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Future Exploration and Exploitation Potential

8.1 INTRODUCTION

Large amounts of oil and gas have been discovered in Libya in the 60 years since exploration began, and large reserves remain to be produced. This chapter will attempt to examine some of the key features: discoveries already made, production, remaining reserves, incremental reserves and yet-to-find reserves, and will offer comments on under-explored and poorly explored areas, neglected hydrocarbon plays, and on strategies for developing discoveries currently regarded as subcommercial.

Much obfuscation exists in the discussion of hydrocarbon reserves as organisations attempt to promote or protect their interests, so a few critical definitions may be helpful. Oil in place is oil in the ground, proven reserves are those established by appraisal drilling to determine the extent and thickness of the oil or gas pool, recoverable reserves are those which can be extracted, remaining reserves are those remaining to be produced, and ultimate potential is the total amount produced when the pool (or field, or province) is finally abandoned. Primary recovery is oil produced without resort to significant additional extraction techniques, and is commonly about 20–25% of the oil in place, but in order to increase production secondary recovery options are available, from water or gas injection to the installation of downhole pumps, drilling of deviated wells, fracking, and various other physical, chemical and biological methods. As an example the Intisar fields have a primary recovery rate of less than 10%, but with water injection this can be increased to over 30% and with additional gas injection to almost 70%. These are known as enhanced oil recovery (EOR) techniques. Consequently the calculation of recoverable reserves needs to be qualified with a statement as to what EOR techniques have been applied to a given field. Since EOR techniques can be very expensive they are not normally commercially viable for small or difficult fields, so it cannot be assumed that EOR techniques are generally applicable on all (or even a majority of) fields. The same comments are applicable to gas, although the primary recovery figure for gas is usually much higher than oil (often around 75–85%), and gas is more complicated to calculate as its volume increases as pressure is reduced. Some fields in Libya contain free gas (non-associated, that is without accompanying oil, or as a gas cap above an oil pool), but most Libyan fields...
contain associated gas, that is in solution, from which the gas is only liberated during production. This makes the calculation of gas reserves rather difficult. BCF is billion cubic feet ($10^9 \text{ ft}^3$) and TCF is trillion cubic feet ($10^{12} \text{ ft}^3$). Fig. 8.1 shows the various components which contribute to ultimate potential.

**8.2 OIL AND GAS ALREADY DISCOVERED**

The 2,000 or so exploration wildcat wells drilled in Libya have resulted in about 550 discoveries, many of which are very small. These discoveries have been individually examined and oil in place, primary recoverable reserves, production to date and remaining reserves have been calculated for each field. An attempt has also been made to estimate the potential amount of additional reserves which could be recovered by EOR techniques.

A total of 165 fields have been put on production and a further 185 have oil in place of more than 10 million barrels. The total oil in place discovered to date is about 130 billion barrels, and production to the end of 2014 is about 30.4 billion barrels or 23% of the total oil in place. There are 29 large fields with oil in place greater than 1 billion barrels (Fig. 8.2), which account for 68% of all the oil in place. It is a simple matter to show that with an average recovery rate of 30%, remaining reserves would be 8.6 billion barrels, at 35% 15.1 billion barrels, and at 40% 21.6 billion barrels. Of course in practice recovery rates vary widely from field to field, but for the 29 large fields tend to lie between 30% and 55%. These figures however cannot be matched on the smaller fields as the cost of employing EOR techniques becomes disproportionately high, and in any case all of the economic factors are ultimately determined by the oil price. These issues are examined in more detail below.1

The exploitation of Libya’s gas reserves started much later than that of oil. Esso built a gas pipeline to collect gas from Hutaybah, Nasser, Raqubah and a few smaller fields in the 1960s and built an LNG plant at Marsa al Brayqah with a capacity to handle 100 BCF per year, from which gas was exported by LNG tanker. Production began in 1970 and the first shipment was made in 1971. Gas from most other fields was simply flared. However starting in the 1980s a gas-gathering

**FIG. 8.1 Components of Ultimate Potential.**

Ultimate potential is the total amount of oil and gas recoverable from an area. It is made up of hydrocarbons already discovered plus hydrocarbons yet to find, and includes oil and gas recoverable by both conventional and enhanced means and oil and gas already produced.
pipeline system was gradually installed which allowed most gas to be collected and used domestically or exported. The discovery of the large gas fields in the north-western offshore and at Al Wafaa in the Ghadamis Basin led to the construction of a major gas terminal at Mellitah on the coast and ultimately to the construction of the 32 in. GreenStream subsea pipeline to Sicily. The total gas in place (non-associated, gas cap and solution gas) so far discovered is about 72.4 TCF and production to the end of 2014 is about 11 TCF, or 16% of the total gas in place. Assuming an average recovery rate of 75% this suggests remaining recoverable reserves of about 42.6 TCF. There are currently 11 fields with over 1 TCF of original recoverable reserves (ORR) which collectively contain about 53% of all the currently-known recoverable gas reserves.

8.3 EXPLORATION POTENTIAL

There is a constant need to make new oil and gas discoveries in order to maintain, and hopefully to increase, current reserves. Before 2011 the annual oil production rate was about 600 million barrels, and taking 100 million barrels of recoverable oil as a fairly standard sized field in Libya, this level of production would require six new discoveries of this magnitude every year just to maintain the current level of reserves. Looked at another way, experience in Libya shows that about one exploration well in four finds some trace of hydrocarbons, but it has required 2,000 wells to find 130 billion barrels of oil in place. Assuming 30% recovery this means that, using historical data, it would need a minimum of 30 exploration wells per year to have a reasonable expectation of finding the 600 million barrels needed to balance the oil produced. In fact this figure has been reached in less than half the years since exploration began, and there have only been 18 years in which reserves added have exceeded oil produced. Oil reserves in Libya are being depleted faster than they are being replaced.

There are really only five possible solutions to this problem: to drill exploration wells in established oil provinces in known hydrocarbon plays, secondly to develop new plays in these areas, thirdly to extend existing hydrocarbon plays into new areas, and fourthly to develop new plays in new areas. The fifth option is to introduce more EOR schemes to increase recoverable reserves in existing fields. These options will be reviewed below. The following section reviews the exploration potential of Libya’s different basins and regions (Fig. 8.3).
Areas assessed as under-explored and with encouraging exploration attributes are shown with green circles, whilst areas assessed as having few or no encouraging attributes are shown with red circles.
8.3.1 Kufrah Basin

In the Kufrah Basin exploration results have been very disappointing. Although only a relatively small number of wells have been drilled, the indications are not good. None of the three main source rocks of Libya have been found, and most of the Palaeozoic sediments indicate a nearshore setting in which shales—viewed either as potential source rocks or as regional seals—are largely absent. The supposed infra-Cambrian grabens may be present, but evidently have so far given no encouragement for either source rocks or reservoirs. The Silurian hot shale may possibly be present in depositional lows, but wells drilled in these areas have found no trace of it, and the facies of the Tanzuft shales is not encouraging. Samples analysed from Silurian outcrops are discouraging and no hydrocarbon shows of any significance have been found anywhere in the basin. The potential of the basin on present evidence must be rated as low.3

8.3.2 Murzuq Basin

The Murzuq Basin, however, is a different matter. About 45 discoveries have been reported in the Murzuq Basin of which 10 have been put on production, 5 from the Ordovician glacial Mamuniyat Formation, and 5 from the older Hawaz Formation. Almost all the significant discoveries have been made in the northern half of the basin, where the glacial reservoir is well developed, the Silurian hot shale is present and the Bi'r Tlakshin Formation is patchy, so does not form an effective barrier between the source rock and the reservoir. The distribution of the Mamuniyat Formation is determined by the palaeeogeography of the late Ordovician glaciation. It is well developed in a NW-SE trough in the area of the Shararah B and El Feel fields in structures which owe their origin to glacial action, but to the east it is progressively cut out beneath the Caledonian unconformity. In this area, where the Mamuniyat is missing, oil has been able to migrate into the underlying Hawaz reservoir. To the west the Mamuniyat is largely absent on the Tiririne High. There is evidence to suggest that the Mamuniyat Formation passes northwards into a glacio-marine facies, and to the south the quality of the hot shales quickly deteriorates, so the area of prospectivity is limited. There have been reports of traces of oil, and thin zones with high gamma-ray values in Silurian shales from wells in northern Niger (Fig. 5.3), but none of the wells in the southern Murzuq Basin in Libya have shown any encouragement. This leaves two possibilities in the northern part of the basin. Could there be other troughs in which Mamuniyat sands are preserved, for instance to the west of the Tiririne High? And secondly, are there other areas where the Hawaz Formation could be prospective where the Mamuniyat Formation is absent? No significant oil or gas discoveries have been made in younger sequences, but there is good evidence that oil has migrated from the centre of the basin through Middle and Upper Devonian reservoirs to the Qarqaf outcrops. Are there any structures along this route which could have trapped hydrocarbons?4

8.3.3 Ghadamis Basin

The earliest discoveries of oil and gas in Libya were made in the Ghadamis Basin adjacent to similar discoveries in Algeria. The Ghadamis Basin in Libya now has about a hundred discoveries, mostly in structural traps of modest size. The reservoirs are almost all thin sandstone units in formations ranging in age from late Silurian to Devonian, and in a few cases into the Carboniferous. The principal source rock is the Taznbbuhot shale, and there is a second source rock in the Frasnian Cues Limestone. In the northern part of the basin most of the discoveries are in the Silurian Akakus reservoir, but in the south where the seal above the Akakus Formation becomes ineffective, oil is found in the overlying Tadrart Formation of Devonian age. In a few cases oil has leaked up into the Tahara and Marar formations. In the north a number of small discoveries have been made in Akakus sandstones truncated beneath the Hercynian unconformity, sealed beneath Triassic shales or evaporites. There are one or two examples of oil in the Triassic Kurrush (Ra's Hamia) Formation charged by a complex migration route from the Devonian source rock via the Hercynian unconformity, but the prospective area is limited by the extent of the overlying evaporite seal. The most impressive accumulation in the Ghadamis Basin is the Al Wafaa strati-graphic trap in the Devonian F3 sand, in which a large gas field with a thin oil leg is trapped in an up-dip pinch-out of the sand.

There are a number of under-explored plays in the Ghadamis Basin. The section below the Akakus Formation is poorly known, and the Mamuniyat Formation is generally assumed to be in a glacio-marine facies. However recent seismic data suggests that glacially formed structures may be present as far north as Ghadamis, but in this area the presence of the Bi'r Tlakshin Formation between the reservoir and the hot shale could be a problem. The truncation traps beneath the Hercynian unconformity on the northern margin of the basin, particularly in the Akakus and Tadrart reservoirs, merit further investigation. The Devonian of eastern Algeria contains several excellent oil-bearing sandstone reservoirs (labelled F2–F6) which pinch-out towards the east. The F3 sandstone at Al Wafaa is one of these units, and there is the possibility of similar up-dip pinch-out traps in several of these sandstones. The limits of these reservoirs are not well documented in Libyan territory. The Triassic sandstone reservoirs are prolific
oil and gas reservoirs in Tunisia and Algeria, but they thin towards Libya, and the evaporite seal eventually becomes ineffective. There may be prospective traps in the Triassic sandstones in areas where there is a demonstrable migration route between the Devonian source rock and the Triassic reservoir, and where the evaporite seal is intact.5

8.3.4 Jifarah Arch and Terrace

The Ghadamis Basin is terminated to the north by the Jifarah Arch which in turn is flanked to the north by the Jifarah Terrace, and the Sabratah Basin. This area has a complex tectonic history with several periods of uplift and erosion. No significant hydrocarbon discoveries have been made on either the arch or the terrace, but further west the extension of the arch into Algeria (the Talemzane Arch) hosts the giant gas accumulation of Hassi R’Mel. To the north there are major hydrocarbon deposits in the Sabratah Basin and to the south in the Ghadamis Basin. On the arch in Libya, to the south of Tripoli, the entire Palaeozoic section has been removed, and elsewhere only the lower Palaeozoic is preserved. However above the Hercynian unconformity a thick section of Permian, Triassic and Jurassic rocks appears to the north of the arch, which thickens rapidly over the terrace and into the Sabratah Basin. The Silurian hot shale is a potential source rock, but it is absent over much of the arch, and the Devonian Frasnian source rock is not present north of the Ghadamis Basin. Other possible source rocks are present in the Triassic Aziziyah Formation, and within the Mamuniyat sequence, but many of these shales are either lean or immature for hydrocarbon generation. The best quality reservoir rocks are the Silurian Akakus Formation (where preserved) and the Triassic Kurrush (Ra’s Hamia) Formation. There are several regional seals, like the Bi’r Tlakshin Formation of late Ordovician age and the Permian Bi’r al Jaja Formation but these may prevent communication between the potential source rocks and reservoirs. The combination of complex tectonic history, absence of most of the Palaeozoic formations, the limited distribution and questionable quality of the source rocks, and the presence of significant barriers to migration, is not encouraging, and the prospectivity of this area has to be rated as low.6

8.3.5 The North-Western Offshore

Large oil and gas discoveries have been made in the Libyan part of the Sabratah Basin but at present are limited to only two petroleum systems, the Hallab (Mletaoui) →Jdeir system and the Bahloul →Jdeir system. The Jdeir Formation is an Eocene nummulitic limestone trend which extends from onshore Tunisia at least as far east as Tripoli. It forms an excellent reservoir and contains about 35 oil and gas accumulations along its length including Bouri, Bahr Essalam, Al Jawf and Ashtart. Geochemical evidence suggests that the oil is derived from a deep-water facies of early Eocene age and has migrated updip into the Jdeir reservoir, and the gas is derived from Upper Cretaceous shales, most probably of late Cenomanian/Turonian age which has migrated through porous beds and up fault conduits into the Jdeir reservoir. A small amount of oil and gas has leaked into younger reservoirs. All the structural traps in Libyan territory are formed by halokinensis, in which early Jurassic salt has flowed to form domes and ridges over which the younger formations are draped.

In the surrounding areas of offshore Tunisia, Malta and Sicily oil is found in Triassic, Jurassic and Cretaceous reservoirs, in addition to the Eocene, derived from a several different source rocks. Two main questions arise. Are any of these reservoirs and source rocks present in Libyan waters, and secondly what happens to the Jdeir nummulitic trend to the east of Tripoli? Only one well L1-137 has penetrated the Triassic section in Libyan territory, but evidence from surrounding areas shows that Triassic shelf carbonates are present in southern Sicily which are oil productive at Gela and Ragusa, and around Malta these carbonates were the principal target of several exploration wells. Offshore Tunisia Jurassic dolomitised limestones are oil productive at El Biban and Ezzaouia near Djerba, and offshore Sicily the Vega field produces from Jurassic platform carbonates. Evidence from the Cretaceous shows a stacked sequence of carbonate shelves which in general pass from a low-energy lagoon facies in the south to a shallow-marine open shelf further north. Cretaceous carbonates contain oil and gas at El Biban, Miskar, Isis, and several other fields in Tunisia, and there are proven source rocks in the Albanian and Cenomanian section. In Libya only a small number of wells have penetrated the Cretaceous section. To date no evidence has been found of Albanian, Cenomanian, or Turonian source rocks and the carbonates tend to reflect a low-energy protected-shelf environment. It should not be forgotten however that the large volumes of gas trapped in the Libyan part of the Sabratah Basin imply the presence of a deep Cretaceous gas-prone source kitchen in the area. This, along with the evidence from Tunisia, Malta and south of Sicily, coupled with the very small number of wells drilled in Libyan waters, means that the Mesozoic carbonates cannot yet be written off as unprospective. In certain areas, however they are very deep.

The eastward limit of the Eocene nummulitic trend has long been a source of speculation. Eocene oil or gas bearing nummulitic reservoirs are known onshore on the Jahamah Platform (Abu Quray and Tabit) on the Assumud Ridge (Assumud and Sahel), and as at least as far east as the Jalu field. Could there be continuity...
between the nummulitic trend of the Sabratah Basin and the onshore occurrences to the east? Two factors need to be noted. The offshore nummulitic trend is Ypresian in age, whereas most of the onshore occurrences are Lutetian in age. Secondly the offshore structures are all salt related but the onshore structures are all either structural traps or small biohermal features. A case can be made for a more or less continuous trend of shelf-edge nummulitic limestones, apparently diachronous, extending from the Sabratah Basin onto the Jahamah Platform and Assumud Ridge and then passing around the Ajdabija Embayment and continuing eastwards to Jalu. But for the offshore the salt related closures are limited by the eastern extent of the salt, which does not appear to extend far to the east of Tripoli. There may of course be non-salt related structures further east, but these have yet to be identified.

8.3.6 Sirt Basin and Adjacent Offshore

The Sirt Basin contains most of Libya’s oil and gas reserves, and upwards of 300 oil and gas discoveries. There are literally dozens of possibilities for yet-to-find discoveries in the Sirt Basin, and it is far beyond the scope of this book to review more than a handful. The following section picks out some of the more intriguing possibilities.

The western part of the Sirt Basin—the Hun Graben and Waddan Platform—appears at first glance unattractive for oil and gas exploration. It is close to the basin edge and no significant shows have been found (except for the B1-10 well which was probably charged from an offshore source kitchen). But beneath the edge of the Mesozoic basin, a Palaeozoic section is present which may offer some encouragement. Well evidence shows that the northern part of the Hun Graben and Waddan Platform are underlain by the Zamzam Depression, an eastward extension of the Ghadamis Basin, which contains a thick section of Devonian, Silurian and Cambro-Ordovician sequences, which include several potential reservoirs and both the Tanzuft and Awaynat Wanin formations. The critical questions are whether the hot shale is developed within the Tanzuft Formation and whether the Frasnian source rock is present and what level of maturity has been reached in these formations. Well evidence from B1-39 and C1-39 shows that both source rocks are present, and geochemical modelling suggests that the Tanzuft hot shale in this area ranges from early mature to late mature, whilst the Devonian source rock is early mature. It appears therefore that the Tanzuft hot shale in this area could be an effective source rock capable of generating hydrocarbons, although it is probably thinner than in the Ghadamis Basin. This leads to the conclusion that further exploration effort is justified in the poorly explored Palaeozoic section beneath the north-western corner of the Sirt Basin.

There are about 40 discoveries in the Zallah Trough almost two-thirds of which produce from the early Eocene Facha dolomite. A second hydrocarbon bearing formation is the Middle Palaeocene Furud Formation. Both of these reservoir units are capped by evaporites which provide excellent regional seals, with the Ghani field providing a typical example. In a few cases oil is found in the Lower Palaeocene Upper Satal Formation and in the Upper Palaeocene Zahrah Formation, but these depend on local factors and are of limited extent. Structurally most of the Zallah Trough fields are located in or adjacent to the Ma Amir Graben which is a north–south feature in the centre of the trough. To the south the graben disappears beneath Al Haruj al Aswad basalt flows. The area beneath the volcanics is poorly known because access onto the rugged volcanic topography is difficult, and the quality of seismic data beneath the volcanics is not good. There is however every reason to believe that the graben continues beneath the volcanics and a couple of small oil pools (Themar and Abraq) have been found in this area. The evaporite seal for the Facha dolomite is still present at Themar and there may well be other oil and gas accumulations present further south. The effects of the recent volcanism however need to be considered. It is known that several wells in the area recorded high volumes of CO₂ and the passage of basalt lava through the section may have affected already existing oil and gas pools. Nevertheless the area is very under-explored and may offer some hope of success.

Throughout much of the Sirt Basin the Nubian Group is silicified and not particularly attractive as an exploration target, but around the periphery of the basin the Nubian is represented by unsilicified sandstones. These sandstones contain very large volumes of oil and gas in the Eastern Embayment, and they are also present in the Zallah Trough where they have been encountered in three or four wells. The difference between the two areas is that in the east there are several source rocks and fairly simple migration routes from the source rocks to the reservoir. In the Zallah Trough there is no evidence of pre-Upper Cretaceous source rocks and no obvious migration routes by which the deeper Nubian sandstones could be charged from shallower Upper Cretaceous source rocks. This remains an interesting but highly speculative possibility.

Palaeocene carbonate formations host large volumes of oil and gas in the Sirt Basin, mostly in structural traps. Some of the accumulations however have an element of stratigraphic closure either due to local changes in permeability or to the passage of shelf carbonates into deeper water marl and shale facies. A small example is the E-92 discovery on the Zahrah-Hufrah Platform where oil and gas migrating updip from the Maradah Trough through Palaeocene carbonates has been trapped.
in a stratigraphic trap where the upper part of the Zaltan limestone shales-out to the west. Although the reservoir is thin well evidence suggests that it extends over a considerable area. Given the shifting nature of the Palaeocene carbonate shoals it seems likely that other similar up-dip shale-out traps may be present, for instance at the western end of the Satal Shelf in the Danian, and perhaps on the Bayda Shelf in the Mid Palaeocene where there are oil pools in the Upper Bayda Formation without any obvious structural closure. Most of the Palaeocene carbonate banks have a ramp margin, but on the west side of the Upper Sabil Shelf in the late Palaeocene there is evidence of what appears to be a high-energy rim which is oil bearing in wells B1 and D1-NC 171. There is scope for further discoveries in Palaeocene carbonates in similar unconventional trapping situations. The jewel in the crown would be to find another area of pinnacle reefs like those at Intisar but so far the search has proved fruitless. The Intisar reefs appear to be unique.

The Wahah Formation of Maastrichtian age is a prolific oil and gas reservoir particularly on the Zaltan, but also on the Bayda Platform. This is a play which has frequently been misunderstood. It is not a continuous sheet of calcarenite uniformly spread over the platform areas, but a late-stage transgressive unit which was deposited on an irregular surface in an archipelago, with the Wahah Formation showing a variety of facies from beach to upper shoreface, lower shoreface and beyond. Islands were present at Nasser, Jabal, SE Nasser, Raqubah and several more, so these areas are bald of Wahah Formation on their crests. The fringe of good quality reservoir facies around the islands can be relatively narrow and it is often difficult to define the up-dip pinch-out of the formation and the down-dip transition into a shaly facies on seismic data. There are several undrilled leads and prospects in the Wahah play awaiting drilling. In addition, on the platform margins adjacent to the Nasser and Wahah fields, there is evidence of thick fans or sand-wedges on the downthrown side of the platform margin faults which are presumed to represent accumulations of Wahah sediments transported from the platform areas and dumped over the edge of the platform. This model has been proved in well YYY1-6 which although dry, demonstrates the potential of such prospects and their proximity to the mature Sirt Shale source rock. Seismic data suggest that there are several such fans in areas where Wahah Formation is present on the adjacent platform.

In the Eastern Embayment the Nubian Group contains the most prolific oil reservoirs in Libya in which about 70 discoveries have been made, including the giant Sarir, Messlah, Abu Attiffel and 6J-59 fields. Many of the traps are structural closures, often fault assisted, but some are true stratigraphic traps where the reservoir pinches out on the flank of a high, or has been truncated at the top by the mid-Cretaceous unconformity. Messlah and 6J-59 are the best examples of stratigraphic traps so far discovered, but 6J-59 lay undiscovered for 30 years in an area considered fairly well explored. A glance at the Nubian isopach map (Fig. 3.26) shows that there are numerous bald uplands with potential for stratigraphic traps on their flanks. It also requires a plausible migration route from the source kitchen in the Hameimat Trough, or from one of the local source kitchens, but this is not a major problem as long range migration has been demonstrated in the area. Only the extreme south and south-east appear to be beyond the range of known migration fairways. These potential stratigraphic trap possibilities have not been systematically studied and may yet provide more surprises.

The offshore Sirt Embayment is very lightly explored with only a few exploration wells, mostly drilled in the shallow-water areas, and there is scope in the offshore for several frontier play concepts. The geology of the offshore Sirt Embayment is essentially a seaward extension of the Sirt Basin. The major elements such as the Adjabiya Trough and the Zaltan-Jahamah platforms can be followed into the offshore area, but seismic data shows that the section thickens seawards with the addition of a very thick Neogene section, and marine Lower Cretaceous, Jurassic and Triassic formations. There are however conspicuous gaps in the section, as shown in well A1-NC 42, where six unconformities have been recognised between the Eocene and Jurassic. The main formations affected are the Palaeocene and the late Cretaceous. The situation is further complicated by the presence of Messinian salt which varies rapidly in thickness and has a detrimental effect on the quality of seismic data. In the west well C1-87 contains proven source rocks in the Sirt-Rakmat and Etel sections of the Upper Cretaceous which have probably sourced the oil in onshore well B1-10. Gas discoveries have been made on the B-88 and D-88 structures in Cenomanian clastics, and at A-54/1 in Cenomanian carbonates, immediately below the base Tertiary unconformity. The source rock for A-54/1 is probably the downflank Sirt/Rakmat or Etel shales, as in the area further west. At A-54/1 the discovery was made in limestones and dolomites which have been extensively karstified, implying a long period of sub-aerial weathering. The offshore extension of the Zahrah-Hufrah and Waddan platforms is complicated by the eastern extension of the Nafusah Arch, but seismic data shows the presence of a number of horst-like structures in this area which may also be prospective for Cretaceous objectives. Further offshore there is scope for turbidites and slump features on palaeoslopes beneath Tertiary cover. The pre-Cretaceous section is virtually unknown in the Sirt Embayment, and may well contain source rocks, but almost nothing is known about potential reservoirs or traps.
The Ajdabiya Trough and its offshore extension the Sirt Trough are characterised by enormous thicknesses of Tertiary sediments deposited in an actively subsiding sag basin. The A-54/1 discovery discussed above is located on the western margin, and on the eastern margin there are discoveries onshore at Antlat in Lower Eocene chalky carbonates, and in Middle Eocene nummulitic limestones at A1, B1 and C1-NC 129 and in offshore well A1-NC 202. On the trough margin north of Benghazi the A1-NC 120 well tested oil in the Albian Daryanah Formation, and had shows in the Cenomanian-Turonian Al Baniyah Formation. The Cretaceous oil pools were probably sourced from late Jurassic-early Cretaceous black shales which have been found in the area, or from Upper Cretaceous Sirt Shales in the Ajdabiya Trough. Geochemical fingerprinting shows that the oil at Antlat was sourced from local Eocene shales, and other Eocene pools were probably similarly sourced, with a possible additional contribution from Cretaceous shales in the Ajdabiya Trough. As discussed above the Eocene nummulitic trend may extend around the margin of the Ajdabiya Trough, before heading towards the east where it forms the principal reservoir of the giant Jalu field. Recent seismic evidence shows that along the eastern flank of the Ajdabiya Trough the Eocene shelf has a ramp margin which plunges steeply into the axis of the trough, with evidence of debris flows, slumps and turbidites. These represent potential exploration targets, which may be replicated in other places around the margin of the trough including the Sirt Trough offshore. Little is known about pre-Eocene formations in the trough as they are extremely deep. The presence of large gas accumulations on the Assumud Ridge suggests that a substantial Sirt/Rakhmat gas-prone source kitchen is present in the deep Ajdabiya Trough. Around the periphery of the trough older formations become accessible, firstly the Palaeocene which contains the pinnacle reefs at Intisar and then the Cretaceous which contains the Nubian sandstone play of the Eastern Embayment. These plays have already been discussed.

8.3.7 Cyrenaica and Adjacent Offshore Areas

Oil exploration in Libya began in Cyrenaica with well A1-18 on the Jabal al Akhdar Uplift. Subsequently about 70 wells have been drilled with virtually no success (excluding the wells on the flank of the Ajdabiya Trough). Minor oil shows were found in well A1-2 and gas in B1-2 in Devonian sandstones, sourced presumably from the underlying Silurian shales. Several attempts have been made in recent years to claim that Cyrenaica possesses both viable source rocks and reservoirs, and whilst it is undeniable that the odd sample shows fair total organic carbon values, there is no consistency to these analyses, and no clearly defined potential source kitchens. Furthermore most of these supposed potential source rocks appear to be immature or early mature and incapable of generating significant hydrocarbons. The key source rocks of other areas, like the Tanzuft hot shale, the Frasnian hot shale, and the Cretaceous Sirt/Rakhmat shales have not been identified in Cyrenaica. Nevertheless Cyrenaica is surrounded by petroliferous regions: the Hameimat Trough, Maragh Trough, the Antlat region, and the western desert in Egypt. Oil has certainly migrated out of the Ajdabiya and Maragh troughs to charge the Amal and Awjilah/Nafurah fields on the Amal Ridge, and it is arguable that hydrocarbons could have migrated from some of these areas into the high-energy rims found around the margin of many of the stacked carbonate shelves on the Cyrenaica Platform. However none of the wells drilled in these areas have encountered hydrocarbons.

Offshore the situation is different. The Jabal al Akhdar Uplift and the offshore area to the north have been extensively deformed by compression which has been the prevailing tectonic regime since the mid-Cretaceous. This area extends from the northern flank of the Binghazi Ridge to the Egyptian border. No hydrocarbons have yet been found in this area, but it is more promising than the onshore area to the south. There is evidence that the Nubian Group, which is totally continental to the south, passes into a marine facies in northern Cyrenaica and there is evidence of black shales in the late Jurassic-early Cretaceous in this area. Sedimentological evidence suggests that the area between Tulmithah and Darnah contains potential reservoir facies throughout the Cretaceous and Tertiary, but the area from Darnah to the Egyptian border is mostly represented by deeper-water distal marlstones and limestones. This is illustrated by comparing the successions in the A1-NC 120 well to the west with the A1-NC 128 well to the east. Seismic evidence shows the presence of major features like the Darnah and Marmarica ridges, faulted structures, rollovers and most significantly excellent evidence of slumps and slides on the steep continental margin, with the likelihood of debris flows, submarine channels, submarine fans and turbidites. In some areas the continental slope is so steep that the entire Upper Cretaceous and Tertiary section appears to have become detached and slid into deep water. On the Darnah and Marmarica ridges sediments thin, and sometimes pinch-out on the flanks of the ridges, creating a number of trapping possibilities. This is a frontier area, and merits much further investigation.

8.3.8 Yet-to-Find

Is it possible to estimate the amount of oil and gas yet to find? There are three commonly used approaches to this problem (Fig. 8.4). The first might be termed source to trap analysis, which consists of a series of steps from...
the calculation of the amount of organic matter in a source kitchen, through generation, expulsion, migration, entrapment, subsequent possible degradation of the trap, and the amount of oil and gas already produced from fields within the area. This is a very imprecise method where minor differences can be hugely magnified, and the end result is almost meaningless. The second method is based on creaming curves in which a plot is made of cumulative discoveries of recoverable oil and gas versus time and projects the curves to a point of convergence which represents ultimate potential; and (C) parabolic fractals in which known recoverable hydrocarbons are plotted on a log/log scale in order of size. The area beneath the curve represents ultimate potential.

When compared with existing discoveries gives an indication of oil in-place yet to find. This method works well in mature basins like the Sirt and Ghadamis where there is a large amount of data, but less well in poorly explored areas like the central and eastern offshore. By using these methods we believe that yet to find will add a further 10–15% to the present figure of known oil and gas in place. For assessing the chance of success of individual prospects the so-called Monte Carlo simulation technique is commonly used, a stochastic computational method which involves repeated pseudorandom sampling of the various components of risk applicable to a prospect. The results allow the relative merits of different prospects to be compared.

**8.4 EXPLOITATION POTENTIAL**

Of the 550 discoveries in Libya only 165 have been developed and put on production. The remaining 385, many of which are very small, collectively contain about 5 billion
barrels (Bbbls) of potentially recoverable oil which remains to be exploited. ‘Potentially’ because many of these pools are very small and below even the most conservative economic threshold. The most significant of these undeveloped accumulations, each of which pose major technological challenges, are Antlat, Haram, and Chadar. Exploitation of Libya’s larger oil reserves began in the early 1960s when the first Sirt Basin discoveries were brought on stream. In most of these ‘old’ fields reservoir pressure has declined and is no longer sufficient to drive oil to the surface and water injection and pumps have had to be employed in order for production to be maintained. These
are the most basic forms of EOR, a range of techniques for increasing the amount of oil that can be recovered from a field. EOR techniques can be classified as primary, which include water and gas injection and the use of surface pumps, secondary which include horizontal drilling and downhole pumps, and tertiary which include more exotic (and expensive) techniques such as acidisation, fracking, and thermal and chemical treatments. It is important to emphasise however that the remaining potential of fields already on production is much greater than the undeveloped fields, with between 10 and 15 Bbbls still to be recovered using conventional and EOR techniques.30

As production from a field declines progressively more sophisticated EOR techniques are required, depending on the size of the field and the prevailing economic conditions. Gas injection is the second most commonly used EOR method. The gas may be re-injected solution or gas-cap natural gas, CO₂ or more rarely nitrogen. The gas is injected into the reservoir to improve ‘drive’. The injected gas acts both to displace the oil and to render it less viscous. In Libya, injection of solution and/or gas-cap natural gas has commonly been used, whilst CO₂ injection may be feasible in some instances.

Artificial lift can be achieved using beam pumps and/or electrical submersible pumps (ESPs), and gas lift. Individual wells will eventually ‘water-out’ as the oil–water contact rises as a result of oil extraction. In some cases it is possible to seal off the water producing zone and recomplete the well at a higher level. It is also common for tubing to become blocked with sediment and for downhole pumps to fail, so it is important to have workover facilities available in order to be able to repair damaged wells. Simple secondary recovery techniques and regular workovers are standard practice on most Libyan producing fields, and are invariably adopted before more innovative and expensive recovery methods are considered.

Horizontal drilling has been used widely in Libyan oil fields since 1994 when the first horizontal well was drilled on the Nasser field. Horizontal drilling is used to increase flow rates and drain the reservoir more efficiently. This technique has become much more common in the last 15 years, and horizontal wells have now been drilled on most of Libya’s large fields.

Tertiary oil recovery techniques have been developed to tackle specific problems, such as reducing oil viscosity in low viscosity fields using thermally enhanced oil recovery methods (TEOR). Examples are steam injection, used to increase oil production from reservoirs containing heavy oils, and in situ heating to reduce viscosity in similarly heavy oils. Other tertiary oil recovery methods include CO₂ injection and the use of detergents to decrease oil viscosity and lower capillary pressures, and polymers to increase the effectiveness of waterflood. Reservoir acidisation is often effective in carbonate reservoirs and fracking can be used in tight reservoirs such as quartzites. There are few tertiary oil recovery projects in Libya at the present time and considerable potential exists for enhancing future recovery with these techniques. CO₂ injection projects may be viable, for instance in the southern Zallah Trough with the utilisation of CO₂ generated by the volcanic activity on the adjacent Haruj al Aswad.

8.4.1 Remaining Ultimately Recoverable Oil Reserves

Elsewhere in this book we have generally preferred the use of ORR, as opposed to other types of reserves figures, as the basis for comparing pools and fields. In this chapter, where the recovery factor (RF) is the subject being addressed, the ‘oil originally in place’ (OOIP) figures provide a more meaningful basis for the purpose of comparison.

As noted above, Libya has 29 oil fields with greater than one billion barrels of OOIP; 22 of these fields lie in the Sirt Basin (the vast majority of which were brought on stream in the 1960s and early 1970s), 6 in the Murzuq Basin (on stream in the late 1990s and 2000s) and Bouri in the Sabratah Basin offshore northwest Libya (on stream in 1988) (Fig. 8.2). All these fields are on production except for Antlat, which has a very low permeability carbonate reservoir, and the very complicated structural/stratigraphic trap of North Jalu (6J-59), discovered in 2001 and still under appraisal in 2012. In an independent reserves audit by Nubian Consulting these 29 fields are estimated to have held about 38 Bbbls of ultimately recoverable reserves (URRs). This was calculated by assessing the conventionally recoverable reserves and adding an EOR increment (the increment being determined by considering the most likely EOR methods to be applied on each individual field). The average RF for these 29 largest oil fields proved to be 43% with a very wide range from 24% (Bilhizan) to 74% (Intisar D), but excluding the undeveloped Antlat Field where the RF is essentially unknown. Using data for cumulative production to end 2012, the most recent year for which we have a complete set of reliable figures, 69% of the URRs of the 29 largest oil fields had been produced by end 2012, leaving some 11–12 Bbbls yet to be produced from these fields. The same approach can be applied to the many other fields in Libya with less than 1 Bbbls OOIP.

Fig. 8.6 lists Libya’s 21 oil fields that have more than 200 million barrels ‘remaining reserves’, these being the difference between our estimate of URRs and cumulative production to end 2012. Jalū Main, North Jalū and Sarīr Main are the largest in this analysis, each having more than 1 Bbbls yet to produce and therefore representing a very important remaining resource. The location of these
fields in the Eastern Embayment of the Sirt Basin reflects the importance of this region.

In addition to the reservoirs currently on production many fields such as Jalu, Nasser and several fields in the Zallah Trough contain oil in secondary or minor reservoirs which in most cases remain untapped. Where these reservoirs are shallower than the currently producing reservoir, wells can eventually be recompleted in the higher secondary reservoir when the main reservoir is exhausted. The potentially recoverable reserves in these secondary reservoirs have been included in our calculations of ultimate potential.

To summarise, it is estimated that Libya’s fields already on production contain between 10 and 15 billion barrels of remaining recoverable oil whilst undeveloped fields contain about 5 billion barrels. These estimates assume recovery utilising conventional recovery techniques and our best assessment of production likely to be achieved by the continuation of existing EOR programmes and the implementation of new EOR techniques in the future.

8.4.2 Production Rates

Average daily production figures from 2010 have been used to assess reservoir and field performance and likely future potential (figures for more recent years are less reliable for this purpose, due to the effects of the civil war). As a general rule it might be expected that the larger the ‘remaining reserves’, the larger the production rate will be. However, where a field has undeveloped reservoirs as outlined above, production will not ‘match’ reserves. This is the case with Jalu Main which has surprisingly high ‘remaining reserves’. Fields brought on stream recently might be expected to show the highest production rates and the largest remaining reserves. This is the case with the Mamuniyat-reservoired fields of the Murzuq Basin (most of the Shararah fields and El Feel). But it is striking how well many of the larger old giant oil fields still perform. These ‘old giants’ are likely to continue to make a very significant contribution to Libya’s future production.

The character of the reservoir obviously affects production rate. The complex Murzuq Ordovician fields have production rates of up to 95,000 barrels of oil per day (bopd) and URR RF typically around 40%. By comparison the high quality fluvial Sarir reservoir, despite having been on production much longer, performs much better with production rates up to 174,000 bopd with URR RF values of 46–56%.

It follows that the ranking of fields by ‘remaining reserves’ presented in Fig. 8.6 should be treated with care and should be viewed in the light of the age of the field, reservoir quality, production rate, URR RF and whether there are undeveloped reservoirs.

Jalu, Dayfah and Awjilah-Nafurah oil fields all stand out as being exceptional fields with the potential for further additional development, being old fields with good production rates, high URR RFs and the presence of undeveloped reservoirs, and the Sarir-reservoired oil fields of Sarir and Abu Attiffel have similar potential, except

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### Table: Libyan Oilfields Ranked by Remaining Recoverable Reserves

<table>
<thead>
<tr>
<th>Field name</th>
<th>Ultimately recoverable reserves estimate (incl EOR), MMB</th>
<th>Remaining reserves’ (URR less production to end 2012), MMB</th>
<th>Av daily production (2010), kbopd</th>
<th>Main oil reservoir(s)</th>
<th>Other reservoirs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jalu Main (E-69)</td>
<td>4,370</td>
<td>1,510</td>
<td>82</td>
<td>Chadora and Jalu Formations</td>
<td>Yes</td>
</tr>
<tr>
<td>Sarir Main (C-65)</td>
<td>4,600</td>
<td>1,430</td>
<td>174</td>
<td>Sarir Formation</td>
<td></td>
</tr>
<tr>
<td>North Jalu (J-59)</td>
<td>1,030</td>
<td>1,030</td>
<td>0</td>
<td>Sarir Formation</td>
<td></td>
</tr>
<tr>
<td>Nasser Main &amp; South (C-6)</td>
<td>3,100</td>
<td>630</td>
<td>31</td>
<td>Zaltan Formation</td>
<td>Yes</td>
</tr>
<tr>
<td>Awjilah-Nafurah</td>
<td>2,420</td>
<td>630</td>
<td>61</td>
<td>Taqifat and Maragh Formations &amp; Basement</td>
<td>Yes</td>
</tr>
<tr>
<td>Abu Attiffel (A-100)</td>
<td>2,410</td>
<td>570</td>
<td>74</td>
<td>Sarir Formation</td>
<td></td>
</tr>
<tr>
<td>Dayfah Main (B-59) &amp; South (Q-71)</td>
<td>2,910</td>
<td>550</td>
<td>102</td>
<td>Dayfah Formation</td>
<td>Yes</td>
</tr>
<tr>
<td>H-NC 186</td>
<td>530</td>
<td>500</td>
<td>8</td>
<td>Hawaz Formation</td>
<td></td>
</tr>
<tr>
<td>Shararah B (B-NC 115)</td>
<td>800</td>
<td>500</td>
<td>58</td>
<td>Mamuniyat Formation</td>
<td></td>
</tr>
<tr>
<td>Amal (B-12)</td>
<td>1,560</td>
<td>450</td>
<td>25</td>
<td>Maragh and Amal Formation</td>
<td>Yes</td>
</tr>
<tr>
<td>Shararah M (M-NC 115)</td>
<td>450</td>
<td>420</td>
<td>6</td>
<td>Mamuniyat Formation</td>
<td></td>
</tr>
<tr>
<td>Elephant (El Feel) (F-NC 174)</td>
<td>580</td>
<td>320</td>
<td>95</td>
<td>Mamuniyat Formation</td>
<td></td>
</tr>
<tr>
<td>Wahah Main (A-59)</td>
<td>1,480</td>
<td>350</td>
<td>24</td>
<td>Waha Formation</td>
<td>Yes</td>
</tr>
<tr>
<td>Shararah H (H-NC 115)</td>
<td>520</td>
<td>350</td>
<td>48</td>
<td>Mamuniyat Formation</td>
<td>Yes</td>
</tr>
<tr>
<td>Messlah South &amp; North</td>
<td>1,660</td>
<td>310</td>
<td>120</td>
<td>Sarir Formation</td>
<td></td>
</tr>
<tr>
<td>Mabruq (A-17)</td>
<td>410</td>
<td>310</td>
<td>22</td>
<td>Zahrah Formation</td>
<td>Yes</td>
</tr>
<tr>
<td>Sarir (L-69)</td>
<td>780</td>
<td>300</td>
<td>19</td>
<td>Sarir Formation</td>
<td></td>
</tr>
<tr>
<td>Shararah A (A-NC 115)</td>
<td>740</td>
<td>240</td>
<td>91</td>
<td>Mamuniyat Formation</td>
<td></td>
</tr>
<tr>
<td>B-NC 186</td>
<td>290</td>
<td>240</td>
<td>51</td>
<td>Hawaz Formation</td>
<td></td>
</tr>
<tr>
<td>Zahrah-Hufrah</td>
<td>860</td>
<td>220</td>
<td>8</td>
<td>Salat and Zahrah Formations</td>
<td>Yes</td>
</tr>
<tr>
<td>Bouri (B-NC 41)</td>
<td>770</td>
<td>210</td>
<td>42</td>
<td>Jdeir Formation</td>
<td></td>
</tr>
</tbody>
</table>

they have no undeveloped reservoirs. Messlah lies within this category except that it has surprisingly low ‘remaining reserves’ given its production rate, an anomaly that may be related to the difficulty of establishing original oil in place figures for stratigraphic traps. Development of subsidiary undeveloped reservoirs will be important in the future development of Jalu and Awjilah-Nafurah whilst wax and sulphur content, sanding problems in the well bore and tar mats are technical challenges with the Sarir reservoir fields. The Jalu, Awjilah-Nafurah, Sarir and Messlah oil fields are described in Chapter 7.

8.4.3 Gas Reserves

Unlike Libya’s oil fields, the gas accumulations remain poorly exploited. Out of about 90 discoveries country-wide with free gas reserves (non-associated gas fields and fields with gas caps) there are about 70 that remain undeveloped. For example a discovery in 2008 by Hess in well A1-54/1 (Arous Al-Bahar) in the Gulf of Sirt, although partially appraised, has yet to be developed despite having rumoured reserves of 2 TCF. In fact only four fields with free gas were developed before 2000. Gas from associated fields (oilfields with gas in solution under normal reservoir conditions) was routinely flared in the early days, but a gas-gathering pipeline was developed during the 1980s and 1990s which now collects gas from the principal fields.

Exploitation of the non-associated gas fields of the Sabratah Basin, northwest offshore, commenced with Bouri in 1988 where 63% of the reserves remained to be produced in 2012/2013 (Fig. 7.3). Bahr Essalam, Libya’s largest gas field, also located in the Sabratah Basin, with about 70% of remaining reserves, came on stream in 2004. Gas from Bouri and Bahr Essalam is combined with gas from Libya’s second largest gas field, Al Wafaa (located in the southern Ghadamis Basin), and is exported to Europe via the GreenStream pipeline which started operation in 2004 (Fig. 7.3).

Exploitation of the non-associated gas fields of the Zaltan Platform commenced with As Surah (1971) and Hutaybah (1977), followed by Sahel (1990) and Assumud (1993) and finally by Attahadi (2005). Hutaybah is interesting in that, together with Bouri, these fields are the only examples of non-associated gas fields brought on stream before 2000 with remaining gas reserves of more than 500 BCF. This makes both of these fields attractive targets for further development, though reservoir characteristics at Bouri may hamper efforts to increase production significantly. Other producing gas fields include those elsewhere in the Sirt Basin such as Kalanshiyu in the Nubian province, and in the Ghadamis Basin where the Al Wafaa field is located. As mentioned previously Al Wafaa is the only example of a pinch-out/truncation trap housing a major gas accumulation. The future exploitation potential of these gas fields utilising modern development techniques is less easy to define than for Libya’s oil fields either because the remaining reserves fall below likely economic thresholds, or the field is at an early stage of primary development. See Chapter 7 for a description of the Bahr Essalam, Al Wafaa and Bouri fields.

Total original recoverable gas reserves of Libya are estimated to be about 53 TCF, 18 TCF in non-associated gas fields and 23 TCF in fields with gas caps, the remaining 12 TCF being oil field solution gas. Cumulative commercialised gas production to 2014 was about 11 TCF, the vast majority of this from non-associated gas fields and fields with gas caps. This leaves more than 30 TCF of free gas yet to be produced, and considerably more when solution gas is taken into account.

8.5 CONCLUSIONS

In this chapter we have attempted to show that in calculating reserves the following categories need to be considered:

- Oil and gas remaining in producing fields.
- Oil and gas known to exist in secondary reservoirs in producing fields.
- Oil and gas known to exist in undeveloped discoveries.
- Oil and gas that may be recoverable in future by applying EOR techniques.

The calculation of oil and gas in place is a relatively simple matter, but the calculation of recoverable reserves is much more difficult since it requires knowledge of the geology and reservoir characteristics, and for gas a calculation of the amount of gas that will be released from solution and the expansion that takes place between the reservoir and the surface. We have shown also that the application of EOR techniques can greatly improve recovery, but it is a process of diminishing returns, as the more sophisticated the technique the more expensive it becomes. It is for this reason that EOR techniques are not viable on the smaller fields. Our analysis has also revealed a number of other points:

- Historically insufficient exploration wildcat wells have been drilled to have any realistic chance of replacing the amount of oil produced.
- There is still very large potential (and less risk) in developing new and better EOR schemes on currently producing fields.
- Production could be significantly increased by developing the best of the hundreds of undeveloped discoveries.
- There is much remaining potential in Libya’s undeveloped gas fields.
• The political constraints of the last 40 or so years have had the effect of conserving reserves, since oilfield equipment was embargoed for long periods.
• NOC’s introduction of EPSA IV licences in 2004 proved a great boost to exploration activity, and similar initiatives will be needed in the future.

Endnotes
1. Nubian Consulting Ltd, proprietary data.
2. Nubian Consulting Ltd, proprietary data.
8. Kuragli et al., 2008; Huffman et al., 2008; Yanilmaz et al., 2008.
10. Nubian Consulting Ltd, proprietary data.