Libya's mature & frontier basins

New opportunities for hydrocarbon exploration and production with an emphasis on Palaeozoic prospectivity

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Libya has been a global favourite for hydrocarbon exploration ever since 1956, when the first wildcat well was drilled. This attraction was primarily a result of the phenomenal success rate of oil discovery in the Sirt Basin (Figure 1) where 19 of the 21 giant fields, with recoverable reserves of 40 billion barrels of oil (bbl), are located. Surprisingly, its ease of exploitation has not diminished the drive for hydrocarbon exploration in neighbouring basins to the west (Ghadames) and southwest (Murzuq) where the search for hydrocarbons continues unabated. It is worth noting that several of the most important, recent discoveries were made between 1979 and 2000, in the absence of an aggressive drilling programme. New play concepts developed during this period have undoubtedly contributed to recent successes, through fruitful collaborations between oil companies and academia.

A new phase in the exploration of this vast country has been marked by the return of Libya to the international exploration arena with two bid rounds in 2005 and the arrival of new major international oil companies (IOCs). Armed with state-of-the-art imaging technology and new stratigraphic concepts, the exploration for new oil will extend to the frontier Palaeozoic basins. These include the Murzuq, Kufra and Cyrenaica Platform regions, (Figure 2), as well as the deeper Palaeozoic plays in the semi-mature (Ghadames) and mature (Sirt) basins. The offshore region (Figure 1) is also under-explored but is gaining a new exploration momentum with the launch of new 2D regional seismic and geological research activity.

This article offers a broad overview on petroleum systems in the sedimentary basins of Libya. It highlights recent advances made in geological and sedimentological understanding, especially of the frontier basins and the regional impact these will have on locating twenty-first century reservoirs in the Infracambrian to Palaeozoic sedimentary sequences.

Ever since the early phases of exploration in the 1950s, Libya has been ideally positioned to contribute significant oil exports to neighbouring European markets. Infrastructure developed over recent years, including a subsea gas pipeline to Italy and, most recently, upgrading of refining facilities by IOCs, means that emerging basins will be well served and are thus becoming increasingly attractive.

Only around 30 per cent of Libya has been explored for hydrocarbons. IOCs have, understandably, been reluctant to invest in frontier provinces but Libya's recent exploration history is particular testament to the rewards that can be reaped from exploration of emerging Palaeozoic petroleum systems. In the Murzuq Basin, shows in oil wells in the early 1980s, followed by the discovery of giant fields such as Elephant in 1997, have completely opened-up a vast, formerly condemned, marginal province. The potential of these ancient petroleum systems, still poorly understood and little exploited, is enormous.

Exploration provinces

Based on the age of the hydrocarbon basins, and their sedimentary fill, Libya can be split into two discrete geological provinces. The first province, dealt with first in this article, comprises a belt of tectonically active basins of Mesozoic-Cenozoic age that includes the complex, prolific and mature Sirt Basin in central-northern Libya as well as the emerging NW offshore and NE offshore areas (Figure 1). Discussion of this province pays special attention to the prospectivity of the largely undrilled, deep Palaeozoic succession.

The second province, shown on Figure 2, is a regionally extensive Palaeozoic mega-province, comprising two intracratonic basins in western Libya (Ghadames and Murzuq), and three located in eastern Libya (Kufra, Cyrenaica, and the Daklha Basin on the Egyptian border). During the Palaeozoic, all these basins appear to have been connected along a relatively stable platform area because they show similar sedimentological character and geological history: play concepts, such as regionally developed source rocks, should be readily transferable between them. This province is predicted to contain the largest untapped volume of remaining reserves in Libya (Figure 3) and is set to become of increasing strategic importance.

Tectonically active basin province (Figure 1 - see page 60)

Sirt Basin (Onshore)

Owing to remarkable rates of oil discovery, this mature and successful basin has historically been Libya's exploration focus. Basin formation was initiated

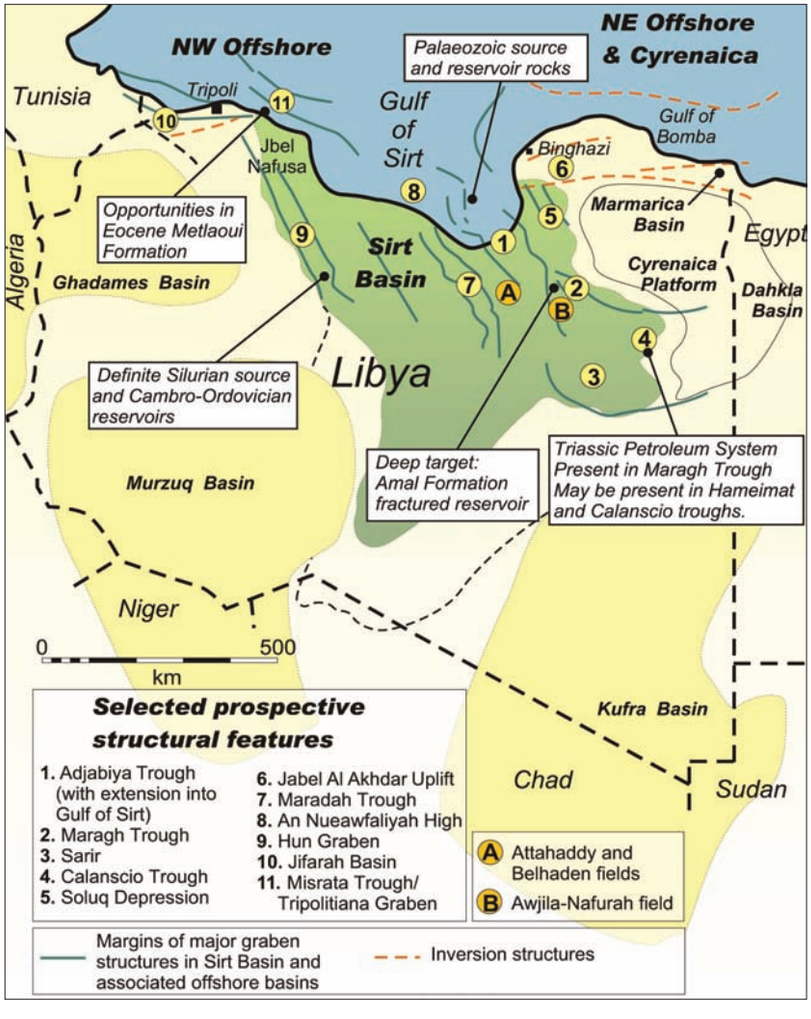
Production in the Sirt Basin comes from more than 20 intervals ranging in age from Precambrian to Oligocene

by the post-Hercynian collapse of the NE-SW trending Sirt Arch, forming a rift basin with NW-SE trending horst and graben structures. The basin fill can be divided into pre-rift, syn-rift and post-rift successions.

Most oil pools discovered are located on horst structures at relatively shallow depths. The grabens, where exploration potential is equal if not greater than the horst structures, remain almost unexplored and thus can be considered a new exploration frontier within the Sirt Basin.

Production in the Sirt Basin comes from more than 20 intervals ranging in age from Precambrian to Oligocene, but the most important finds have been in the Lower Cretaceous Nubian sandstone, although Palaeocene reefs are also important reservoirs. Hydrocarbons are sourced from Upper Cretaceous and Paleocene shales, and numerous oil traps occur both within the sedimentary fill and by wedging out against basement.

Figure 1: Map illustrating key, prospective and underexplored elements of Libya's tectonically active basin province, a region encompassing the successful Sirt Basin and frontier NW offshore, NE offshore and offshore Cyrenaica Platform.



Emerging Mesozoic petroleum systems: A Triassic petroleum system, relating to the earliest phases of Sirt Basin development (early synrift), is known from the eastern Sirt, Maragh Trough, and may also occur in the axes of the Hameimat and Calanscio troughs. Source rocks are mid-Triassic lacustrine shales with type II and III kerogen, derived from land and lake plants. It is known that the giant Awjila-Nafurah field was at least in part fed from this source. The Triassic petroleum system is still poorly understood and will be the focus of new exploration in this region.

Mid-Cretaceous "variegated shales" are under-investigated but viable source rocks, and may have considerable potential as the regional overview by Donald Rusk (2001) revealed. They have a Total Organic Carbon content of ~3 per cent. These lacustrine to marginal marine shales, of Early Cretaceous (Barremian-Aptian) age, are recognised in the Maradah Graben and southern Hameimat Trough. In the Sarir area of the southern Hameimat Trough this source rock yields a waxy crude with mostly type II and III kerogen. This source rock is probably locally developed, having fed adjacent structures. Predicted to have developed in southern areas of Sarir, this interval will be pursued in future exploration programmes.

Deep Palaeozoic reservoirs: Production is already occurring from deeper Palaeozoic reservoirs in the central Sirt Basin. In the south-central region, fractured quartzite forms an attractive hydrocarbon-bearing fairway. Definitive ages for these reservoirs, deposited in a subtidal to shallow marine environment, are Late Cambrian, Late Devonian and Devonian-Carboniferous. The giant Attahady gas reservoir of Late Cambrian age, and the Belhaden reservoir of Late Devonian to Early Carboniferous age, are located within this fairway in the south central Sirt Basin. In the Maragh Trough, eastern Sirt Basin, where deep targets are also increasing in importance, the Amal Formation is a major fractured sandstone reservoir. Fossil evidence shows that the upper part of the Amal is Triassic but the lower part is of probable Cambro-Ordovician age. A possible Infracambrian play in the Maragh Trough is untested, and Permo-Carboniferous sands have additional reservoir potential.

According to NOC figures, ~ 131 bbl of oil have been recovered from the Sirt Basin, but with

381 bbl expelled from source rocks, some 250 bbl remain unaccounted for. It is anticipated that a significant volume of these yet to be recovered reserves are located in deep, Palaeozoic pre-rift reservoirs. In the western extremity of the basin (Hun Graben), a definite Silurian source rock, the Tannezuft Formation, exists. According to the work of Belhaj, a complete Palaeozoic sequence is preserved beneath it - including unexplored Cambro-Ordovician reservoirs.

Eastern Sirt Basin and Cyrenaica (Offshore)

In the Gulf of Sirt Basin, offshore on the An Nueawfaliyah High, small gas pools are known to exist in the Cretaceous/Tertiary sediments, and were probably sourced from Upper Cretaceous shale to the north. This area will receive considerable attention for new exploration with the completion of current 2D seismic profiling.

Deep Palaeozoic plays: Silurian shales (Tannezuft Formation) are the main source rocks and Cambro-Ordovician (Gargaf Group) key reservoirs in the hydrocarbon system of the Palaeozoic mega-province, which is discussed in detail below.

In the eastern offshore Sirt Basin, graptolitic shale of the Tannezuft Formation has been drilled, locally capping a basal sandstone that is probably Silurian or older. Potential upper Ordovician shallow marine sand reservoirs are known from onshore Cyrenaica.

Palaeogeographic reconstructions for this region produced by Smith and Kirki (1996) show the deposition of shallow marine clastic reservoirs of Cambro-Ordovician age capped by Silurian shale, with reservoir geometries potentially influenced by NW-SE transtensional faults. These intervals have not been explored but comparison of stratigraphy to the neighbouring Cyrenaica Platform and Ghadames Basin suggest that offshore Sirt may also share elements of the same hydrocarbon system.

Mesozoic and Cenozoic petroleum systems: The tectonically active basin province also encompasses the Cyrenaica offshore and the bordering Jabal Al Akhdhar onshore area. In offshore Binghazi, one proven oil discovery occurs in the Lower Cretaceous and basal Upper Cretaceous carbonates which were sourced from the Jurassic shales. South of Binghazi, both the offshore and onshore portions of the Ajdabiya Trough are under-explored and are attracting the attention of IOCs in present and future bid rounds.

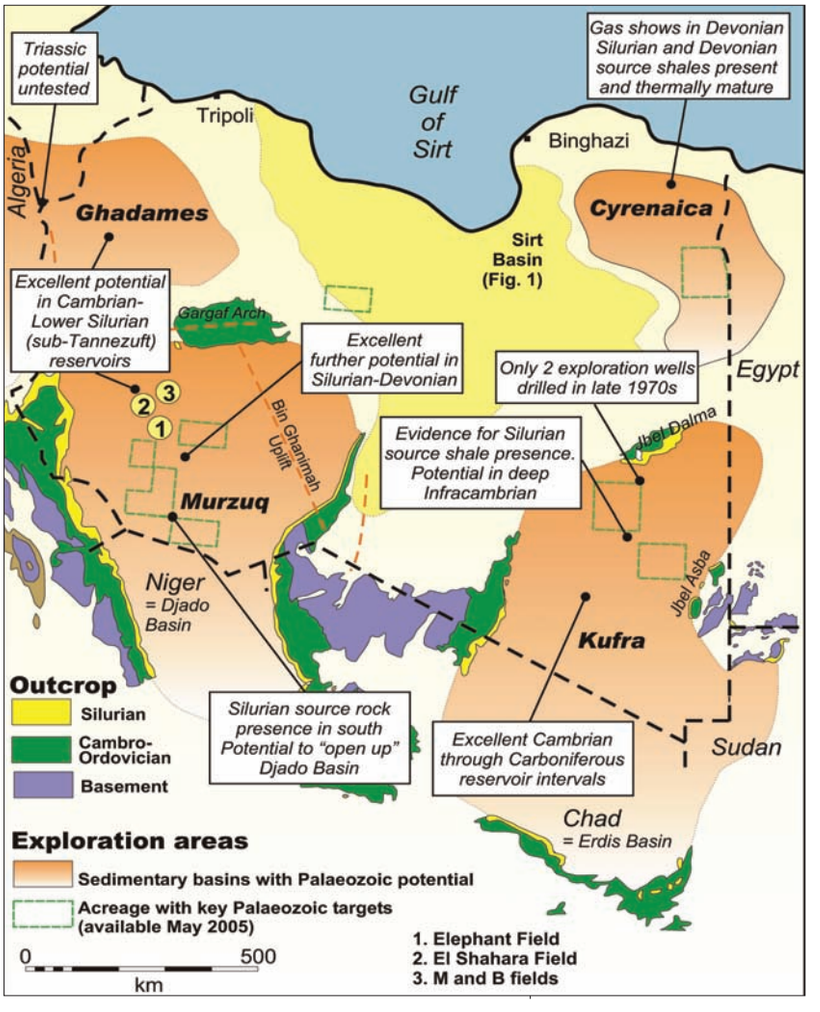
Oil seeps occur onshore in off-bank facies of the Eocene age carbonates. These carbonates (nummulitic limestones) are equivalent to the Metlaoui Formation of Tunisia and western Libya where they form an important fairway (see below). In onshore northeast Cyrenaica, an oil discovery was made in this interval in the 1970s, prior to those in the Metlaoui of Tunisia and Western Libya. In this early phase of exploration, its importance was overlooked.

One deep offshore well has been drilled in the Gulf of Bomba in northeast Cyrenaica, together with several onshore wells in the coastal region (Marmarica Basin). The latter wells terminated in Jurassic sediments. They show similarities to the Binghazi offshore oil well and the area is now under active investigation following the May 2005 bid round.

The eastern part of this region is virtually unexplored. In common with onshore NE Cyrenaica, lower Eocene Metlaoui carbonates provide much promise as they have successfully yielded oil and gas condensate further west in the far NW offshore. There have also been shows within the Misrata Trough and onshore Jifarah Basin, although no discoveries have yet been made. Silurian source rocks, the famous "hot shale", should also be present.

Potential upper Ordovician shallow marine sand reservoirs are known from onshore Cyrenaica

Figure 2: Map showing key basins and opportunities (acreage as of May 2005) in Libya's Palaeozoic Mega-Province.



Eocene carbonates in NE Libya provide much promise as they share similarities with the Metlaoui carbonate reservoirs in the NW offshore

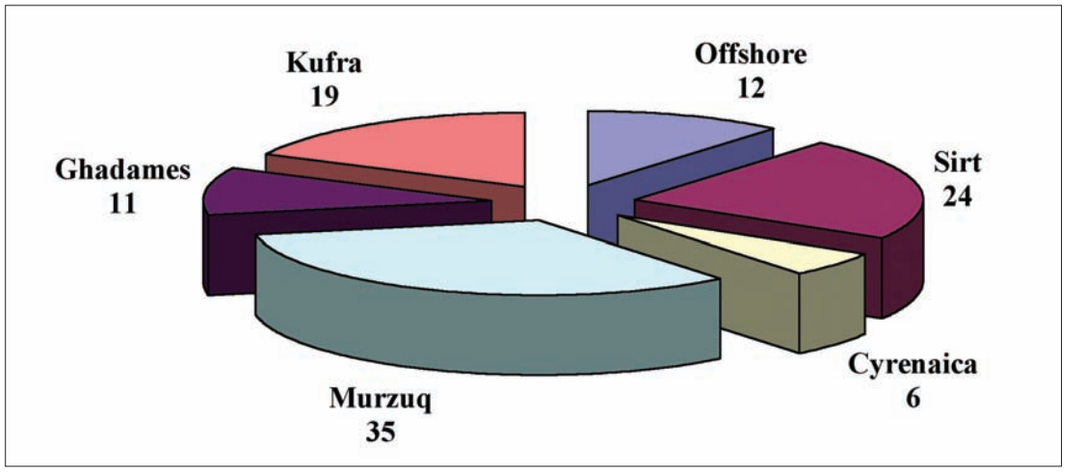


Figure 3: Remaining hydrocarbon potential of the sedimentary basins of Libya (based on 1999 National Oil Company estimates). Pie chart shows estimated reserves from a 1999 total of 107 billion barrels, though this has now been revised upwards. The "offshore" includes prospective areas in the Mediterranean offshore Sabratha Basin (Misrata Trough, Tripolitiana), Gulf of Sirt, and Cyrenaica (Gulf of Bomba, offshore Binghazi) areas.

There are also shows in the Triassic, which also hosts source shale, and within the Permian (Palaeozoic).

Future outlook for Sirt Basin surrounding area

• Enhanced recovery from existing reservoirs will be possible using 4D seismic. Application of 3D seismic to existing plays will enhance exploration of proven intervals;

• The distribution of Triassic and Lower Cretaceous source rocks should be fully evaluated, as they are particularly important in the east of the basin;

• Volumetric studies (low percentage of oil discovered: oil expelled) point to the strategic importance of deep targets in the SE Sirt Basin;

• The Infracambrian-Carboniferous interval has exploration potential in the Maragh Low;

• Mesozoic and Palaeozoic plays in deep trough areas deserve serious consideration.

Figure 4: Glacial striations within the Upper Ordovician Mamuniyat Formation. A major glaciation affected Libya in the Late Ordovician, depositing sands which are now the best oil reservoir in the Murzuq Basin.

Palaeozoic Mega-Province
(Figure 2 - see page 61)
Ghadames Basin

The semi-mature Ghadames Basin is the second most important basin in Libya in terms of production, which currently comes from fluvio-deltaic sands of mid-Late Silurian (Acacus Formation) and Devonian age ("A" unit, Tadrart and Kasa formations). These plays have been successfully explored to the neglect of both shallower and deeper targets.

Emerging Mesozoic reservoirs: Anadarko has made significant discoveries in the Berkine Basin, eastern Algeria, within the Triassic. The Libyan equivalents of the so-called TAGI reservoirs in eastern Algeria have excellent potential within the Ghadames Basin, particularly since attractive buried channels/ palaeovalleys are imaged on seismic data. Like their Algerian counterparts, these palaeovalleys may contain major oil accumulations.

Silurian reservoirs: In the 'Z' Field, western Ghadames Basin, lower-Mid Silurian sands return up to 1000 BOPD from the so-called Z 2-Pay. This

unit correlates with the upper Tannezuft Formation, a principal source rock in its lower part in western Libya. This pay occurs in several concessions in northwest Ghadames Basin. Amplitude anomalies within the Acacus-Tannezuft transition demonstrate the development of stratigraphic sand pinch-outs within the Tannezuft Formation, on the flanks of many structures. Seismic stratigraphic studies and special processing tools including 3/4D seismic study will permit the delineation of these stratigraphic plays in future exploration drilling.

Cambro-Ordovician reservoirs: No significant discoveries have yet been made in the Cambro-Ordovician interval in the Ghadames Basin, yet in the neighbouring Murzuq Basin to the south, Mid and Upper Ordovician sands are major reservoirs in giant fields such as the Elephant discovery (NC174). In this region, Ordovician sands are often topsealed and sourced by the Lower Silurian Tannezuft Formation ("hot shale"). In the Ghadames Basin, like the Murzuq Basin, the Tannezuft shale is considered the major source rock (an estimated >200 bbl oil expelled), although the upper Devonian Awaynat Wanin shale is also of great importance. With the neighbouring Murzuq Basin in mind, there is no reason why Cambro-Ordovician reservoirs should not be exploited with equal success. Several concessions were identified in the May 2005 bid round where Late Ordovician sands were reservoir targets, and potential accumulations in fault closures or hydrodynamic traps.

Murzuq and Kufra basins

Available geological evidence indicates that these basins share a closely similar geological evolution, pointing to a common history of source rock deposition, petroleum generation, hydrocarbon migration and entrapment.

The Murzuq Basin was unproven until the early 1980s, but 4 large discoveries, including a giant field, as well as 16 smaller discoveries and 12 shows, have since been made. These discoveries have shattered previous scepticism that the basin was marginal with little promise. Lower Silurian source rocks, estimated by Lüning and co-workers in 2000 to be the source of some 90 per cent of North Africa's Palaeozoic hydrocarbons, are present. Mid to Upper Ordovician sandstones (Figures 4 & 5) are major reservoirs and the primary exploration target, with Mid to Upper Silurian Acacus sands a secondary play. Major fields including Elephant, El Shahara, M and B fields, testify to a successful European exploration programme prior to re-entry of the American companies. During the course of this programme, new play concepts have been generated to form the building blocks of 21st century exploration. Today, like the Murzuq Basin 25 years ago, the Kufra Basin is a high-potential frontier area.

Exploration in the Palaeozoic of the Murzuq Basin will benefit from comparative analysis of aspects of the petroleum system in the neighbouring Illizi Basin of Algeria, and vice-versa.

Silurian and Devonian reservoirs: Well established in the Ghadames Basin, this interval forms a secondary play in the Murzuq Basin after the Cambro-Ordovician. Targets include delta-top sands, with potentially large oil accumulations occurring in incised valleys near the boundary between Silurian (Acacus Formation) and Devonian (Tadrart Formation) rocks. The Late Devonian (Frasnian-Fammenian), a well-known source rock in the Illizi and Ghadames basins, is expected to form a regional seal for Devonian reservoir sands.

Ordovician reservoirs and source rocks: Sands near the top of the Cambro-Ordovician succession (Mamuniyat Formation) are excellent exploration targets because of their intimate relationship with the transgressive Lower Silurian source shale that lies above them. This shale developed in "pools" in topographic depressions between "buried hills" following the retreat of the Late Ordovician ice sheets (Figure 4). The buried hills define the flanks of large palaeovalleys carved directly by ice sheets or their meltwater. The valleys acted as repositories that trapped sediment including attractive, clean reservoir sands (Figure 5). The Silurian source shale occurs where the valleys were ▶

Exploration in the Palaeozoic of the Murzuq Basin will benefit from comparative analysis of aspects of the petroleum system in the neighbouring Illizi Basin of Algeria, and vice-versa

Figure 5: Spectacular sandstone columns of the Upper Ordovician Mamuniyat Formation at the flanks of the Murzuq Basin, SW Libya (north of Ghat town). These rocks are key reservoirs in the subsurface Murzuq Basin. Cambro-Ordovician reservoirs will be of increasing importance in the subsurface Ghadames and Kufra basins, and under the Cyrenaica Platform. Their attraction lies in exceptional permeability and close communication with overlying Silurian source shales, which form a regional seal.

not completely filled with glacial sands.

In the first EPSA-IV bid round, the concept of an intra-Upper Ordovician source rock was introduced by the National Oil Company (NOC) for the Murzuq Basin. However, there is mounting evidence for at least two laterally extensive shaley units separating glacial reservoir sands across North Africa. Their oil-generating potential has never been properly evaluated. Underlying shallow marine/tidal sands of the Haouaz or Ash Shabiyat formations are prospective reservoirs but these are less commonly in direct communication with the Lower Silurian source rock and topseal than the overlying Mamuniyat Formation. There are excellent prospects for Ordovician source rocks within the Ash Shabiyat Formation with a major shale interval and flooding surface already identified.

In the Murzuq Basin, the Late Ordovician Mamuniyat Formation, underlying Haouaz Formation (mid Ordovician) and Hassouna Formation (Cambrian) will be important targets. Exploration in the latter area, where the Tannezuft source shale is known to be present, is also expected to open up the exploration opportunities in the southern extension of the Murzuq Basin (=Djado Basin in Niger).

Potential of Cambrian and "Infracambrian" petroleum systems

Boreholes in the Ghadames basin have encountered Infracambrian quartzite of the Mourzidie Formation, and are also present in the Murzuq and Kufra Basin. In Kufra, large pull-apart basins with a threefold sedimentary fill have been recognised on seismic lines. These ancient rocks share similarities with equivalent-age pull-apart basins in Oman, including the same threefold subdivision. In Oman, the middle unit of this basin fill is organic-rich. In the Kufra, Murzuq and Ghadames Basins, there have been no serious attempts to evaluate the potential of Infracambrian petroleum systems, which could represent a key element of Libya's unfound reserves.

Cyrenaica Platform

Exploration in the Mesozoic and Tertiary: With the aid of newly acquired 3D seismic data, Arabian Gulf Oil Company (AGOCO) has made new Mesozoic discoveries south of Binghazi in the Soluq Depression, NW Cyrenaica Platform. To the east of this discovery, the Jabel Al Akhdar region also holds potential in the Jurassic and Cretaceous. A rapidly subsiding trough during the Mesozoic, this region preserves an almost complete Mesozoic stratigraphic record.

Exploration in eastern Cyrenaica could potentially mirror recent successes across the border in Egypt. In the neighbouring Western Desert, significant discoveries in multiple oil-bearing intervals in the Jurassic and Cretaceous have recently been made in the El-Diur Concession. Sharing many stratigraphic similarities with the Mesozoic of Cyrenaica, source rock ▶

Stratigraphic comparison to the neighbouring Cyrenaica Platform and Ghadames Basin suggests that offshore Sirt may also share elements of the same Palaeozoic hydrocarbon system

Figure 6: Glacial channels are large glacial valleys (450 Million years old) cut within the Ordovician Mamuniyat Formation on the Gargaf Arch, Libya. These valley systems were cut by glacial melt waters and filled with reservoir-prone sands, yielding stacked oil bearing pay zones. These glaciogenic sands will remain a primary exploration focus in southern basins of Libya and adjacent regions.

intervals will occur in the Jurassic-Lower Cretaceous.
Deep Palaeozoic plays: A large, unexplored Palaeozoic frontier basin lies beneath the Cyrenaica Platform that deepens toward the Egyptian border, showing remarkable similarities to the Ghadames Basin. This basin, which was the focus of the second bid round in 2005, is under-explored. The area has remained under-explored because of the high success rate in the adjacent Sirt Basin. Gas has already been found in Late Devonian sand reservoirs (BP Well B1-2).

Both Silurian and Devonian source rocks occur in Cyrenaica. These are thermally mature, and, in common with the Western Desert, a Carboniferous source rock should also be present. Viable traps should occur within faulted structural closures with additional pays where reservoirs are juxtaposed against pre-Late Cretaceous unconformities. Similar Infracambrian and Cambro-Ordovician sequence sands to those in the Kufra Basin are also present. Where there is good communication between these and Silurian source rocks, they are expected to provide excellent reservoirs.

Future outlook for Palaeozoic Mega-Province

• In some new contract areas, no less than 14 shale-prone intervals with source potential are recognised in the Ordovician-Carboniferous succession;
• Exploration efforts must address the origins of heterogeneities within the Cambro-Ordovician succession, particularly those within the Late Ordovician glaciogenic target. These studies will also be invaluable for modelling during the production phase. In the northernmost sector of the Ghadames Basin, carbonate build-ups, with major thickness changes also occur in the upper Ordovician. These require detailed evaluation;
• The search for Palaeozoic oil across Libya should not be restricted to traditional Silurian and Devonian intervals. As Cambro-Ordovician reservoirs increase in importance, so new play concepts entertain the possibility of three new source rocks - one within the Ash Shabiyat Formation, and two additional sources within the Mamuniyat Formation.

Conclusions (Figure 7)

The short review presented here demonstrates the high potential of finding new oil fields. Many international surveys conducted in the last seven years rank Libya as one of the top destination of IOCs for new oil exploration. One of the key challenges to IOCs is to undertake high-risk, high-reward exploration for deeper Mesozoic and older Palaeozoic petroleum systems in both mature and frontier provinces. In doing so, a regional approach to these petroleum systems will be necessary, utilising subsurface data and field observations to generate new play concepts across Libyan sedimentary basins.

The Kufra, Murzuq and Ghadames Basins could represent a key element of Libya's unfound reserves

Figure 7: A simplified summary of Palaeozoic hydrocarbon occurrences and the of Palaeozoic systems in mature (Sirt), semi-mature (Ghadames) and Frontier Sedimentary basins (Murzuq, Kufra & S.Cyrenaica) of Libya.

BASINS AGE	Sirt (onshore)	Sirt (offshore)	Ghadames	Murzuq	Kufra	Cyrenaica
Permo-Carboniferous	**West**: Unexplored. Gas potential (central area) **Central**: Sands with gas potential **East**: Volcanic sand reservoirs with oil/gas shows	Unstudied	Underexplored	Unstudied	Underexplored. Potential reservoir	Understudied. Sand reservoir
Devonian	**West:** Unexplored but reservoir sands and possible source rocks **Central**: Highly prospective gas reservoirs - Belhaden field **East**: Unknown	Unstudied. Reservoir sands and source shale likely	Principal reservoir/source interval. Excellent additional potential	Secondary source, good quality sands. Underexplored	Underexplored. Good quality sands. Secondary source potential from shales	Excellent source and reservoir with gas potential
Silurian	**West**: Good quality, understudied source present **Central**: Unknown **East**: Unknown	Understudied. Graptolitic shale with source potential recorded	Key reservoir/source interval. Z-2 pay within Tannezuft Formation and stratigraphic traps. Underexplored	Principal source. Deltaic sand reservoirs. Unexplored, prospective	Underexplored. Source rocks understudied, lack of data, presence predicted in local pools	Excellent source potential. Underexplored
Ordovician	**West**: Unexplored, though good quality reservoir sand present **Central**: Understudied but gas prospective **East**: Lower Amal: oil producing sands	Reservoir sands	Underexplored but highly prospective	Principal reservoir and additional source potential	Unexplored. Reservoir characteristics similar to Murzuq, prospective	Underexplored. Good quality reservoir sand
Cambrian	**West**: Unexplored **Central**: Late Cambrian highly prospective. Excellent gas sandstone reservoir in Attahaddy field **East**: Lower part of Amal formation - excellent oil reservoir	Reservoir sands	Underexplored. Prospective	Unexplored. Prospective	Unexplored. Prospective	Unknown. Possibly eroded
Infracambrian	**West**: Unknown **Central**: Unknown **East**: Possible presence in sand reservoirs of Maragh Trough	Unknown	Unexplored	Unexplored. Half-grabens	Unexplored. Pull apart basin on seismic lines, similarities with Omani pays	Unstudied. Potential sand reservoirs