Seychelles and the Western Indian Ocean Palaeo-Reconstruction by Recourse to Biomarker Assemblages from Significant Oil Accumulations and Shows in the Present Day Indian Ocean Margin

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Seychelles Petroleum

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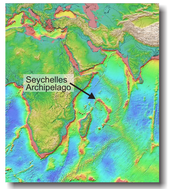
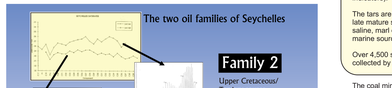


INTRODUCTION

In the same way that West African geochemical data, (stable isotope measurement and biomarker analysis from gas chromatography-mass spectrometry) derived from oil accumulations in coastal South America and conjugate West Africa were used to predict the likely Paleoenvironment of deposition on each side of the Atlantic, the more complex break up of Gondwanaland and the separation of East Africa, Seychelles and India can also be charted.

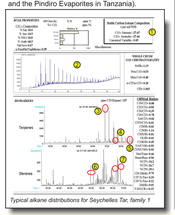


Ref. SEPEC database & Philp 1995

Oil samples and oil show extracts from the limited number of wells and the known seeps are used to help understand the multiphase break up of the East African margin, India and the Seychelles Mirco-Continent.

Geochemical data is presented with current plate tectonic reconstruction models to contribute to the understanding of the rifting sequences that were initiated during the Triassic that have resulted in the present day continental settings with seemingly contradictory oil geochemical signatures.

The initial break up of Gonwanda started in Permian times however rifting was not successful and a series of intermontane basins were created in which classic terrestrial source rocks developed (eg Sakamena, and Sakoa formations, Madagascar and the Pindiro Evaporites in Tanzania).



1. Isotope ratios. The saturate (aliphatics) values for the tars compare well with those of the source rocks – the aromatics do not always match – this MAY be due to the residence time for the tar balls floating in the water and the soluble aromatics being lost – aliphatics are not so soluble.
2. Waxy n–alkane distribution – algal?
3. High C_{27} not Hopane, if ⅓ of the peak hight of the adjacent C30 or more this is indicative a carbonate setting.
4. Small but significant Gammacerane peak may indicate stratification in the water column /salinity. The amount varies, perhaps indicating degree of salinity.
5. Elevated C35 doublet (Pentakishomohopane), again indicating salinity.
6. Diasterenes, therefore source has a clay input, but because of the carbonate indicators the source is likely to be Marl.
7. Form left to right the first peak is the S configuration and the second peak is the R epimer of the C_{22} αββ stirane. R is the preferred configuration and with increasing time the proportion of the R epimer increases as it is thermodynamically stable – this and other indicators would suggest the tars are from a mid mature source rock – the extracts from the source rock in the wells may be marginal more mature, However the Ro% values are much higher. This apparent contradiction is explained by the proximity of volcanic centres to the three closely spaced Amoco wells.

Some of these failed rifts persisted to end Triassic times, eventually Madagascar, with Seychelles attached successfully rifted from East Africa by Lower Jurassic times and this allowed restricted marine / inland sea conditions to persist between Seychelles, Madagascar and East Africa throughout the Lower Jurassic to early-mid Jurassic times. Periodic sea ingress would have allowed more fully marine conditions to occur from time to time then. From mid Jurassic times to the present day fully open marine conditions were firmly established and were not conducive to source rock formation.

India, with Seychelles attached, separated from Madagascar in the early Late Cretaceous, there seems to be no source rock development associated with this rifting event, perhaps because the seaways were open and again fully marine oxic conditions prevailed.

Finally India pulled away from Seychelles at the end of the Cretaceous and some similarities can be seen in the oils from India and the tars from NE Seychelles (Praslin Island). These oils are thought to represent the second family of oils.

This work would have not been possible without the assistance of the Seychelles Petroleum Corporation (SEPEC) access to the BP core store in Texas, access to GeoMark Research's O.I.L.S database base or funding by Petroquest International and East African Exploration Limited, all of whom I wish to thank.

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Upper Palaezoic, incipient break up

To date evidence for the early failed rift source rocks have not been encountered in Seychelles as the wells drilled thus far have only tagged the top of the exceptionally thick Karoo section. However throughout much of the Western Indian Ocean both Permian coals and Triassic lacustrine shales are recorded. There is also evidence for interior grabens within the Seychelles Plateau and the separation of the Seychelles from both India and Madagascar may also have been related to early Permo-Trias lines of weakness.

Seychelles Petroleum

The Tars

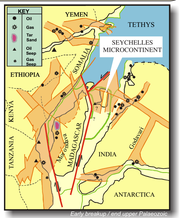
Note the elevated C_{29} norHopane peak, presence of Gammacerane and elevated C_{35} Hopane doublet, absence of Oleanane and presence of Diasteranes (as well as carbonate indicators).

The tars are sourced from a mid-to-late mature source rock, with a saline, marl dominated, restricted marine source signature.

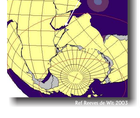
Over 4,500 samples have been collected by SNOC (SEPEC).

The coal mined in South Africa and found in Madagascar in Mozambique and Tanzania is of Permian age. The lacustrine Sakamena formation found to the south on Madagascar is believed to be the source of the giant Tsimiroro and Belomanga biodegraded oil deposits (fig GCMS - source contender 1a). The Triassic lacustrine Maji-ya-Chumvi Fish beds were encountered in Ria Kulai #1, southern and conjugate Kenya and the oil shows here from Tanzania (fig GCMS source contender 1a) are also believed to be derived from a Triassic lacustrine source. It is anticipated that a deeper Karoo exists under Seychelles EEZ; however the Liassic oil biomarker signature is so dominant it would mask any lacustrine oil input, if it were present. Upper Triassic, near exhausted, source rocks were encountered in the Reith Bank #1 well. (TOCs up to 6.7%).

Seychelles' oils (see GCMS) and source rocks seeGCMS) reflect the initial, but successful phase of rifting (200ma) and the biomarker traces shown here, extracted from side wall cores, clearly show an oil extract with the classic saline, stressed carbonate origins; namely elevated C_{29} Pentakishomohopane doublet, the elevated C_{35} norHopane, Gammacerane and low Diasterane peaks. The same signature can be seen in the majority of the tar balls washed up around the islands.



PermoTriassic



Ref Bosca de Wit 2003

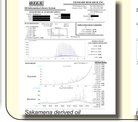
Contender 1a

Oils, Madagascar & Tanzania

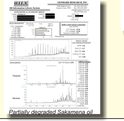
- Lacustrine derived oil
- Low maturity oil
- Other occurrences:
  Mozambique, coastal Rovuma, Pemba seeps said to be Triassic (and lower Jurassic sourced)

Source Rocks

- Mid Triassic Pindiro evaporates (10% TOC)
- Permian source rocks, Lake Nyasa, Tanzania
  Maji-ya-Chumvi, Permo-Triassic, lacustrine fish beds in Ria, Kalui #1, southern Kenya



Sakamena derived oil



Partially degraded Sakamena oil

Permo Triassic lacustrine derived oil, Tanzania

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The Seychelles Oils

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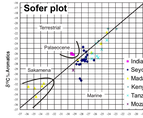
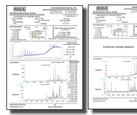
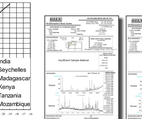
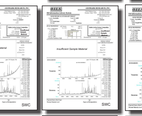
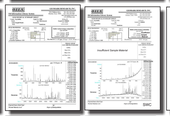
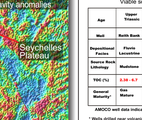


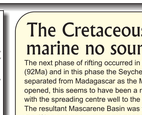


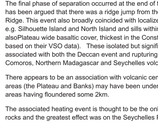


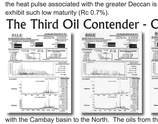


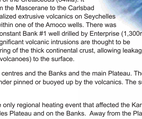


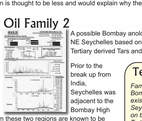




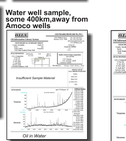








Water well sample, some 400km,away from Amoco wells

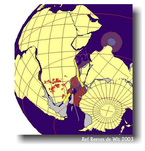


Present day hydrocarbon accumulations on the flanks of a former inland sea / lake complex at Liassic times

The development of world class source rocks can be seen on both sides of the rift margin. The Liassic of Tanzania, for example in the Mandawa basin Type I source rocks exhibit TOC values up to 8.7%. The Liassic in Seychelles AMOCO wells reach 5.8%, however the HI values are low due to elevated maturity in the well location. The following figure shows GCMS data for two oils collected from Northern Tanzania (fig Contender 1b). Similar oil extracts have been collected in Kenya.

Interestingly the thermal maturity of all Seychelles' oil extracts and the tars is low. This implies a low geothermal stress from the Liassic, or earlier, onwards. (fig GCMS of Seychelles oil). The initial phase of rifting did not invoke oceanic spreading ridges and consequent high heat flow. Eastern Gondwanaland moved obliquely along the Davies Fracture Zone. There were no spreading centres. The rifting of Seychelles from Madagascar in the vicinity of Seychelles appears not to have involved any significant spreading centres and possibly no centres at all. The Deccan event was perhaps the most significant, albeit distal and short lived.

Lower Jurassic



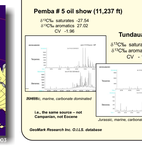
Ref Bosca de Wit 2003

Contender 1b

Western Indian Ocean Margin, Lower Mesozoic Oils; Tanzania, Kenya

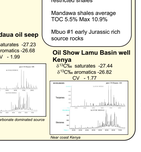
Pemba 8 5 oil show (11,237 ft)

$\delta^{13}C_1$ saturates -27.64
$\delta^{13}C_1$ aromatics 27.02
OV - 1.96



Tundaua oil seep

$\delta^{13}C_1$ saturates -27.23
$\delta^{13}C_1$ aromatics -26.68
OV - 1.99



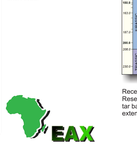
Contender 1b
Source rocks
Thick synrift-eeudic lagoonal marginal marine restricted shales

Mandawa shales average TOC 5.5% Max 10.9%

Mbuo #1 early Jurassic rich source rocks

Oil Show Lamu Basin well Kenya

$\delta^{13}C_1$ saturates -27.44
$\delta^{13}C_1$ aromatics -26.82
OV - 1.77



New coast Kenya

Source: marine, carbonate dominated

Lacustrine, marine, carbonate dominated source

C_{29}, the same source – not Comparison, not Excess

GeoMark Research Inc. O.I.L.S. database

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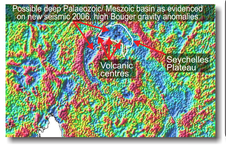
Seychelles source rocks

Seychelles Petroleum



The source rocks of Seychelles

	Viable source rocks			Non-source rocks	
Age	Upper Triassic	Early Jurassic	Middle-Jurassic	Late Jurassic-Early Cretaceous	Maastrichtian
Well	Reith Bank	Sangail Bleuch (Reith Bank)	Dzumi Bank (Reith Bank)	Dzumi Bank	Reith Bank (Sangail Bleuch)
Depositional Facies	Fluvio Lacustrine	Deltaic/ Lagoonal	Marginal marine (inner shelf	Carbonate	Marine (inner shelf
Source Rock Lithology	Mudstone	Mudstone	Carbonate	Mudstone siltstone	Mudstone
TOC (%)	2.38 - 6.7	Up to 5.8	Up to 2%, Max 5%	0.8 - 1.7	0.73 - 7.82
Overall Thermal Maturity*	Early Mature	Mature	Oil Mature		

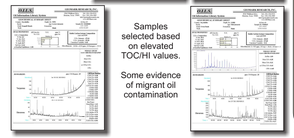
AMOCO well data indicate that the pre and early rift sequences contain the source rocks

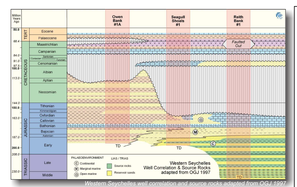
*Wells drilled near volcanic centre. Offshore source intervals likely to be very much less mature

Lower Jurassic Shale Extracts

Samples selected based on elevated TOC/HI values.

Some evidence of migrant oil contamination





Recent work on source rocks and migrant oils from Seychelles undertaken by GeoMark Research has demonstrated a positive correlation between the well data (source and shows) tar balls and contaminant oil in the Coetivy water well, indicating the presence of a regionally extensive and potent Karoo source rock system.

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The Cretaceous, open-marine no source rocks

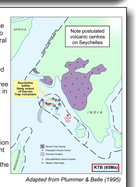
The next phase of rifting occurred in the Cretaceous (92Ma) and in this phase the Seychelles and India separated from Madagascar as the Mascarene Basin opened, this seems to have been a relatively quick event with the spreading centre well to the south of Seychelles. The resultant Mascarene Basin was fully marine early on in the rifting and no source rocks appear to be associated with this event. Oxic open ocean conditions prevailed throughout the Cretaceous, this was not conducive to source rock formation.

The Kimbaji wells in Tanzania have often been cited as the type examples for Cretaceous source and closer inspection of the well data clearly shows that no source rocks whatsoever are present. (Ref. CJ Matchette Downes, Entebbe 2005). None of the Amoco (or Enterprise) wells on Seychelles, TOTAL's Simba #1 deep water well in Kenya or the recent Nyuni well encountered a Cretaceous source. Only low values and type III/IV kerogens were reported in these wells and in Madagascar.

So there are no Cretaceous oils to chart the Cretaceous event.

Coeval with the late Cretaceous/ Early Tertiary alkaline volcanic activity believed to have originated from several centres on Seychelles Plateau (Stephens and Davey, 1992) which, it is postulated, are represented by localized high Bouguer gravity anomalies. The three AMOCO wells were drilled in close proximity to one or more of these gravity anomalies, hence the elevated maturities, which are atypical of the region.

Palaeographic reconstruction showing the possible extent of the Deccan Trap volcanism coincident with the Cretaceous / Tertiary boundary (KTB)



Adapted from Plummer & Belle (1995)

Ref Bosca de Wit 2007

Tertiary

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The Tertiary

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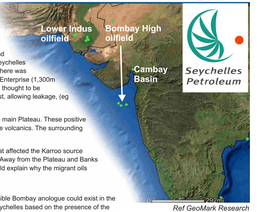
The final phase of separation occurred at the end of the Cretaceous (64Ma). It has been argued that there was a ridge jump from the Mascarene to the Carlsbad Ridge. This event also broadly coincided with localized extrusive volcanics on Seychelles e.g. Silhouette Island and North Island and sills within one of the Amoco wells. There was also/Palaeo wide basaltic cover, thickest in the Constant Bank #1 well drilled by Enterprise (1,300m based on their VSO data). These isolated but significant volcanic intrusions are thought to be associated with both the Deccan event and rupturing of the thick continental crust, allowing leakage, (eg Comores, Northern Madagascar and Seychelles volcanoes) to the surface.

There appears to be an association with volcanic centres and the Banks and the main Plateau. These positive areas (the Plateau and Banks) may have been under pinned or buoyed up by the volcanics. The surrounding areas having foundered some 2km.

The associated heating event is thought to be the only regional heating event that affected the Karroo source rocks and the greatest effect was on the Seychelles Plateau and on the Banks. Away from the Plateau and Banks the heat pulse associated with the greater Deccan is thought to be less and would explain why the migrant oils exhibit such low maturity (Ro: 0.7%).



Ref GeoMark Research O.I.L.S. Database

Third Oil Contender - Oil Family 2

A possible Bombay analogue could exist in the NE Seychelles based on the presence of the Tertiary derived Tars and remnant geological fabric.

Prior to the break up from India, Seychelles was adjacent to the Bombay High with the Cambay basin to the North. The oils from these two regions are known to be derived from Tertiary source rocks with a considerable amount of higher plant/terrestrial input. It is perhaps no coincidence that some of the tars washed up on the Northern Islands, Praslin in particular, are perhaps also derived from a local Tertiary source yet to be encountered by the drill bit.

The analysis of the Praslin tars reveals the presence of large amounts of Oleanane and other higher plant biomarkers. (See GCMS of Praslin tar vs. Bombay High Oil).

These highly waxy oils have all the characteristics of classic higher plant derived oil. The suggestion is that, prior to break up, a precursor basin existed with ideal conditions for the development and accumulation of plant debris, there are many examples. As the basin pulled apart three areas of accumulation resulted; Cambay, Bombay High and NE Seychelles and the right conditions for the accumulation and preservation of plant matter continued into the Oligocene and then the accumulations of organic matter were drowned.

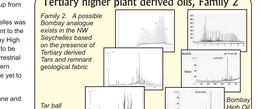
At the moment there are no wells in Northern Seychelles to test this hypothesis unlike for the Liassic and Upper Triassic source rocks found in the AMOCO wells on the south western flank of the Plateau. Both oils are waxy and share similarities, so care is needed when determining the origin of tar balls. The 'northern' family (family 2) of tar balls are more mature (Ro: 1%) perhaps reflecting a greater heat input from the more proximal, but waning Deccan event.

GCIRMS is perhaps the best way to distinguish the two families. It is therefore perhaps possible to speculate that there is a conjugate Bombay/Cambay source kitchen in Northern Seychelles.

As the western Indian Ocean margin is explored there will be a greater number of oil samples available to tighten this early correlation. It would be difficult to separate a mix of older lacustrine oils from the overlying Liassic oils.

Tertiary higher plant derived oils, Family 2

Family 2. A possible Bombay analogue exists in the NW Seychelles based on the presence of Tertiary derived Tars and remnant geological fabric



Conclusions

Interior/failed rifts Oil family 1a & 1b

Inboard of the western Indian Ocean and early conjugate East Indian Ocean fringe the source rocks were deposited in interior / failed rifts (eg Selous, Ruvu, Mandawa, Ruvuma, Lamu, etc) and the presence of these intermontaine basins can be evidenced through analysis of the resultant oils. (Tsimiroro and Bemolanga 28 billion bbls.)

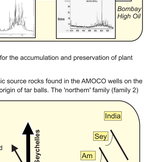
As rifting became successful through the early Jurassic, progressively less stressed environments prevailed, resulting in oils with a marine carbonate signature.

Eventually fully marine conditions were established from mid Jurassic times to the present day, thus preventing the formation of source rocks.

a) Lacustrine settings predominate
b) Increasing salinity (Gammacerane)
c) Restricted / stressed environments depleted ^{13}C, diagnostic biomarker assemblages: C_{29} Hopanes, C_{35} Hopane and Pregnane

Higher Plant Tertiary Oils, Family 2

Relict graben structures allowed the accumulation of significant quantities of higher plant matter with high lipid content at times of optimal sea level, giving rise to highly enriched source rocks and the potential to generate significant quantities of oil eg Bombay High (5.5 billion bbls, 15.8 tcf) Cambay Basin (2.0 billion bbls, 3 tcf)and Indus Basin oils. Could such a play exist in the NE Seychelles given the presence of the Tertiary Tars and well and similar palaeography?



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