vary as a function of the size and transport properties of the river plus the lithologic composition of the sand; they are often good reservoirs. Generally, sands supplied by axial rivers have had longer transport distances, and are texturally more mature than those introduced from flexural margins.

Nearshore facies are a function of wave energy, which increases directly with fetch and water depth. Large lakes often have high-energy coastlines with a variety of sandy facies as demonstrated by Lake Turkana, Lake Malawi and Lake Tanganyika in East Africa (see, for example, Wells *et al*. 1994; Scholz 1995; Cohen 1990). Shoreline sands are deposited in a variety of upper shoreface, beach and coastal dunes settings that are remarkably similar to those on open marine shorelines, and with equally good reservoir potential due to wave action that tends to increase textural maturity. It is important to recognize that not all sedimentologically deep lakes have sandy-shoreline deposits. Small shallow lakes generally have small waves and low-energy, often muddy, shorelines. With the small waves, wave base is shallow so that lake-bottom sediments can still be deposited below wave base as an apparent deep-water facies. This, apparently, was the depositional setting in parts of the Central Sumatra Basin, where subwave base lacustrine shales with low-energy shorelines occur in small sub-basins (Pertamina BPPKA 1996).

Fan deltas form at the base of the steep slopes along basin-bounding faults. They are composed primarily of coarse-grained facies, including turbidites and debris flows in the subaqueous part of the fan and braided-stream and alluvial-fan facies in the subaerial part. Sandy turbidites, and, more rarely, debris flows, that are not associated with fan deltas can also occur on the lake floor. Generally, these are delta-front turbidites originating along the flexural margin of the basin (Smith 1995; Scholz *et al*. 1990). Their abundance and thickness vary significantly as a function of sediment supply rate. Reservoir potential also varies with composition because these facies tend to be texturally immature, although they are of proven reservoir quality in the South Gabon Basin (Smith 1995) and in the Reconcavo Basin, Brazil (Magnavita & da Silva 1995; Carozzi & Fonseca 1989).

The presence of abundant distal turbidites within a lacustrine mudstone succession does not imply that there is an equivalent proximal sandy facies. Thin, silty distal turbidites that form from fluvial density underflows are abundant in nearly all lacustrine mudstone successions (Scholz *et al*. 1997).

Lacustrine carbonates, primarily algal mounds, are occasionally deposited in areas with minimal clastic input. Generally, this occurs along the bounding fault shoreline and on top of shallowly submerged fault blocks (Cohen & Thouin 1987); a suitable water chemistry is critical for their deposition. Lacustrine carbonates are relatively rare in rift basins, but they have proven to be prolific reservoirs in the Cabinda enclave of Angola (McHargue 1990).

(v) *Source-rock potential*

Many lacustrine shales deposited in rift lakes are well known as excellent potential source rocks, and are credited with sourcing numerous hydrocarbon accumulations worldwide. Katz (1995) reviewed the controls on the distribution of lacustrine synrift source rocks, and concluded that lakes that occupy the deep sediment-starved basins that form at the beginning of stage 2 tend to accumulate organic-rich shales. However, organic productivity and preservation depend on numerous factors, among them latitude, water chemistry and sediment supply, which vary considerably even among different depocentres of one rift system. Consequently, source-rock quality, quantity and kerogen type can also vary significantly within one system, as well as from one rift system to another.

Stratigraphic succession

Although the facies distribution within a large, deep rift lake has several components and is reminiscent of a marine basin, the topography that generates the lake is a product of tectonics and is, therefore, dynamic. As noted earlier, the deepest lacustrine environments occur at the base of the stage 2 succession, followed by a shallowing upward trend to the top of the succession, which generally ends with deltaic deposits. The shallowing is caused by a decrease in the relative rate of subsidence to that of sedimentation, a function of increasing sediment supply and falling

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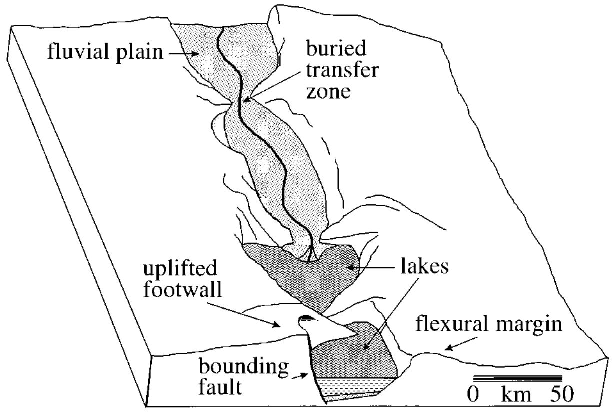

Figure 10. Block diagram illustrating the filling of half-grabens. Stage 2 sediments fill each half-graben to the height of the adjacent transfer zone, at which time sediments spill into the next half-graben and a stage 3 fluvial plain is developed.

subsidence rate. Accumulation rate increases when coarse sediment begins to enter the basin, and sedimentation changes from dominantly shale to sand. Most coarse sediment enters from an adjacent half-graben that has filled and buried the intervening transfer zone (figure 10), or from the termination of a rift segment at a gap or jump, and axial filling predominates.

As subsidence rate decreases relative to sedimentation rate, there is progressively less accommodation space with time because lakes have a spill point so that added sediment displaces water. Therefore, the general facies distribution is that the deepest water deposits occur along the basin-bounding fault (down-dip) at the base of the stage 2 succession, with progressively shallower water deposits vertically and up-dip toward the flexural margin.

Superimposed on the overall shallowing trend are numerous smaller-scale shallowing and deepening events that record lake level changes. Lake level changes occur at many scales and frequencies and are generally attributed to climatic changes (Olsen 1990; Lezzar *et al*. 1996). Scholz & Rosendahl (1988) noted lake level changes of up to several hundred metres in Lake Tanganyika, while Lezzar *et al*. (1996) identified numerous small changes on high-resolution seismic data from the same lake. Reservoir connectivity is related to the number, magnitude and duration of lake level changes; as the lake fills, there are an increasing number of sandy facies, leading to more connectivity of sands, and higher reservoir potential, upward in the succession and toward the flexural margin. Conversely, source-rock and seal potential decrease upward and toward the flexural margin.

(vi) *Stage 3*

Depositional model

Stage 3 deposits are mainly fluvial sandstones (figure 11). The transition from stage 2 to stage 3 is gradual, and is the culmination of the shallowing and filling process that occurred in stage 2.

The depositional model has important implications for hydrocarbon exploration. Among these are that coarse sediment first enters each half-graben in a rift sys-

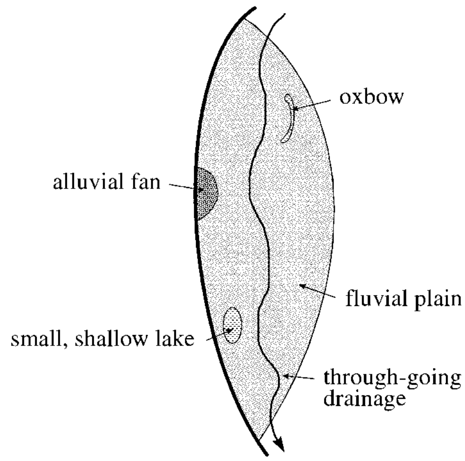

Figure 11. Schematic diagram for general stage 3 facies distribution.

tem at a different time. Therefore, while similar overall, the stratigraphic succession within each half-graben is unique, which causes hydrocarbon potential to vary between depocentres. The age difference between adjacent half-grabens often cannot be determined from stratigraphic data because of poor fossil control in non-marine systems plus reworking of stage 3 fluvial sediments from one half-graben into stage 2 lacustrine deposits of the next half-graben. Sequential filling also implies that the last half-graben to be filled should have thicker stage 2 lacustrine shales and, therefore, better source-rock potential than those filled earlier.

Facies and hydrocarbon potential

The stage 3 fluvial systems generally consist of well-developed braided or meandering rivers. Their deposits cover the entire area of the basin and are generally thick, occasionally as much as 1 km, e.g. southern Sudan (Schull 1988). Stream gradient and provenance affect reservoir potential, which is generally good. Many of the sands are texturally mature because they originate outside of the fault-bounded basin and have been transported a considerable distance. Small shallow lakes, including oxbows, and swamps are common on meandering fluvial plains (figure 11). Fine-grained sediments accumulate in these environments and as fluvial overbank deposits. Generally, the mudstones are neither thick enough nor laterally extensive enough to make good seals. Fluvial systems tend to be sandy with high channel belt connectivity because sediment supply greatly exceeds subsidence, although an exceptionally muddy meandering system could deposit overbank shales that are capable of forming seals. Stage 3 mudstones are not organically rich and, therefore, are not good source rocks.

(*b*) *Post-rift*

(i) *Sag basins*

The transition from syn-rift to post-rift tectonism occurs with the onset of regional subsidence and the coeval cessation of intra-rift subsidence. However, the transition from syn-rift to post-rift deposition is generally defined by a change in stratigraphic geometry. In non-marine sag basins, the post-rift geometry is achieved when rift margins are completely eroded away and sediment enters the basin laterally instead of axially. The transition appears as an unconformity on seismic data, but deposition may be continuous across the boundary; the geometry reflects only a change in style and not necessarily a time-break.

Fluvial sandstones and mudstones dominate the deposits of many non-marine sag basins. Generally, slopes are gentle so that streams have relatively low gradients and tend to be meandering rather than braided. The reservoir potential in the sandstone varies with the amount of overbank shale in the system and the connectivity of channel sands; these vary with provenance and subsidence rate, respectively.

Where a large river system passes through the sag basin, a large swamp or shallow lake may form; these environments will deposit mudstones of sufficient areal extent and thickness to form seals for hydrocarbons. The shallow-water environments usually result in organic matter being oxidized so that the mudstones rarely have source-rock potential. The Sudd in Sudan is a good modern example where the Nile River flows into a sag basin above Tertiary rift basins and, in the wet season, creates a large shallow swamp by flooding an area of several hundred kilometres square.

Occasionally, a sag basin in a wet climate will host a large relatively deep lake that accumulates organic-rich shale and becomes a source rock for hydrocarbons. Notable examples are the Songliao Basin, China (Yan *et al*. 1985) and Cabinda, Angola (McHargue 1990), where the sag-basin shales are both prolific source rocks and seal many of the hydrocarbon accumulations.

3. Marine syn- and post-rift sedimentation, facies and hydrocarbon potential

(*a*) *Syn-rift*

The overall facies distribution and stratigraphic succession in marine rifts is generally similar to that in non-marine basins, although there are some important differences. The key difference is that, unlike lake level, sea level is independent of climate and local tectonics and can vary considerably relative to basin topography. Basal sediments, deposited with stage 1 topography, can vary from shallow deltaic deposits to deep-water turbidites. Shallow-water facies can be either clastics or carbonates depending on climate and sediment supply.

Once stage 2 topography develops and the deep half-graben basins form, lateral facies distribution is similar to non-marine rifts; deep-water environments lie mainly on the down-dip side of the basin, while shallow-water and sandy-shoreline deposits occur preferentially near the flexural edge. In warm climates, carbonates form in areas of low clastic input and are more common than in non-marine rifts. Mudstone deposits in the deep basins are often organic-rich, especially if the marine connection to the rift system forms a restricted seaway with a stratified water column.

Perhaps the biggest difference between marine and non-marine rifts is that the vertical succession in marine rifts is less consistent, and, therefore, less predictable. Maximum sea level is independent of basin topography, whereas maximum lake level is controlled by a spill point; consequently, a marine basin can fill with facies from a variety of water depths and the vertical succession will reflect relative sea level history. Generally, the syn-rift fill of marine rifts contains more fine-grained sediments than non-marine basins, especially in the equivalent to the late stage 2 and stage 3 successions.

Due to their source-rock potential, marine syn-rift basins are often prolific hydrocarbon provinces. Two well-known examples are the North Sea (Cooper & Barnard 1994) and the Sirte Basin (Parsons *et al*. 1980). Shallow-water clastics and carbonates plus turbidites are potential reservoirs. Marine syn-rift sandstones serve as reservoirs for many significant hydrocarbon accumulations, e.g. the North Sea (Casey *et al*. 1993; Coward *et al*. 1991) and the Gulf of Suez (Patton *et al*. 1994). The sands are generally more texturally mature than non-marine syn-rift sandstones because of longer transport distances and the higher-energy hydrodynamic environment typically found in marine basins, although locally derived sands can be immature and have poor reservoir quality (Boldy & Brealey 1990; McGann *et al*. 1991). Seal potential is greater because of the relatively more abundant marine syn-rift shales compared with non-marine successions.

(*b*) *Post-rift*

(i) *Sag basins*

Facies in marine sag basins are highly variable and are controlled by relative sea level. They can range from shallow seas with shoreline sands or carbonates plus shelfal muds to deeper water successions consisting almost completely of marine mudstones. Evaporite successions develop where a restricted shallow sea occurs in a dry climate. The higher-energy nearshore facies occur preferentially along the edges of the basin, with their basinward extent controlled by sea-level lowstands. The nearshore clastics—which can include deltaic and shoreface sands, and, less commonly, carbonates—have good reservoir potential.

Possibly the most important contribution of marine sag basins to hydrocarbon prospectivity is the regional seals that are formed by marine mudstones and evaporites (Morley 1999). Cretaceous shales are an important seal in the North Sea (Spencer & Larsen 1990) and Tertiary marine shales seal virtually all the known accumulations in the Central Sumatra Basin (Williams & Eubank 1995). The thick Cretaceous evaporite succession of the West African continental margin seals a number of oil fields as does the Tertiary salt succession of the Gulf of Suez (Patton *et al*. 1994).

(ii) *Passive margins*

The stratigraphic development of passive margins is a study in sequence development as a function of sea level change (see, for example, Posamentier & Vail 1988) and is beyond the scope of this paper. Although not really part of the rift basin, passive-margin stratigraphy is important because many hydrocarbons generated in rifts become trapped in overlying passive-margin strata, as discussed below. Potential reservoirs occur in several facies, including deltaic and shoreface sandstones and carbonates; these are sealed by shelf and deep marine mudstones deposited during sea-level highstands.

4. Play concepts

It is clear from the spatial distribution of the various facies that source rocks, reservoir rocks and seals are not randomly distributed in rift basins, but occur preferentially in

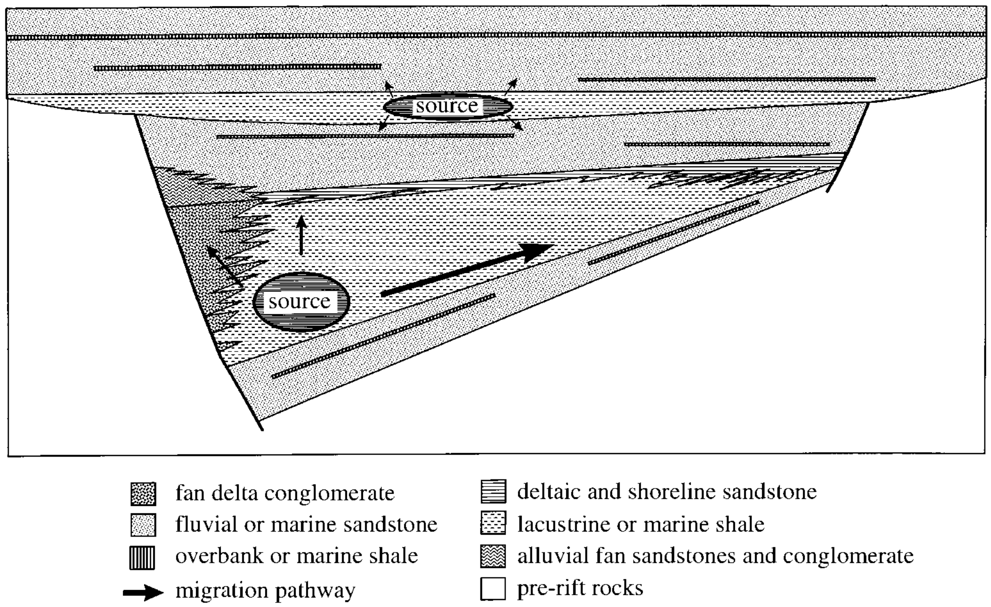

Figure 12. Schematic diagram of hydrocarbon source rock, reservoir and seal distribution in syn- and post-rift sediments. All sandstone and conglomerate facies are potential reservoirs, and all shale facies are potential seals; see the text for an explanation of their relative quality. The distribution of potential source rocks and migration pathways is shown schematically.

certain geographical and stratigraphic positions. Therefore, hydrocarbon plays can be derived from an understanding of the depositional processes and stratigraphic architecture of rift basins.

Successful plays can be developed by identifying those geographical and stratigraphic areas where source rocks and hydrocarbon migration pathways, reservoirs and seals are most likely to occur in conjunction. Potential sandstone reservoirs occur in a variety of locations in the syn-rift succession, including stage 1 fluvial sandstones, stage 2 fan deposits near the basin-bounding fault, deltaic and shoreline sands along the flexural edge, and on either end of each half-graben, delta front turbidites and carbonates, and stage 3 fluvial sands in non-marine basins, as well as in fluvial and marine post-rift sandstones and carbonates (figure 12). Each of these facies has a different reservoir potential and occurs in a specific location within the basin, making it possible to predict where reservoirs are likely to occur and to estimate their quality.

The best syn-rift source rocks are most likely to occur on the down-dip side of a half-graben and near the base of the stage 2 succession where the deepest marine or lacustrine conditions prevail; source-rock potential decreases both vertically and laterally, although the vertical decrease can be less consistent in marine rifts. High-quality source rocks can also occur in marine and non-marine sag basins, especially near the base of the succession (figure 12). The issues of source-rock maturity and hydrocarbon generation will not be discussed in this paper, although they are critical to play development and must be addressed specifically for each basin.

Hydrocarbons generated on the down-dip side of a half-graben migrate either

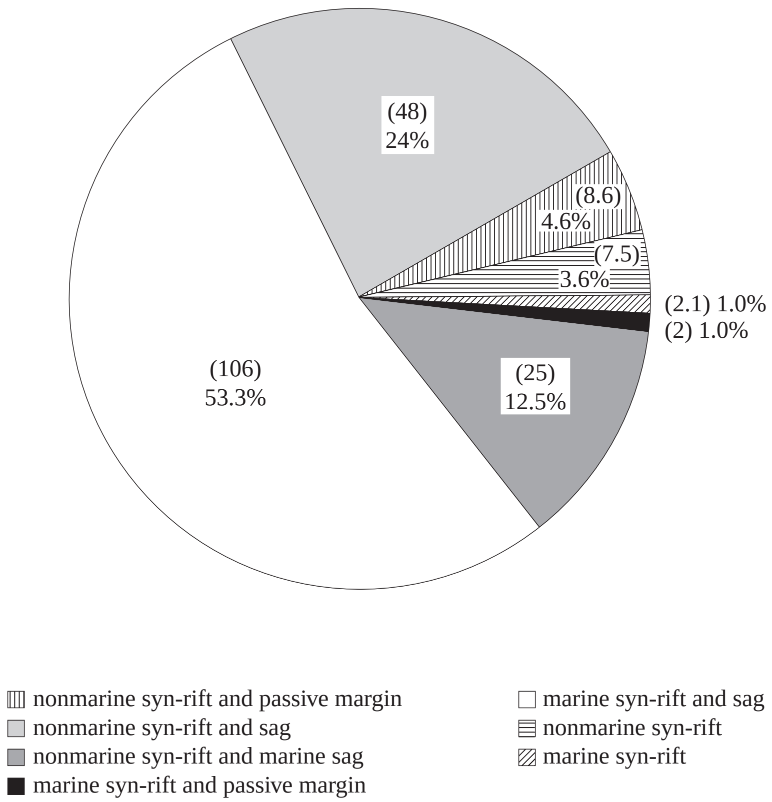

Figure 13. Occurrence of oil in rift basins. The percentage of the estimated total recoverable reserves of 199.2×10^{11} barrels is assigned to the type of rift in which they occur; the reserves, in barrels, are shown in parentheses (after Morley 1999).

up-dip along carrier beds or vertically along the bounding fault and/or adjacent conglomerates; both styles have been documented but the former is much more common. Although much of the succession immediately overlying the source rock usually is fine-grained and relatively impermeable, vertical migration also occurs as a result of faults that leak and/or juxtapose permeable and non-permeable strata. Syn-rift source rocks are capable of charging all the potential reservoirs in the syn-rift and post-rift successions. Source rocks near the base of a marine sag-basin succession can charge stage 3 sandstones as well as post-rift reservoirs.

There are a number of potential seals in rift-basin successions (figure 12), but the presence of good seals is often a problem that reduces prospectivity. This is especially true in non-marine rifts because the stage 3 basin-filling sand succession above the stage 2 shales coarsens upward. Consequently, many of the hydrocarbons that are generated in the syn-rift succession escape to charge post-rift reservoirs. Trapping in stage 3 sandstones often relies on a seal at the base of the post-rift succession.

5. Hydrocarbon habitat

The habitat of the estimated 2×10^{11} barrels of recoverable oil reserves in rift basins can be viewed in terms of the geometry of the basins in which they occur, and the nature of the basin fill. Morley (1999) has divided hydrocarbon-bearing rifts into seven categories, each of which represents a specific combination of basin fill and geometry. These include non-marine simple rift; marine simple rift; non-marine syn-rift with a non-marine sag basin; non-marine rift with a marine sag basin; non-marine rift with a passive margin; marine syn-rift with a marine sag basin; and marine syn-rift with a passive margin. The distribution of the reserves is skewed very heavily towards rifts that have a sag basin associated with them; *ca.* 88% of all the reserves, or 1.79×10^{11} barrels, occur in rifts with sag basins (figure 13). Marine syn-rift and sag basins account for approximately 1.06×10^{11} barrels, or 53% of the total, while 4.8×10^{10} barrels, or 24%, occur in non-marine syn-rift and sag basins and 13% (2.5×10^{10} barrels) in non-marine syn-rift and marine sag basins. Surprisingly, marine simple rifts account for only 1% or 2×10^9 barrels.

Several geological factors contribute to skew the distribution of known reserves towards rifts with sag basins, as does exploration bias. The regional seal that is often formed by sag-basin strata is probably the most important because it allows hydrocarbons that migrate out of the syn-rift succession from stage 2 source rocks, through a coarsening upward succession, to be trapped in the post-rift succession. Another important factor is that in many basins it is the additional burial of syn-rift shales beneath a sag-basin succession that causes the shales to reach thermal maturity and generate hydrocarbons.

Simple rifts are less prolific than rifts with sag basins because the total area under closure tends to be relatively small, they often lack a good regional seal and organic-rich shales are not always thermally mature. The development of a passive-margin wedge can reduce hydrocarbon prospectivity by causing excessive burial of syn-rift shales and tilting of the syn-rift succession that destroys trapping geometries (Gunn & Ly 1989). Traps associated with shale or salt diapirism and drape anticlines are common in the passive-margin succession and are highly productive in Brazil and West Africa.

6. Exploration strategy

A general strategy for rift-basin exploration can be derived from the stratigraphic architecture and the distribution of known hydrocarbon occurrences. The basin geometry and the nature of the fill can be used to identify potential plays based on predicted reservoir, source-rock and seal distributions.

A key factor in evaluating prospectivity is determining the presence or absence of mature source rocks. Despite the overall stratigraphic similarity between half-grabens in one rift system, each sub-basin is filled independently so that details of the stratigraphy vary from basin to basin. Also, in non-marine rifts, large lakes occur in only *ca.* 30% of the depocentres. Consequently, some half-grabens in a system may have source rocks while others do not. It is also apparent that the basins that are last to fill with coarse sediment are more likely to have source rocks, and that they are likely to be thicker than those basins that fill first. Therefore, the source-rock potential of a rift system can only be identified after each half-graben is drilled.

Potential reservoirs and seals can be identified by integrating sequence stratigraphic concepts with the predicted facies distribution. This is readily done in marine systems using well-established principles (see, for example, Posamentier & Vail 1988) because the sedimentary systems in a rift respond to relative sea level changes in

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the same way as other settings. Sequence stratigraphic analysis has been successfully applied to lake successions and distinct highstand and lowstand deposits and systems tracts are recognized (see, for example, Scholz *et al*. 1990, 1993; Shanley & McCabe 1994). However, non-marine systems can be more difficult to interpret because lake level changes can be rapid, so that systems' tracts do not always develop fully before the lake level changes again. Also, lake level falls when water supply decreases and sediment supply also decreases when water supply decreases, which can significantly slow the rate of lowstand deposition.

7. Conclusions

(1) The occurrence of hydrocarbons in rift basins is strongly controlled by the style of post-rift tectonics and the nature of the basin-fill stratigraphy. Rifts with sag basins contain most of the known recoverable oil reserves, and rifts with marine fill are more prolific than non-marine rifts.

(2) Tectonically driven topographic evolution and climate determine sedimentary processes and facies distributions in rift basins. Because topography is the prime control, the geographical and stratigraphic distribution of potential hydrocarbon source rocks, reservoirs and seals is consistent from basin to basin and is, therefore, predictable.

(3) Potential reservoirs are abundant and occur throughout the syn-rift and post-rift successions in most rifts. Source rocks are not found in all basins and their distribution is one of the main factors limiting the occurrence of hydrocarbons. Seals are not common in syn-rift successions and their presence in the post-rift succession is often the critical element for trapping of hydrocarbons. The contribution of post-rift seals partly accounts for the known reserve distribution, as does the sealing capacity of the generally fine-grained sediments in rifts filled with marine strata.

(4) Rift basins can be explored efficiently by developing exploration concepts based on stratigraphic architecture. The predictable spatial distribution of source rocks, reservoirs and seals can assist in identifying the most prospective areas within the syn- and post-rift successions.

The authors thank the many individuals with whom they have had numerous discussions of rift-basin stratigraphy and hydrocarbon habitat. Among these are Bill Bosworth, Andy Cohen, Barry Katz, Paul Olsen and Chris Scholz. We also thank Amoco Production Company for releasing data on reserve estimates.

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Discussion

R. S. White (*Bullard Laboratories, University of Cambridge, UK*). Can I just clarify something about the formation of sag basins? Is that what we could call the thermal subsidence phase?

J. J. Lambiase. Yes.

A. B. Watts (*University of Oxford, UK*). Could Professor Lambiase comment on the role of stratigraphic wedge traps, for example, in either the rift phase or the post-rift phase. What does he feel is their importance in terms of trapping oil?

J. J. Lambiase. I was not intending to discuss trapping geometries, but stratigraphic traps can be important in both the syn-rift and post-rift. However, they are normally restricted to those successions that commonly contain significant mudstones, for example the lower syn-rift, and are unlikely to occur in the upper syn-rift which tends to become sandier upward.

D. Bowler (*The Open University, Milton Keynes, UK*). One of the aspects that Professor Lambiase did not mention is the maturity of the source rocks. Can he comment on maturity, because some source rocks do not appear to have been buried very deeply, and obviously maturity will be very dependent on basin history?

Also, following the previous question, would he agree that, because of the basin geometry, hydrocarbon migration will tend to flow to the thin end of the wedge of sediment fill, resulting in a seal problem with a high risk of fault leakage?

J. J. Lambiase. To answer the first question, maturity varies greatly with basin history, especially post-rift history. In a half-graben, without a thick post-rift succession, burial depth can be insufficient for maturity and overmaturity can result if the post-rift cover is too thick.

Migration will tend to be up-dip to the flexural edge where there is often a seal problem. There also is a lot of vertical migration along internal faults within the basin.

R. Holroyd (*Tunbridge Wells, UK*). Is the thermal gradient higher in the rift valleys or in the rift zone?

J. J. Lambiase. Maturity modelling often suggests an elevated thermal gradient, but how hot is difficult to quantify and it seems to vary considerably from rift to rift.

N. Kusznir (*University of Liverpool, UK*). I am interested in non-marine syn-rift situations. Presumably in those situations the syn-rift burial is actually cooking syn-rift source rocks. Does that mean you have a very fast system from laying down the source rocks to generating hydrocarbon?

J. J. Lambiase. Yes, burial begins very quickly, but a syn-rift succession alone often cannot achieve hydrocarbon generation and a post-rift succession must be deposited before generation occurs.

N. Kusznir. How significant is the contribution of non-marine syn-rift sediments to world production?

J. J. Lambiase. The contribution of non-marine syn-rift systems without post-rift successions is small. The Central Sumatra Basin contains 25 billion barrels of oil generated in a Tertiary syn-rift succession and matured by a later Tertiary post-rift succession. A substantial amount of the hydrocarbons in marine post-rift rocks were generated from non-marine syn-rift sources; examples are Brazil and West Africa, but I don't have the exact numbers.