

## Chapter 22

# LIBYA: PETROLEUM POTENTIAL OF THE UNDEREXPLORED BASIN CENTERS—A TWENTY-FIRST-CENTURY CHALLENGE

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### ABSTRACT

Recoverable reserves in approximately 320 fields in Libya's Sirt, Ghadamis, Murzuq, and Tripolitania Basins exceed 50 billion barrels of oil and 40 trillion cubic feet of gas. Approximately 80% of these reserves were discovered prior to 1970. Since then, there has been a less active and more conservative exploration effort. Complex, subtle and, in particular, deep plays were rarely pursued during the 1970s and 1980s because of definitive imaging technologies, limited knowledge of the petroleum systems, high costs, and risk adversity.

Consequently, extensive undiscovered resources remain in Libya. These resources could be accessed if geologic and geophysical knowledge, innovation, and advanced technologies were used effectively. Three-dimensional seismic acquisition will be required to some degree for reliable trap definition and stratigraphic control.

Predictably, most of the undiscovered resources will be found in the vast, underexplored deep areas of the producing basins. Six areas are exceptional in this regard: the south Ajdabiya trough, the central Maradah graben, and the south Zallah trough–Tumayam trough in the Sirt Basin, and the central Ghadamis Basin, the central Murzuq Basin, and the offshore eastern Tripolitania Basin in the west. These highly prospective basin sectors encompass a total area of nearly 150,000 km<sup>2</sup>, with an average well density for wells exceeding 12,000 ft of 1 well/5000 km<sup>2</sup>.

### INTRODUCTION

The exploration effort in Libya, which began in 1957, has been a phenomenal success. In the Sirt Basin (Figure 1), the drilling of 1600 new-field wildcats resulted in 250 discoveries with recoverable reserves of 45 billion barrels (bbl) of oil and 33 trillion cubic feet (tcf) of gas. These figures include 18 of the 21 giant fields in Libya, which hold reserves of 37 billion bbl of oil. In the Ghadamis Basin (including the Gheriat and Atchan Subbasins), approximately 260 exploration wells yielded 35 oil-field discoveries with an estimated 3 billion bbl of recoverable oil. The 62 wildcats drilled in the Murzuq Basin found 11 oil fields, including two giants, with reserves of approxi-

mately 2 billion bbl. The exploration effort in the offshore Tripolitania Basin has been rewarding as well. Fourteen new oil and gas-condensate fields have been discovered as a result of the drilling of about 50 wildcats. Reserves there are an estimated 2 billion bbl of oil and 8 tcf of gas. These estimates refer to activities through 1998 and include some fields categorized as marginal.

Despite this great exploration effort, the four producing basins are in the emerging stage of exploration maturity. Two aspects in particular are indicative of vast undiscovered resources in Libya and the exploration opportunities to access those resources: (1) numerous poten-

Figure 1. Generalized tectonic map of Libya showing major structural features. Also shown are six underexplored central basin or trough areas, which are the subject areas of this study.

## TECTONIC SETTING

### Paleozoic

Deposition of mostly continental siliciclastics during the Cambrian and marginally marine to marine siliciclastics during the Ordovician and Silurian continued essentially without interruption from Morocco to the Middle East. Uplift and erosion during the Late Silurian Caledonian orogeny initially defined the limits of the Paleozoic basins of Libya. The east-west-trending Qarqaf arch separated the Ghadamis and Murzuq Basins; the north-south-trending Sirt-Tibesti arch separated the Murzuq and Kufrah Basins and, generally, the Ghadamis Basin from the eastern Cyrenaica–Western Desert Basin (Klitzsch, 1971; Bellini and Massa, 1980).

After the dominantly marine siliciclastic deposition during the Devonian and the shallow-marine to continental deposition in the Carboniferous, widespread uplift and severe erosion during the Hercynian orogeny, particularly along the Sirt-Tibesti arch, Qarqaf arch, and Jefara uplift, further accentuated the Paleozoic basin margins.

### Mesozoic

A very thick sequence of continental sediments of Triassic to Early Cretaceous age occupies the central part of Murzuq Basin. Along the Murzuq Basin margins and the nearby Qarqaf and Tibesti arches, Paleozoic and basement rocks are exposed. Gradual northward sag of the Ghadamis Basin throughout the Mesozoic resulted in continental and marine deposition, with a thickness of less than 1000 ft in the south and more than 6000 ft in the north. From the Late Permian to the Cretaceous, the extreme northern margin of the Ghadamis Basin underwent severe northward tilt, an effect of Tethyan subsidence. This resulted in a more pronounced northward increase in sedimentary thickness, with increased marine influence.

This Mesozoic depositional episode continued offshore in the Tripolitania Basin, where the thickness of post-Permian to Upper Cretaceous marine siliciclastics and carbonates may exceed 12,000 ft. Tectonic activity in the Tripolitania Basin and surrounding offshore areas during the Mesozoic was dominated by east-west-oriented dextral transtension related to movement of the African Plate relative to the Eurasian Plate (Van Houten, 1980; Anketell, 1996).

In the general area of the future Sirt Basin, the broad Sirt-Tibesti arch, with basement and Cambrian-Ordovician rocks exposed at the Hercynian surface, remained positive until the Late Jurassic. There were rare exceptions in discrete peripheral areas, where Triassic deposition occurred (the Maragh trough, for example). A variable thickness of continental siliciclastics (in the south) and marginally marine siliciclastics (in the north) of Late Jurassic to Early Cretaceous age, referred to as the Nubian sandstone, was deposited on the Hercynian surface.

Nubian deposition was controlled by surface relief and, to some degree, by faulting.

In the Albian or early Cenomanian, extensional and probably transtensional faulting, followed by uplift and erosion, deformed the Sirt-Tibesti arch. This activity (the Sirt event) was a prelude to subsequent collapse of the arch (El-Alami, 1996b; Gras, 1996; Hallett and El-Ghoul, 1996; Koscec and Gherryo, 1996). The structural alignment created, which is most evident in the south and southeast, was for the most part east-west, east-south-east–west-northwest, and east-northeast–west-southwest. Consequently, the subcrop at the Sirt unconformity is a mosaic of Jurassic to Lower Cretaceous siliciclastics in grabens and half grabens, which are in depositional or fault contact with basement or Cambrian-Ordovician rocks on structural highs. Evidence of this fabric is exhibited in the Faregh, Masrab, Magid, Messlah, Jalu, and other areas in the southeast sector and is suggested by fault trends in the southern parts of the Zaltan and Bayda platforms.

The main Sirt Basin rift phase, which established the distinctive configuration of the basin, began in the Cenomanian with the collapse of the Sirt-Tibesti arch. Basically, five major grabens formed (Hun, Zallah, Maradah, Ajdabiya, and Hameimat), separated by four major platforms (Waddan, Zahrah-Bayda, Zaltan, and Amal-Jalu) (Figure 2). The orientation of these structural features was generally north-northwest–south-southeast, a fabric which persisted throughout the recurrent episodes of faulting during the Late Cretaceous and Paleocene. During this period, a great thickness of shale and subordinate carbonates and evaporites accumulated in the troughs, while a considerably reduced thickness of dominantly shallow-marine carbonates was deposited on the platforms (Barr and Weegar, 1972; Gumati and Kanes, 1985; Baird et al, 1996).

### Tertiary

In the northern sector of the Ghadamis Basin, only a thin section of Tertiary shallow-marine sediments is present, and it thickens considerably northward toward the Tripolitania Basin and eastward toward the Sirt Basin. In the east on the Cyrenaican platform, deposition of thick, dominantly carbonate strata occurred.

In the Sirt Basin, from the middle Paleocene to the early Eocene, rift tectonics had less control on sedimentation, and thickness variation from trough to platform was less pronounced. From the early Eocene to the Pliocene, interior sag dynamics persisted, with a gradual eastward shift of the sag axis.

## PETROLEUM SYSTEMS AND PLAYS

### Summary

The petroleum systems, which have been active in

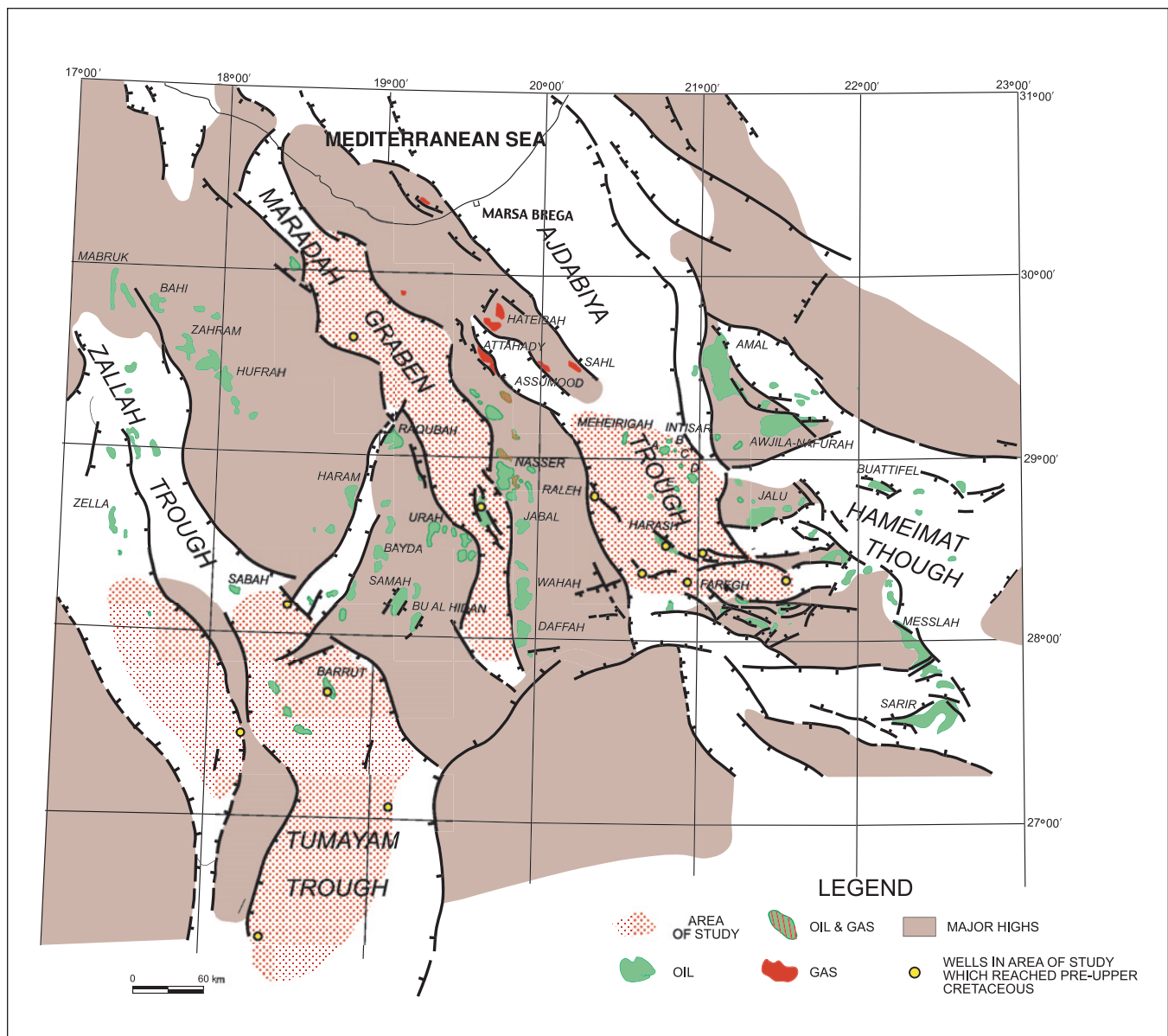


Figure 2. Structural elements of the Sirt Basin, showing oil and gas fields, areas of study, and location of wells with total depths exceeding 12,000 ft in the areas of study. The approximate size of the Sirt Basin areas of study are Ajdabiya trough, 8,500 km<sup>2</sup>; Maradah graben, 10,000 km<sup>2</sup>; and South Zallah trough–Tumayam trough, 25,000 km<sup>2</sup>.

the six basin-center sectors under study, are extensive. The multiple systems in the Sirt Basin include a wide range of Cretaceous and Paleogene reservoir sequences, which were charged by three or four Cretaceous source rocks. The Ghadamis Basin petroleum systems involve Ordovician, Silurian, Devonian, and Triassic reservoirs charged by Lower Silurian and/or Middle to Upper Devonian source beds. A single petroleum system was active in the Murzuq Basin, comprising Ordovician, Silurian, and Devonian reservoirs, which were charged by Silurian source rocks (Boote et al., 1998). The Tripolitania Basin probably has a framework of several petroleum systems, which includes a wide range of Mesozoic and Tertiary formations. In the following paragraphs, the key

hydrocarbon factors (reservoir, seal, source, trap, migration, and timing) will be described for each of the subject areas.

## Sirt Basin

### General

The underexplored sectors of the Ajdabiya trough, Maradah graben, and Zallah–Tumayam trough have important features in common: nearby oil production, only four or five exploration wells which reached sub-Upper Cretaceous horizons, a world-class source rock (the Upper Cretaceous Sirt–Rachmat shale), and large areal extent. The Ajdabiya, Maradah, and Zallah–Tu-

mayam areas cover 8,500 km<sup>2</sup>, 10,000 km<sup>2</sup>, and 25,000 km<sup>2</sup>, respectively.

### Source-rock Summary (Figure 3)

The Campanian-Coniacian Sirt-Rachmat shale sequence, which includes minor amounts of carbonates (Tagrifet limestone) with variable source potential, varies in thickness from 1000 ft to more than 3000 ft in each of the three troughs (Figure 4). The total organic carbon (TOC) of this sequence ranges from 0.5% to 8%, averaging 1.5–4% (Parsons et al., 1980; Hamyouni et al., 1984; Baric et al., 1996).

The Cenomanian-Turonian Etel Formation (evaporites, shale, and minor carbonates deposited in shallow lagoonal to supratidal conditions) exhibits good source-rock characteristics, with TOC ranging from 0.6% to 6.5% in the Hameimat trough (El-Alami, 1996b). These same Etel facies, with net shale thicknesses of 200 ft to more than 1000 ft, are present in the southern Ajdabiya trough and Maradah graben (Figure 5). Therefore, they should be considered an effective source in those sectors. The source quality of the Etel shale is questionable in the southern Zallah and Tumayam troughs, where it exceeds 500 ft in a limited area only.

A third source is the Lower Cretaceous middle shale member of the Nubian Formation. Nubian lacustrine to lagoonal shale has been identified in the Hameimat trough and the adjoining Faregh and Messlah areas, where thicknesses vary from 0 to 1000 ft (Figure 6) and average TOC is approximately 3%. It is most likely a minor source in the southern part of the Ajdabiya trough. In the Maradah graben, based on only two wells (El-Hawat, 1996), the Nubian middle variegated shale member attains thicknesses ranging from 200 to 400 ft. This shale sequence was deposited in a partially anoxic, marginal-marine environment. It may have contributed some hydrocarbon to surrounding areas.

The contribution of variable quantities of oil from as many as four source units (shale or shale and carbonate) at different times

of expulsion (during periods from early Oligocene to early Pliocene) has yielded several distinct crude oils in different areas. One similar characteristic of these oils is the gravity, which ranges from 36° to 40° API. More rock-oil correlation analyses and related studies are needed for more accurate determinations of regional rock-oil-timing associations.

### South Ajdabiya Trough

**Reservoirs.**—The lower and upper sandstone members of the Upper Jurassic to Lower Cretaceous Nubian Formation are clearly the primary reservoir targets for the area (Clifford et al., 1980; Ibrahim, 1991; Abdulgader,

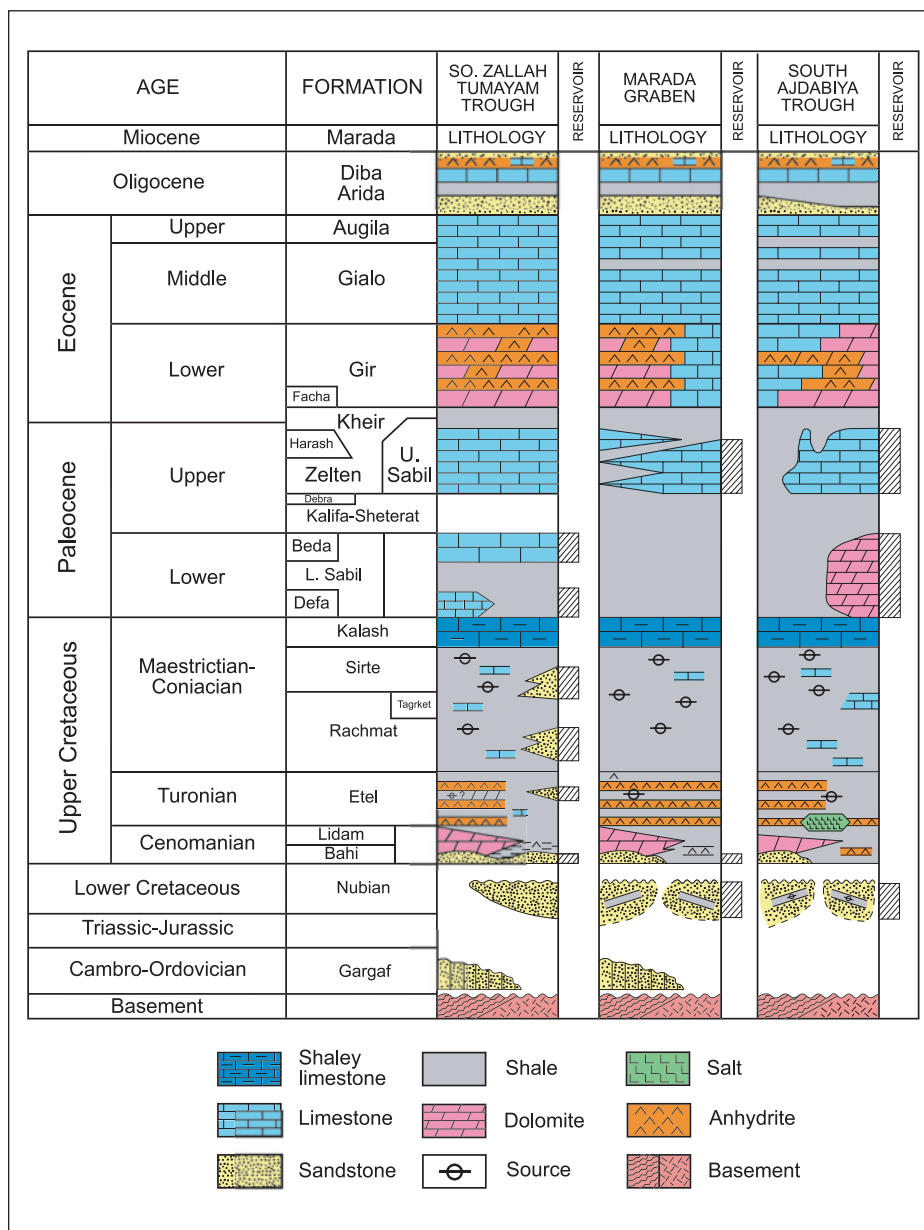


Figure 3. Generalized stratigraphic correlation chart of the Sirt Basin study areas: south Ajdabiya trough, Maradah graben, and south Zallah trough–Tumayam trough. The main reservoir and source intervals are indicated on the chart. Hachured boxes represent main reservoirs.

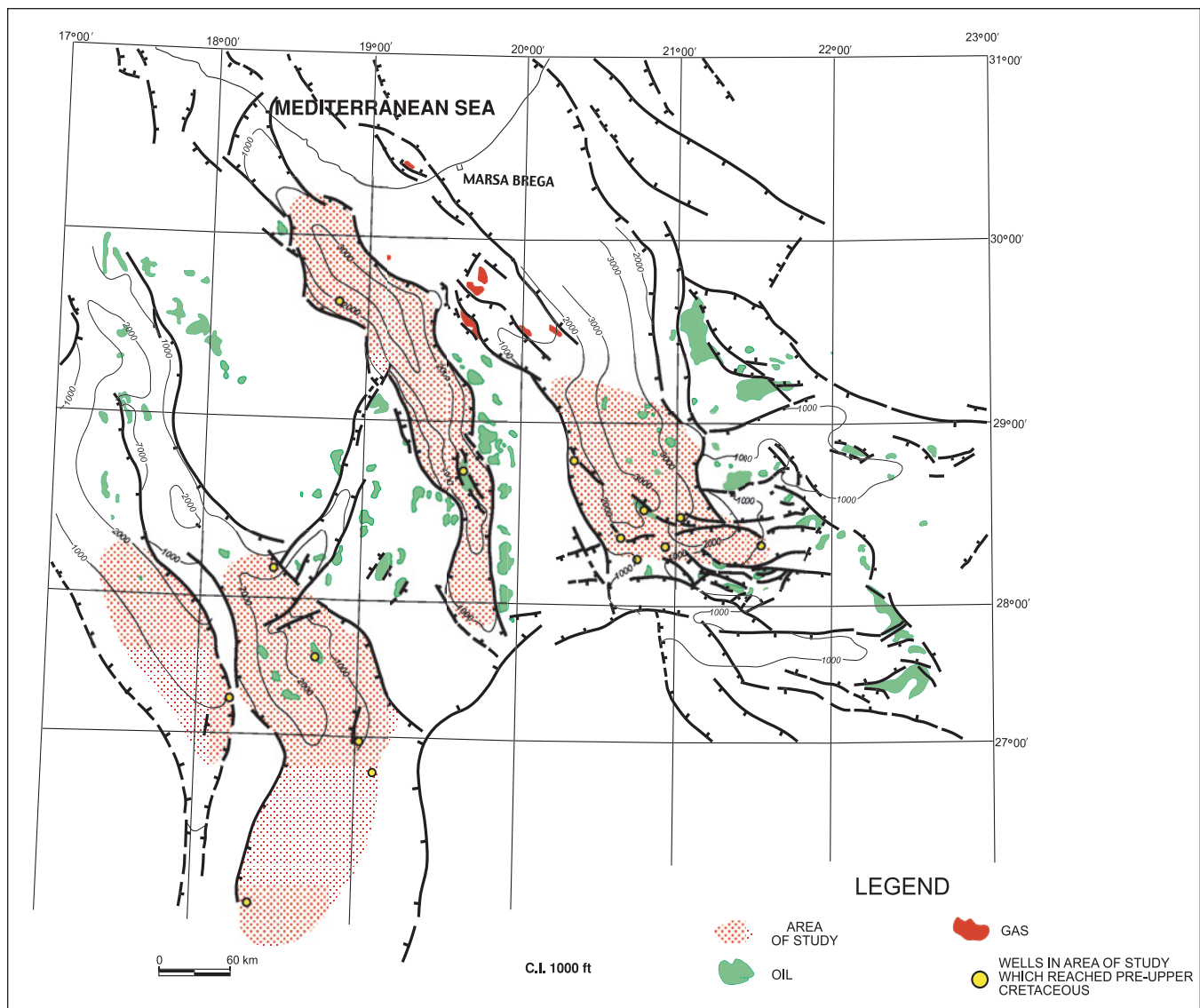


Figure 4. Net shale isopach map of Sirt and Rachmat Formations (Upper Cretaceous), Sirt Basin. Modified from Masera Corporation (1992).

1996; Mansour and Magairhy, 1996). Net sand thicknesses are estimated to range from 0 (at discrete onlap and truncation limits) to 1200 ft (Figure 6). Depth to the top Nubian ranges from 12,000 to 18,000 ft (Figure 7). Despite these depths, it is expected that average porosities will be 12–13%, with maximum porosity exceeding 20%. Average porosity at depths below 15,000 ft ranges from 12% to 13.5% in some wells in nearby Hameimat trough.

Secondary reservoir objectives are high risk in the area because of limited distribution and reservoir properties. The Bahi (Maragh) sandstone equivalent is absent or very thin in surrounding areas, with dominant siltstone and shale lithology suggestive of the Etel Formation. The Lidam dolomite, a facies of the Etel Formation in this sector of the Sirt Basin, is also very thin or absent in nearby wells. The Tagrifet limestone and equivalent Rachmat

limestone beds are thin and generally argillaceous mudstones west of the Amal and Jalu highs.

Possible attractive secondary targets are Paleocene lower and upper Sabil shoal and reef limestones (Spring and Hansen, 1998). Upper Sabil shelf-edge deposition was not controlled by rift phase faulting, and the shelf extended across the southern part of the Ajdabiya trough (Figure 8). This potential reservoir is at relatively shallow depths and consequently has been the subject of exploration programs for some time. However, subtle buildups, overlooked in the past, can be imaged accurately today using state-of-the-art methods.

**Seals.**—Etel shale and anhydrite at the Sirt unconformity provide an effective seal for the Nubian sandstone throughout most of the area. Locally, a thin Bahi (Maragh) sandstone or Lidam dolomite sequence may directly overlie the Nubian, in which case the Nubian lacks a seal.

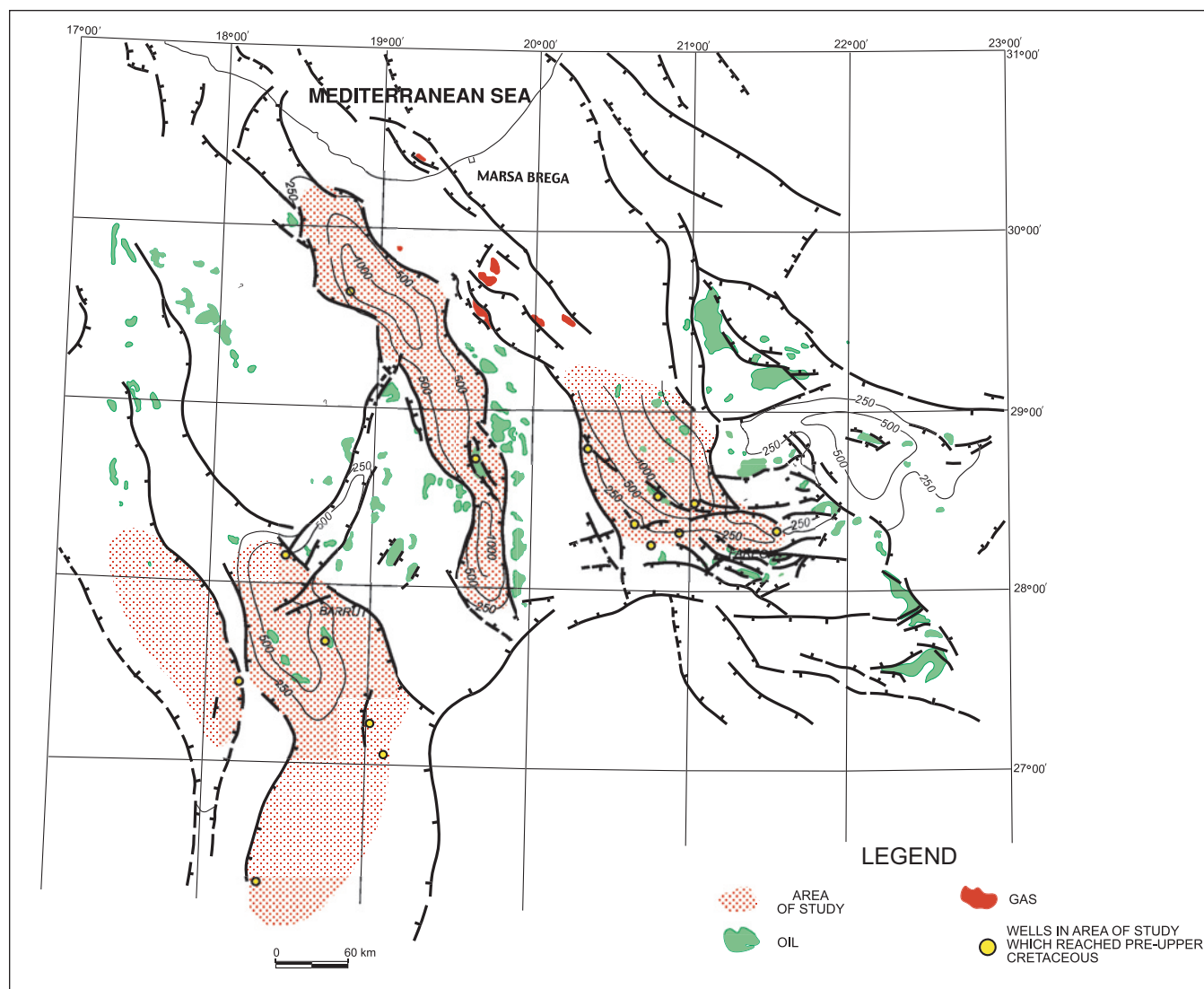


Figure 5. Net shale isopach map of the Etel Formation (Upper Cretaceous), Sirt Basin.

Sheterat and Kheir shales provide excellent seals for lower and upper Sabil carbonates, respectively.

**Timing and migration.**—In the southern part of the Ajdabiya trough, the peak oil-expulsion stage occurred approximately from the late Eocene to the late Pliocene from source beds of the Rachmat and Sirt Formations (Ghori and Mohamed, 1996; Roohi, 1996b; Gumati and Schamel, 1988). This stage occurred generally at depths below 11,000 ft. Because the latest significant structural and stratigraphic trap development was late Paleocene, drainage timing was ideal. The main source rocks (Sirt shale and Rachmat shale) are stratigraphically separated from the Nubian. Therefore, secondary migration would have been via faults or faults in combination with the Sirt unconformity. Migration from Etel source beds would have been accomplished by lateral drainage via the Sirt unconformity to underlying Nubian sands.

Oil from Sirt source beds reached Sabil reservoirs via vertical migration along faults and fractures.

**Traps.**—Trap types for Nubian reservoirs are horsts, tilted fault blocks, updip unconformity truncations, and updip terminations against basement or Cambrian-Ordovician quartzite (Figure 9). Sabil traps are usually drape anticlines over buildups with lateral permeability barriers.

#### *Maradah Graben*

**Reservoirs.**—The lower and upper sandstone members of the Nubian Formation are the primary reservoir targets for the area. The maximum Nubian net sand thickness in the graben is approximately 1000 ft (Figure 6). The Nubian may be absent on Cambrian-Ordovician highs, similar to the setting in the southeast Sirt Basin, but no current data support this hypothesis. Depth to the top Nubian ranges from 11,500 to 15,000 ft in the Maradah graben (Figure 7). It is expected that average porosity will be 12–13%.

Nubian thickness and porosity estimates in the Mar-

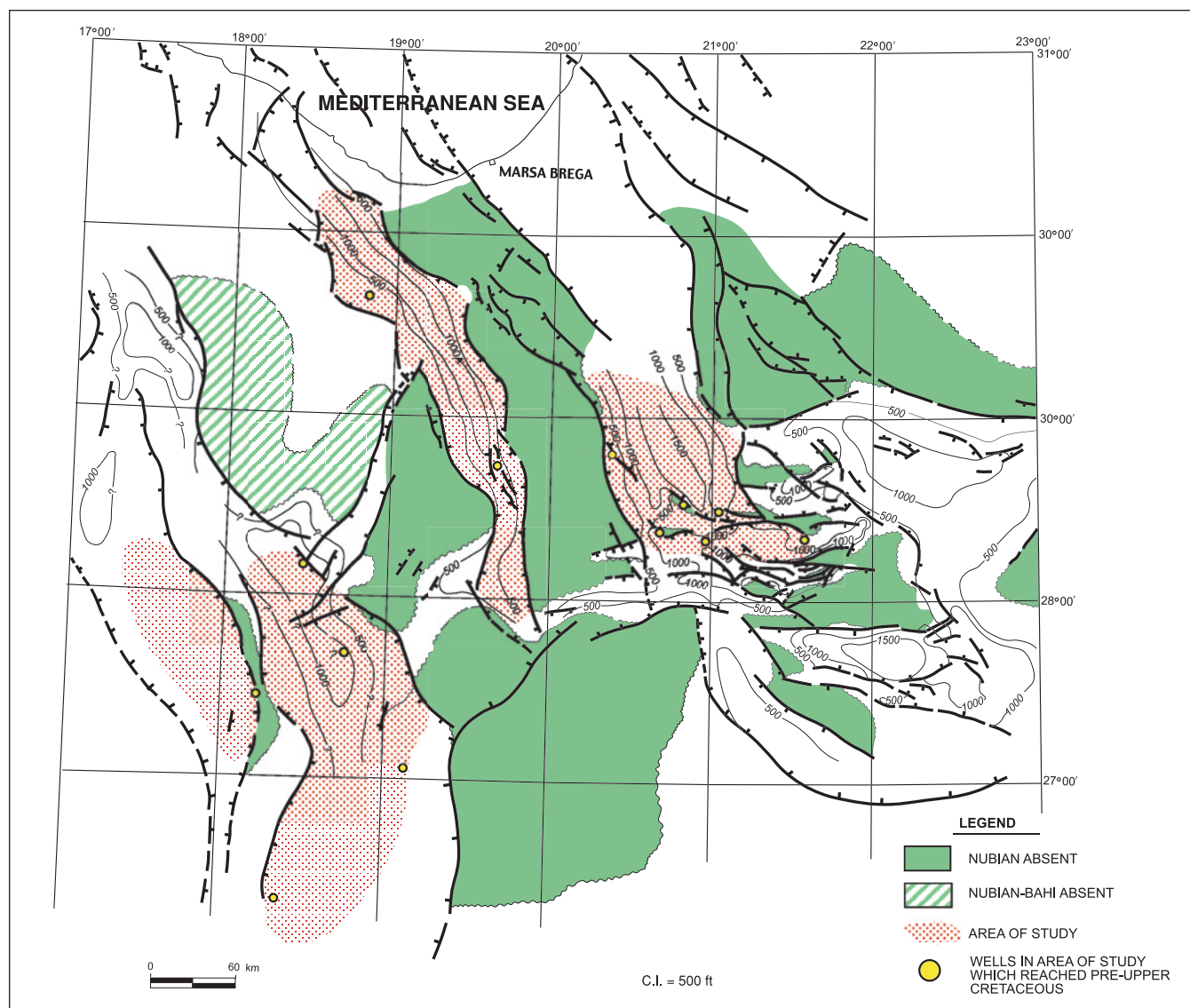


Figure 6. Net sand isopach map of the Nubian Formation (Lower Cretaceous), Sirt Basin. Areas where the Nubian is absent because of erosion or nondeposition are indicated.

adah graben are based only on regional projection and partial data from three widely separated wells (El-Hawat et al., 1996; Bonnefous, 1972): D6-NC149, in the Wadi oil field; P1-16, in the Bazuzi oil field at the northeast edge of the Zahrah platform; and V1-59, in the Bilhizan oil field in the south part of the Bayda platform (Figure 2).

Secondary reservoir objectives are few and high risk in the area because of limited distribution and poor development. The exceptions are reef and shoal carbonates of the Zaltan Formation and the Bahi sandstone. Zaltan Formation facies, consistent with the equivalent upper Sabil carbonate to the east, were not controlled by earlier faulting. A shelf margin extended across the southern part of the Maradah graben. Net thickness of the Zaltan in this area ranges from 0 in the north to more than 400 ft in the south. Depth to the top Zaltan is 7500 to 9000

ft. Because of this shallow depth, the Zaltan has been subjected to considerably more exploration than the Nubian. The basal Upper Cretaceous Bahi sandstone may attain thicknesses exceeding 600 ft in the graben. However, in places, part or all of the so-called Bahi sandstone may be Lower Cretaceous Nubian sandstone.

**Seals.**—Etel shale and anhydrite at the Sirt unconformity provide an effective seal for the Nubian sandstone throughout most of the area. In a few places, the Nubian may lack an effective seal because the Bahi sandstone or Lidam dolomite directly overlies it. The Etel shale-evaporite sequence is also an excellent seal for Bahi and Lidam reservoirs. The Paleocene Harash or Kheir shales provide the seals for the Zaltan carbonates.

**Timing and migration.**—In the Maradah trough, the peak oil-expulsion stage occurred approximately from the early Oligocene to the late Miocene for the Etel,

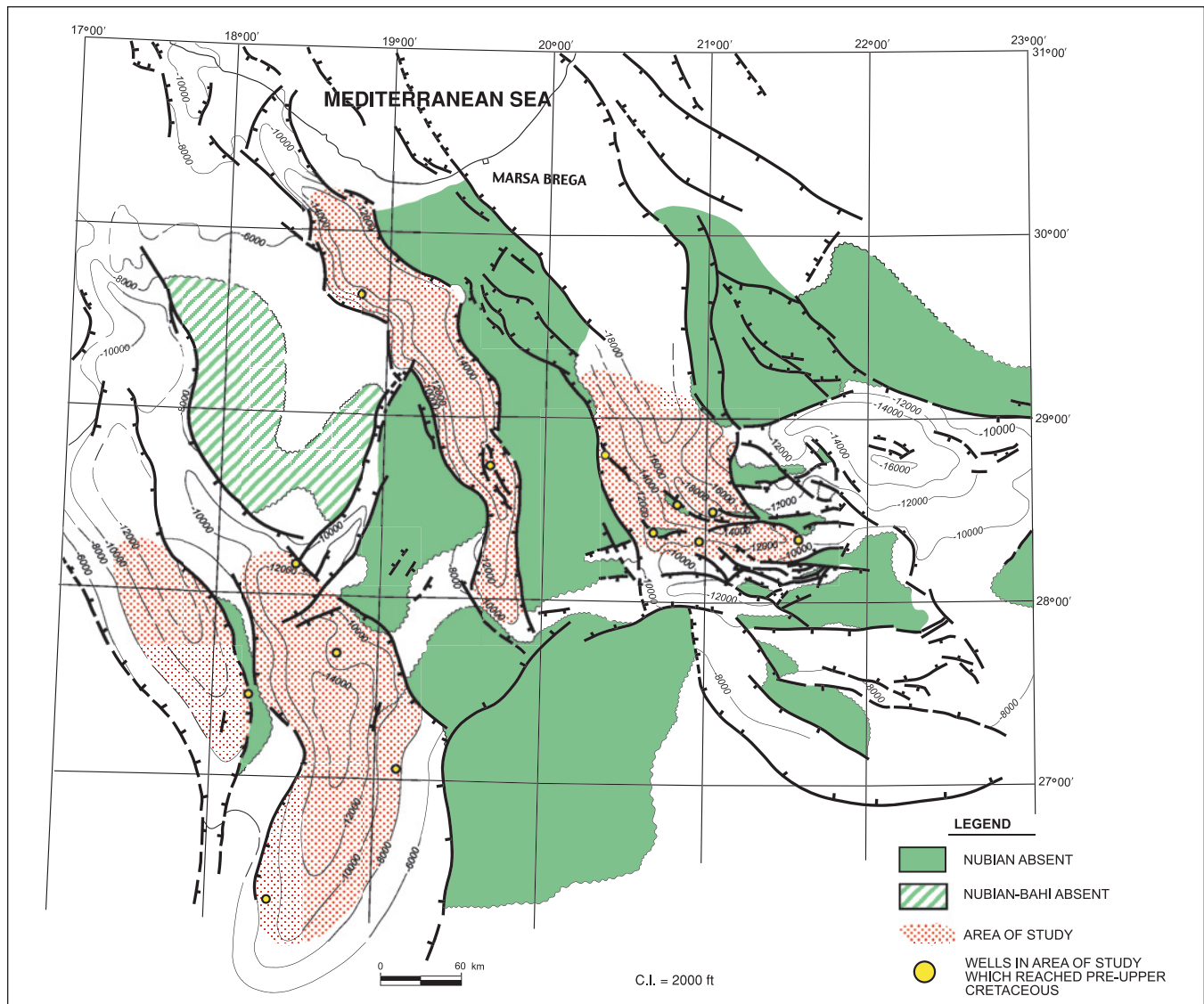


Figure 7. Structure map on the top Nubian Formation, Sirt Basin. Modified in part from Masera Corporation (1992), El-Hawat et al. (1996), and Mansour and Magairhy (1996).

Rachmat, and Sirt Formation source rocks (Roohi, 1996b). As in the case of the Ajdabiya trough, the latest significant structural and stratigraphic trap development was late Paleocene, creating ideal entrapment and retention conditions. Secondary migration from the Sirt shale and the Rachmat shale to the underlying Nubian, Bahi, and Lidam reservoirs would have required an indirect carrier system via faults or faults in combination with the Sirt unconformity. Migration from Etel source beds to overlying reservoirs would have occurred laterally via carrier beds associated with the Sirt unconformity.

Vertical migration from Sirt source beds via faults and fractures provided the charge for the overlying Zaltan reservoir.

**Traps.**—Trap types for Nubian reservoirs are most likely horsts, tilted fault blocks, and faulted anticlines. Combination traps also may be present, involving Nubi-

an sandstone truncated at the Sirt unconformity or updip onlap of Nubian sandstone on the Cambrian-Ordovician surface.

Trap types for the Bahi and Lidam Formations include horsts, tilted fault blocks, drape and faulted anticlines, and pinch-outs. Expected traps for Zaltan reservoirs are reef and shoal buildups, usually in combination with drape and faulted anticlines.

#### *Southern Zallah Trough–Tumayam Trough*

**Reservoirs.**—The lower and upper sandstone members of the Nubian Formation and the Bahi sandstone are among the primary objectives (Schroter, 1996). In this area, it is difficult to differentiate between these two formations. Therefore, the thicknesses reported here are estimates. Nubian net sand thicknesses are estimated to range from 0 (at onlap and truncation limits) to approxi-

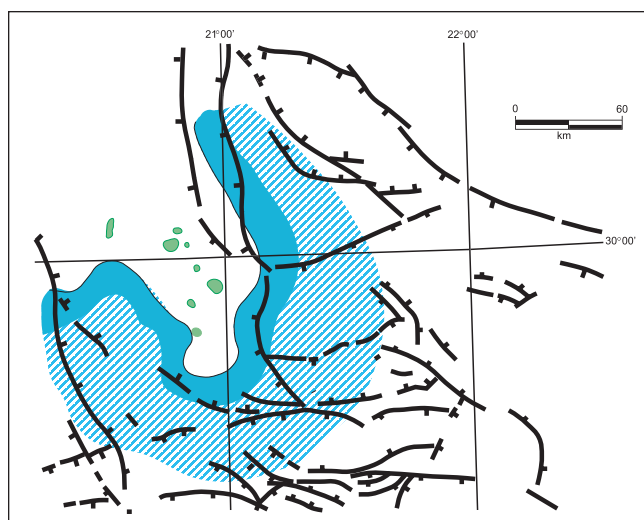


Figure 8. Approximate location of the Paleocene Upper Sabil carbonate shelf edge, Ajdabiya trough—a zone of potential reef and shoal development. Shelf slope pinnacle reef oil fields are shown.

mately 1000 ft. The Bahi sandstone is expected to be from 0 to 300 ft thick. Depth to the top Nubian and Bahi ranges from 9500 to 14,000 ft. It is expected that average porosity will be 12–14% in both formations.

Probably equally important reservoir targets are the Paleocene Defa and Beda Formations and the lower Eocene Facha high-energy carbonate facies. Barrier shoal carbonates are well developed in the Thalith, lower Beda, and upper Beda members of the Beda Formation in the northeast sector of the subject area (Bezan et al, 1996; Johnson and Nicoud, 1996; Sinha and Mriheel, 1996). Porosity in the lower and upper Beda members (Farrud sequence) ranges as high as 35%. Thickness of the Beda Formation exceeds 1000 ft, with as much as 600 ft of net porous carbonate (Figure 10). The Defa carbonate and Facha dolomite attain a net thickness of as much as 400 ft in the area. Approximately 25 wildcat wells have reached these formations in the area at depths of less than 9000 ft. However, the well density of 1 well/1000 km<sup>2</sup> indicates that the area is still underexplored, even at shallow levels.

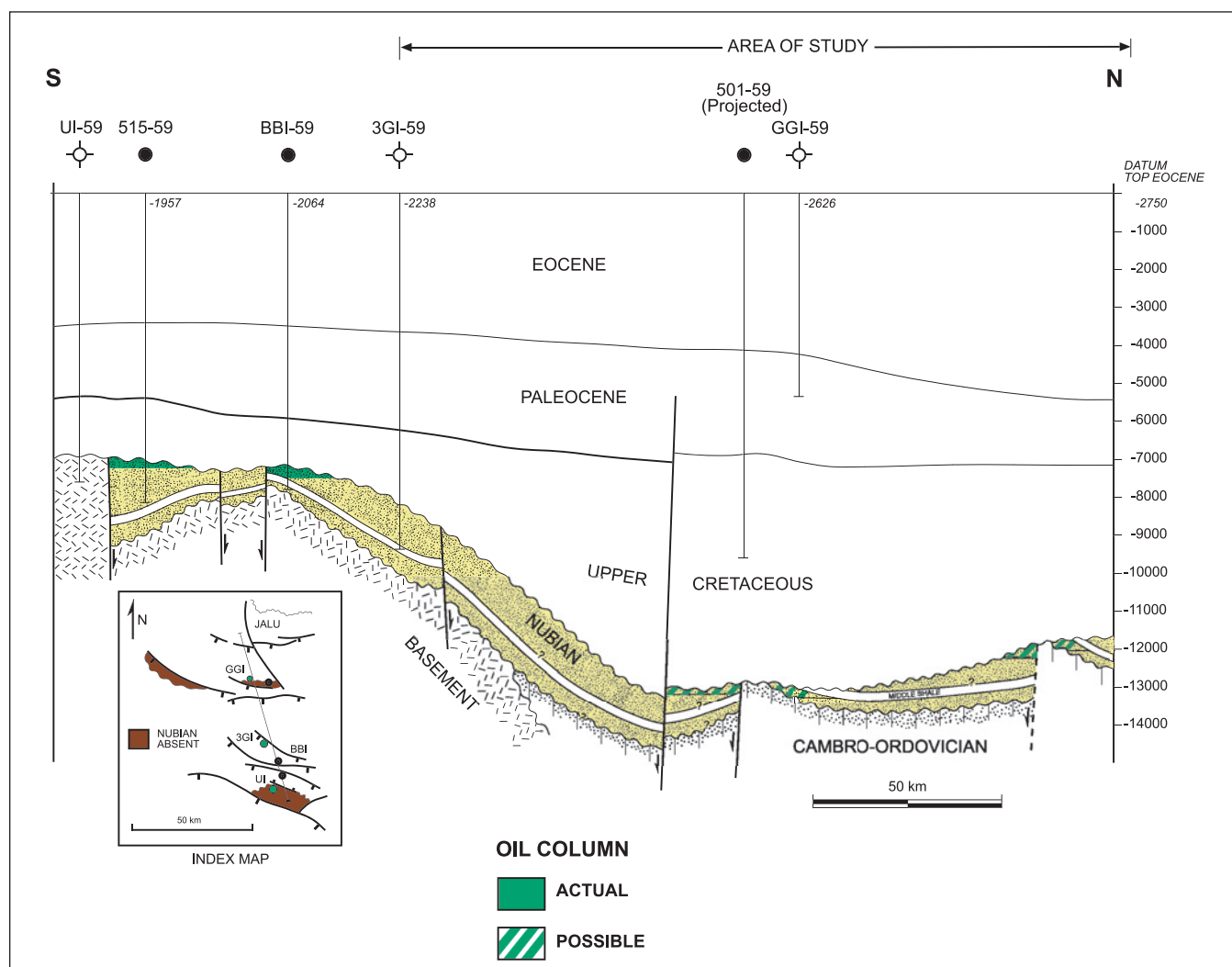


Figure 9. North-south structural cross section from the central part of the Ajdabiya trough to the Faregh oil-field area, depicting actual and inferred Nubian sandstone trap configurations.

A secondary objective that has not been pursued is a Turonian-Senonian sandstone sequence, equivalent to the Rachmat and Sirt Formations, which is developed in the southern sector of the Tumayam trough. These porous sandstone beds thicken rapidly southward from their pinch-out limits to more than 1000 net ft (Figure 11).

**Seals.**—Etel shale and anhydrite provide an effective seal for the Nubian and Bahi sandstones throughout most of the area. Locally, there is a slight risk that a thin Lidam dolomite sequence overlying the Nubian or Bahi would have prevented sealing. Hagfa and Khalifa shales are effective seals for Defa and Beda carbonates, and the Gir evaporites are reliable seals for the Facha dolomite. Interbedded shales should provide adequate seals for the individual Rachmat-Sirt sandstones.

**Timing and migration.**—In the central part of the South Zallah–Tumayan trough area, where the top of the

Sirt shale is between 9000 and 11,000 ft, the main stage of oil expulsion apparently occurred throughout the Miocene. There is little doubt that the Sirt shale is the only important effective source rock in the area, based on organic richness and maturity.

Secondary migration from Sirt shale to underlying Nubian and Bahi reservoirs, as is the case throughout the Sirt Basin, requires a system of faults or faults in combination with the Sirt unconformity.

Vertical migration of oil from Sirt source beds to overlying Defa, Beda, and Facha reservoirs was accomplished via faults, fractures, and local carrier beds.

**Traps.**—Trap types for Nubian reservoirs are expected to be the same here as in the Maradah and Ajdabiya troughs. Trap types for Bahi sandstone should include tilted fault blocks, drape and faulted anticlines, and pinch-outs. Northerly oriented pinch-outs of the Turon-

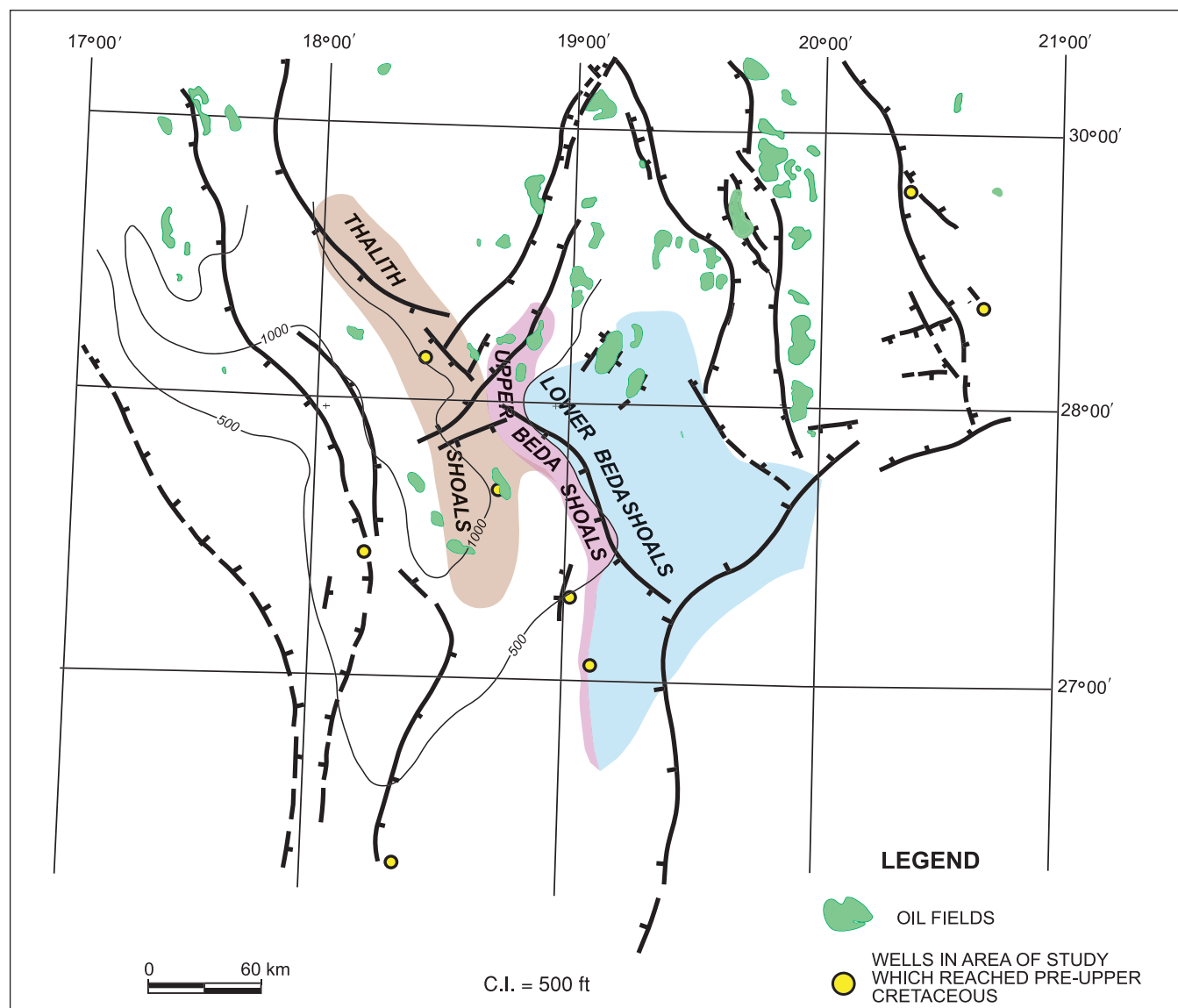


Figure 10. Isopach map of the Beda Formation, showing distribution of barrier shoal carbonate facies of the Thalith, lower Beda, and upper Beda members, south Zallah trough–Tumayam trough. After Bezan et al. (1996) and Sinha and Mriheel (1996).

ian-Senonian sandstones, in combination with dip or fault closures, are expected in the southern sector of the area. Reef and shoal buildups, in combination with anticlinal drape or faults, are the most likely traps for Defa and Beda reservoirs.

## Western Libya

### Central Ghadamis Basin

**General.**—The Ghadamis Basin area of study, which covers more than 20,000 km<sup>2</sup>, is located in the center of the basin bordering Tunisia and Algeria (Figures 12–14a). The basin is continuous across southern Tunisia and central Algeria, covering an area of approximately 200,000 km<sup>2</sup>. It is particularly noteworthy that in the last 10 years, an estimated 5 billion to 6 billion bbl of recoverable oil equivalent has been discovered, mainly from Devonian and Triassic sandstone reservoirs in the Algerian sector of the Ghadamis Basin. The key to these discoveries was an understanding of the plays and 3-D seismic. During that same period, there was minimal success in the Libyan sector, although geologic setting and reservoirs are essentially the same.

In the study area, 27 wildcats yielded one oil and three gas-condensate discoveries with Upper Silurian Acacus sandstone pay in the north, and two oil discoveries with Triassic and Upper Devonian Tahara sandstone pay in the central sector.

**Reservoirs.**—The main reservoir targets for the area are the Upper Silurian Acacus Formation and the Lower Devonian Tadrart and Kasa Formations (Figure 15) (Said, 1974; Masera Corporation, 1992; Echikh, 1998). The Acacus net sandstone thickness ranges from approximately 500 to 1300 ft (Figure 16). The Acacus average porosity is at least 16%. The Tadrart and Kasa Formations should have a net sandstone thickness of 300–700 ft and an average porosity of 14–15% in the study area. These formations, which are a more or less continuous stratigraphic succession, are at depths between 8000 and 12,500 ft (Figure 17). Only eight exploration wells, most of which were in the north, reached these objectives in the study area.

Three other sandstone reservoirs are valid objectives, but because of their shallower depths, they have been the subject of more exploratory

drilling than the above formations. They are the Middle Devonian Uennin sandstone (equivalent of the F3 in Algeria), with a thickness range of 0 to 300 ft; the Upper Devonian Tahara Formation, with a net sand range of 50 to 200 ft; and the Triassic Ras Hamia Formation, with a net sandstone thickness of 200 to 700 ft. All of these sandstones have very good porosity, averaging 14–18%.

**Seals.**—Generally, there is an effective Acacus shale seal above the sandstone. Where it may be absent, however, the overlying Tadrart will form a combined objective with the Acacus sandstone. Shale horizons consistently provide adequate seals for Tadrart, Kasa, F3 equivalent, and Tahara sandstones. Throughout most of the area, there are effective shale, carbonate, or evaporite seals for the Ras Hamia sandstone. Because of a dominant continental siliciclastic facies above the Ras Hamia in the southern part of the area, however, a seal may be lacking.

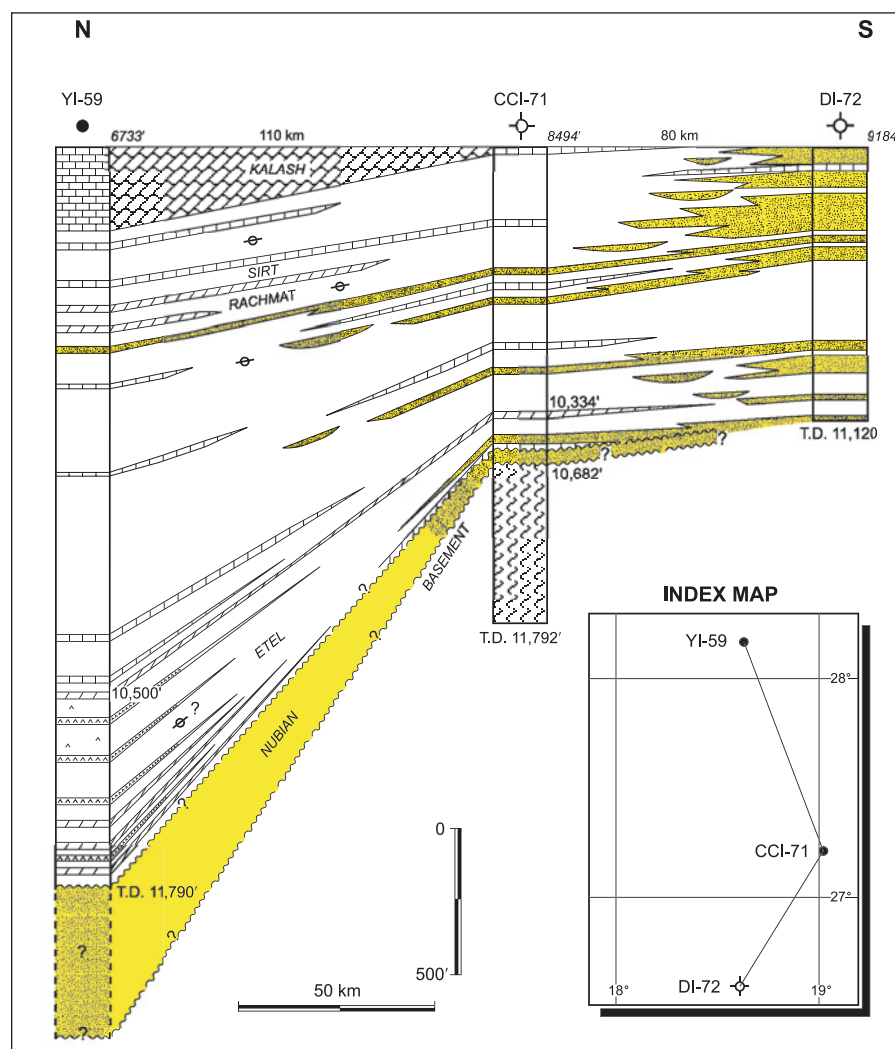


Figure 11. North-south diagrammatic correlation of the Cretaceous section of wells YI-59, CCI-71, and DI-72. Well correlation illustrates probable relationship of the northward sandstone pinch-outs interfingering with Sirt-Rachmat shale source beds. Also shown is the interpreted Nubian sandstone correlation. Datum is the top Cretaceous.

**Source rock, timing, and migration.**—There are two world-class, type II source rocks distributed throughout the entire basin: the Lower Silurian Tanezzuft and the Middle to Upper Devonian Uennin Formations. The two shale formations have an average TOC of 3–5% and are approximately 1000–2000 ft thick in this prime study area.

The peak oil-generation-expulsion window (equivalent to vitrinite reflectance [ $R_o$ ] of 0.8–1.3%) for both formations is approximately 8500–12,000 ft. Depths to the base of the Tanezzuft and Uennin in the area are 12,000–14,500 ft and 8000–12,000 ft, respectively.

The main stage of oil expulsion from the Tanezzuft source probably occurred from the Late Triassic to Early Cretaceous. Oil expulsion from the Uennin source probably occurred from Early to Late Cretaceous. At present, the Tanezzuft shale is in the wet-gas to dry-gas generation stage, and the Uennin source beds are in the peak-oil to late-peak-oil stage.

In this central basin sector, structural traps were essentially established during Hercynian events, although some early development most likely occurred during the Caledonian orogeny. It is unlikely that the Albian Austrian event or the Eocene Pyrennean events, which affected major highs and coastal areas in the region, caused any significant structural modification to this sector. Consequently, traps were in place prior to migration.

Conditions for migration were optimum, in view of the short distance and vertical and lateral carrier systems from the two sources to the multiple reservoirs.

**Traps.**—The expected trap types are low-relief, simple, and faulted anticlines; drape anticlines over paleotopographic relief or faulted structures; unconformity truncation of the Tahara sand in the northern part of the study area; and pinch-outs of the Uennin F3 equivalent sand.

### Central Murzuq Basin

**General.**—This underexplored basin-center area covers more than 30,000 km<sup>2</sup>. Only four wells have been drilled there (Figure 14b), and one well, A1-NC58, is a marginal oil discovery. Within about 50 km to the north are seven small, undeveloped oil-field discoveries, with total reserves of about 150 million bbl, and one major discovery, Elephant (N1-NC174), with estimated reserves of 500 million bbl of oil. The Murzuq oil-field complex (A, B, C, H, and J-NC115

fields), with reserves of about 1 billion bbl of oil, is approximately 100 km north of the subject area. In all these discoveries, sandstones of the Ordovician Memouniat Formation are the reservoirs (Figure 13).

**Reservoirs.**—Main potential reservoirs for the area include the Acacus and the Lower Devonian Tadrart-Kasa sandstones, as well as the main pay in the basin, the Memouniat Formation. The net sandstone thickness of the Memouniat Formation ranges from approximately 500 to 2500 ft and has an average porosity of 10–14%. The Acacus net sandstone thickness is from 0 (at the north edge of the study area, where it is truncated) to 300 ft. The average porosity of the Acacus sandstone is approximately 15%. The Tadrart-Kasa sandstones, undifferentiated, have an estimated net thickness of as much as 200 ft and an average porosity similar to that of the Acacus. This sequence pinches out at the Caledonian surface in the northern part of the area.

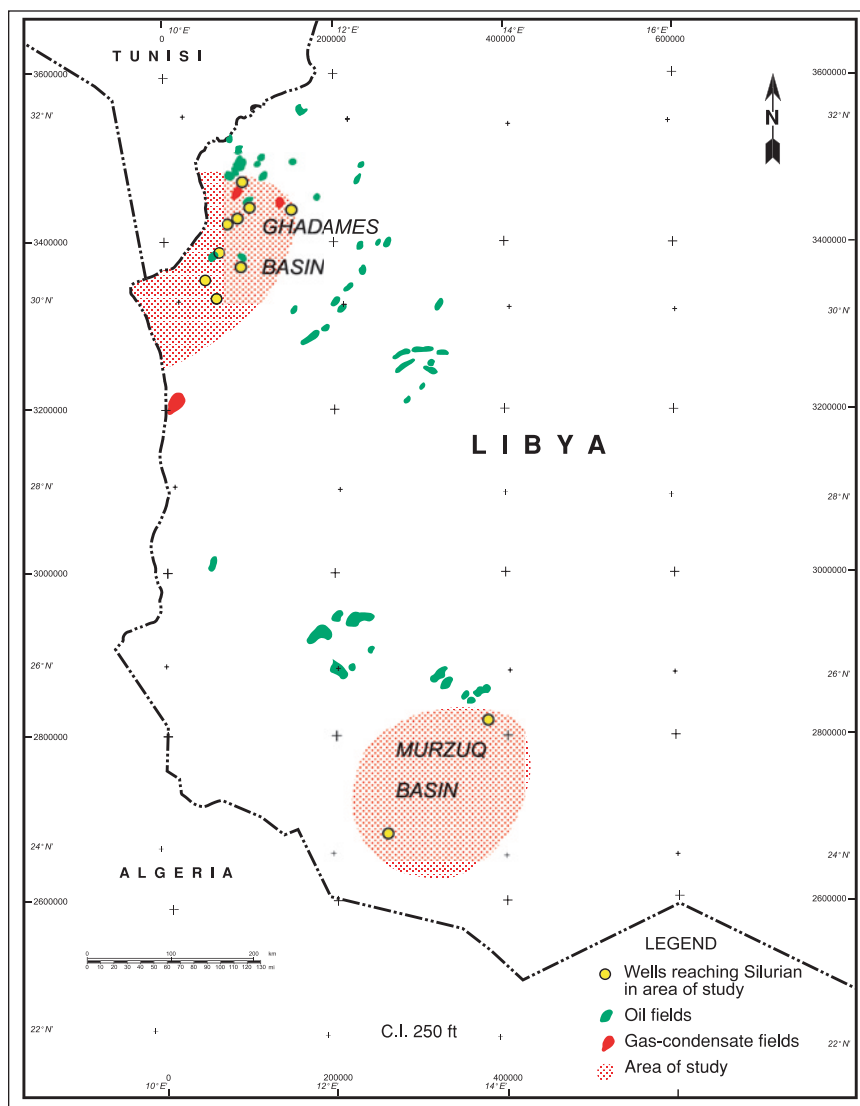


Figure 12. Location map of the Ghadamis and Murzuq Basins, showing the basin-center areas of study. The approximate size of the Ghadamis is 20,000 km<sup>2</sup>; the approximate size of the Murzuq Basin is 30,000 km<sup>2</sup>.

The depth to the Memouniat ranges from 8000 to 11,500 ft. The Acacus and Tadrart-Kasa are at depths of 6500 to 10,500 ft in the Murzuq Basin center (Masera Corporation, 1992).

**Seals.**—The Tanezzuft shale provides a reliable seal throughout the area for the Memouniat Formation. Generally, effective shale seals are interbedded with Acacus sandstone beds. In a few places, upper Acacus sandstones are overlain by Tadrart-Kasa sandstones, which could create a combined reservoir, as in the Ghadamis Basin. Uennin shale beds provide adequate seals for the Tadrart-Kasa sequence.

**Source rock, timing, and migration.**—The Tanezzuft shale is the only effective oil source of importance in the Murzuq Basin (Hamyouni, 1991). It is possible, however, that very minor amounts of early oil were expelled from Devonian Uennin organic-rich shale in the basin center (Meister et al., 1984). The Tanezzuft shale is 400–1600 ft thick in the study area. The average TOC is 1.8%. The peak oil-expulsion window is approximately 6500–9000 ft. Therefore, because the depth to the base Tanezzuft is from 7000 to 11,500 ft in the study area, the Tanezzuft is in peak-oil to wet-gas generation stages.

Vertical, updip, and fault pathways provided easy, short-distance pathways for migration of oil to the adjacent reservoirs. Migration apparently took place from the Early Jurassic to the Early Cretaceous, after the establishment of most, if not all, of the traps in the study area.

**Traps.**—Structural trap types are basically the same as those in the Ghadamis Basin center. Unconformity truncation of the Acacus and onlap pinch-out of the Tadrart-Kasa, in association with dip or fault closure, are also potential traps in the area.

### *Eastern Tripolitania Basin*

**General.**—The offshore Tripolitania Basin (Gabes-Sabrattha Basin) is a deep, highly faulted, elongate trough which extends from the Gulf of Gabes to the northwestern margin of the Sirt Basin. The eastern sector, which covers approximately 20,000 km<sup>2</sup>, is essentially unexplored. To date, one dry hole has been drilled there. The oil and gas-condensate discoveries in the basin are concentrated about 100–150 km west of that area. In general, play concepts

established in the productive western sector of the basin and, to some degree, in the western part of the Sirt Basin are also valid in this undrilled area (Bishop, 1988).

**Reservoirs.**—Based on regional projections, numerous potential reservoir suites are in this basin sector (Figure 18). The lower Eocene El Garia Formation of the Metlaoui group (Jdeir Formation), the main pay in all of the Tripolitania Basin discoveries, is obviously the most important objective in the subject area. El Garia nummulitic bank grainstone-packstone facies and equivalent or underlying dolomite and skeletal limestones (Jirani and Bilal Formations) probably have net thicknesses of as much as 600 ft in the subject area. The effective porosity range is about 5–30%, with an average of 17% in the western part of the basin. These facies pinch out toward the

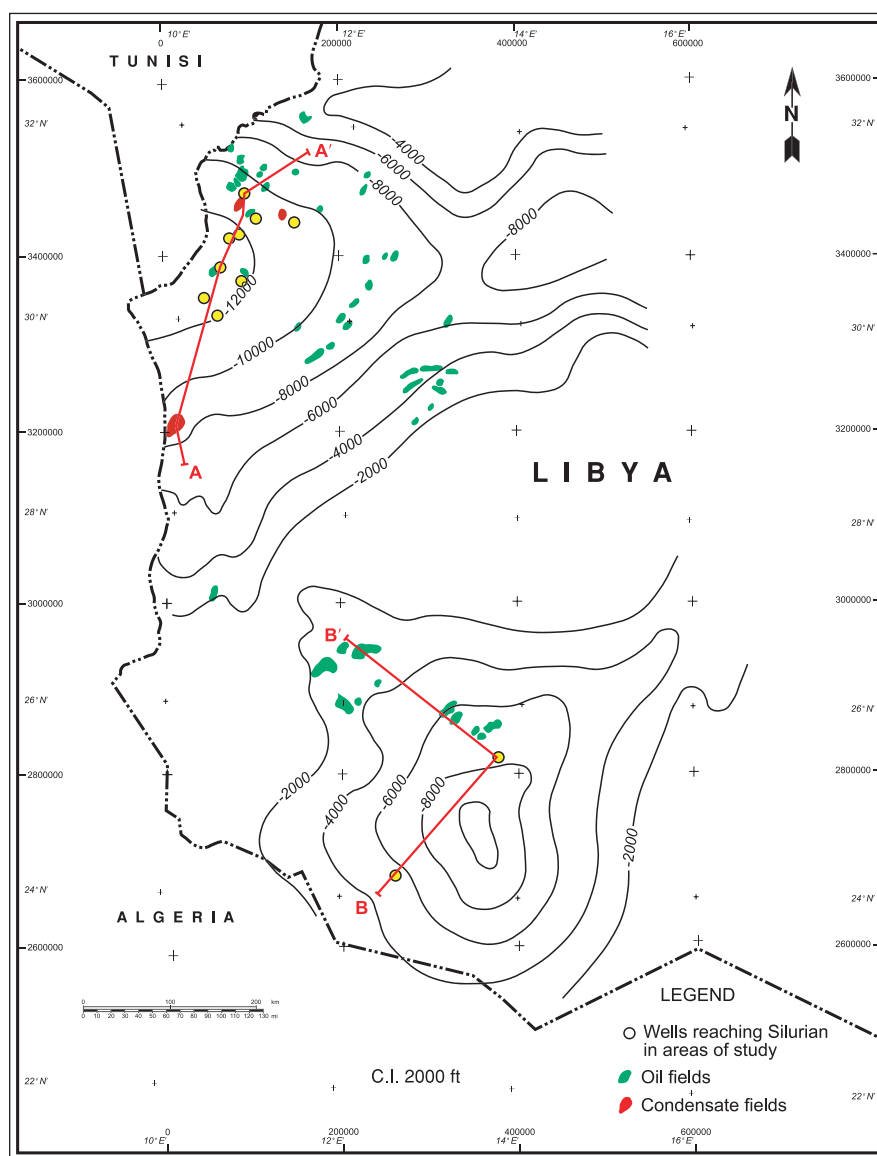


Figure 13. Structure map on the top Ordovician, Ghadamis, and Murzuq Basins, showing oil and gas fields and discoveries. Also shown are locations of cross sections A-A' and B-B' shown in Figure 14. Adapted from Masera Corporation (1992).

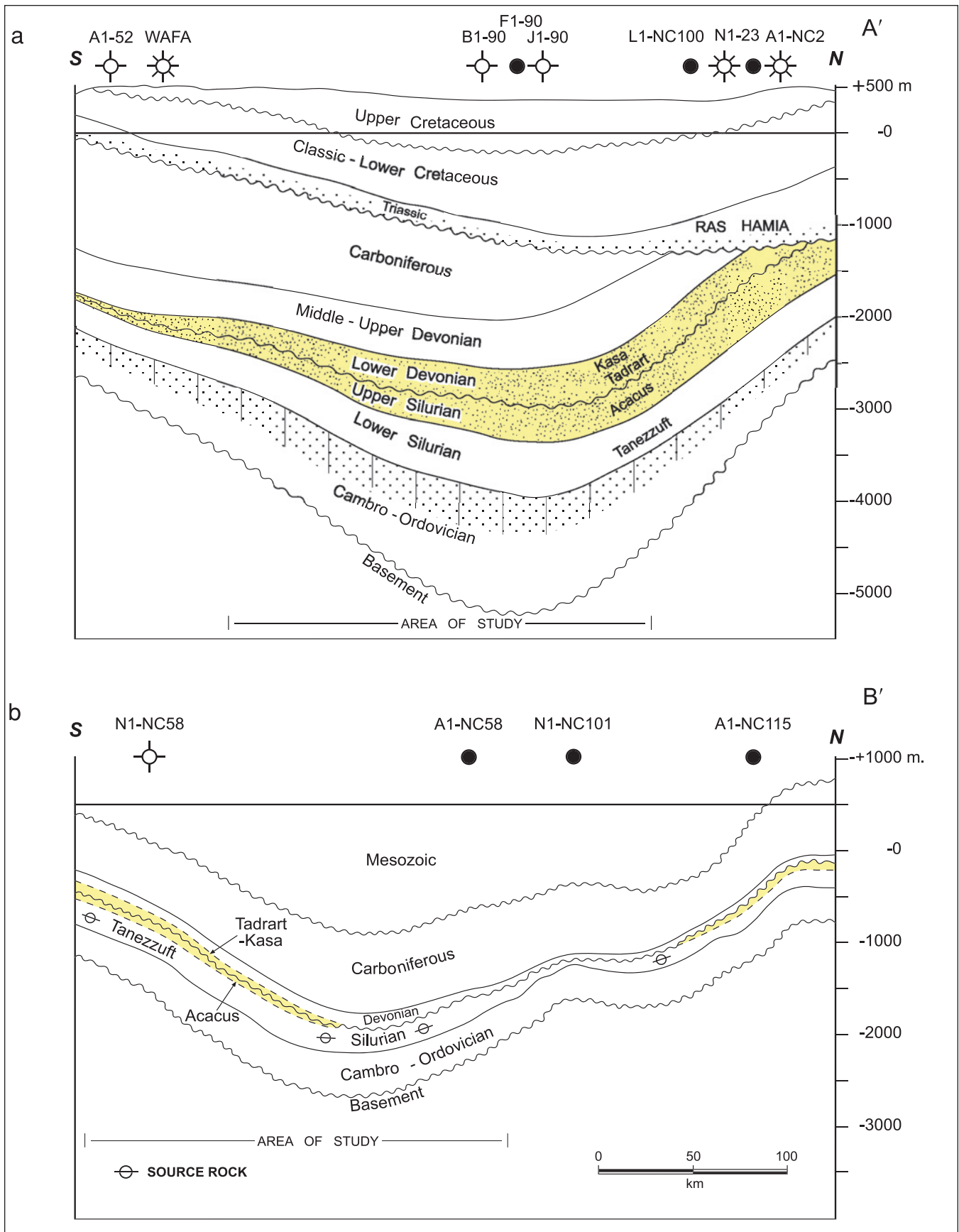


Figure 14. North-south structural cross section A-A', Ghadamis Basin area of study, and (b) north-south structural cross section B-B', Murzuq Basin area of study. Refer to Figure 13 for locations of cross sections.

inner shelf along the southwest margin of the study area and seaward of the shelf edge at the northern limits of the area. The top of the El Garia is at depths from 5000 ft in the southwest to 11,000 ft in the basin center (Bailey et al., 1989; Sbata, 1990; El-Ghoul, 1991; Bernasconi et al., 1991; Loucks et al., 1998) (Figures 19, 20).

Cretaceous reservoir considerations are speculative. However, based on stratigraphic projection from a few wells in the western part of the Tripolitania Basin and the northwestern part of the Sirt Basin, there appear to be several attractive secondary reservoir targets within the Cretaceous section. Probably the most important are the shallow-shelf skeletal limestone and dolomite facies of the Cenomanian-Turonian lower and upper Zebbaj Formations. In the Libyan nomenclature, this sequence equates to the Alagah and Makhbaz Formations and the Lidam-Argub sequence. The net Upper Cretaceous porous carbonate section is estimated to thin basinward from a maximum thickness of 600 ft in the south to about 100 ft along the northern edge of the study area. These objective formations are at depths of 7500 to 15,000 ft (Figure 21).

Lower Cretaceous formations also have potential

reservoir-quality facies. The shallow-marine carbonates and marginally marine sandstones of the Meloussi and Boudinar Formations and the rudist carbonates of the Serdj Formation (probable equivalents of the Turghat-Kiklah sequence) are potential targets. However, distribution and thickness are matters of speculation. Depths to Lower Cretaceous strata are 8000 to 16,000 ft.

**Seals.**—Shale and argillaceous limestone (mudstone-wackestone) beds provide effective seals for the underlying Cretaceous and Eocene reservoirs throughout most of the eastern sector of the basin (Figure 18).

**Source, timing, and migration.**—Mature organic-rich type II source beds have been identified in four formations in the basin. The best known and probably the most important is the Turonian Bahloul argillaceous limestone, with a TOC of 1–10% (Caron, 1999) (Figure 21). The Bahloul Formation is expected to have an average thickness of 100 ft in the study area. The organic-rich shale beds of the Sidi Kralif–Fahdene sequence, which have a TOC of 0.5–10% in offshore Tunisia, may be as effective as the Bahloul. The distribution and thickness of this sequence in the area of study are relatively unknown. However, on the basis of projection from a few wells to

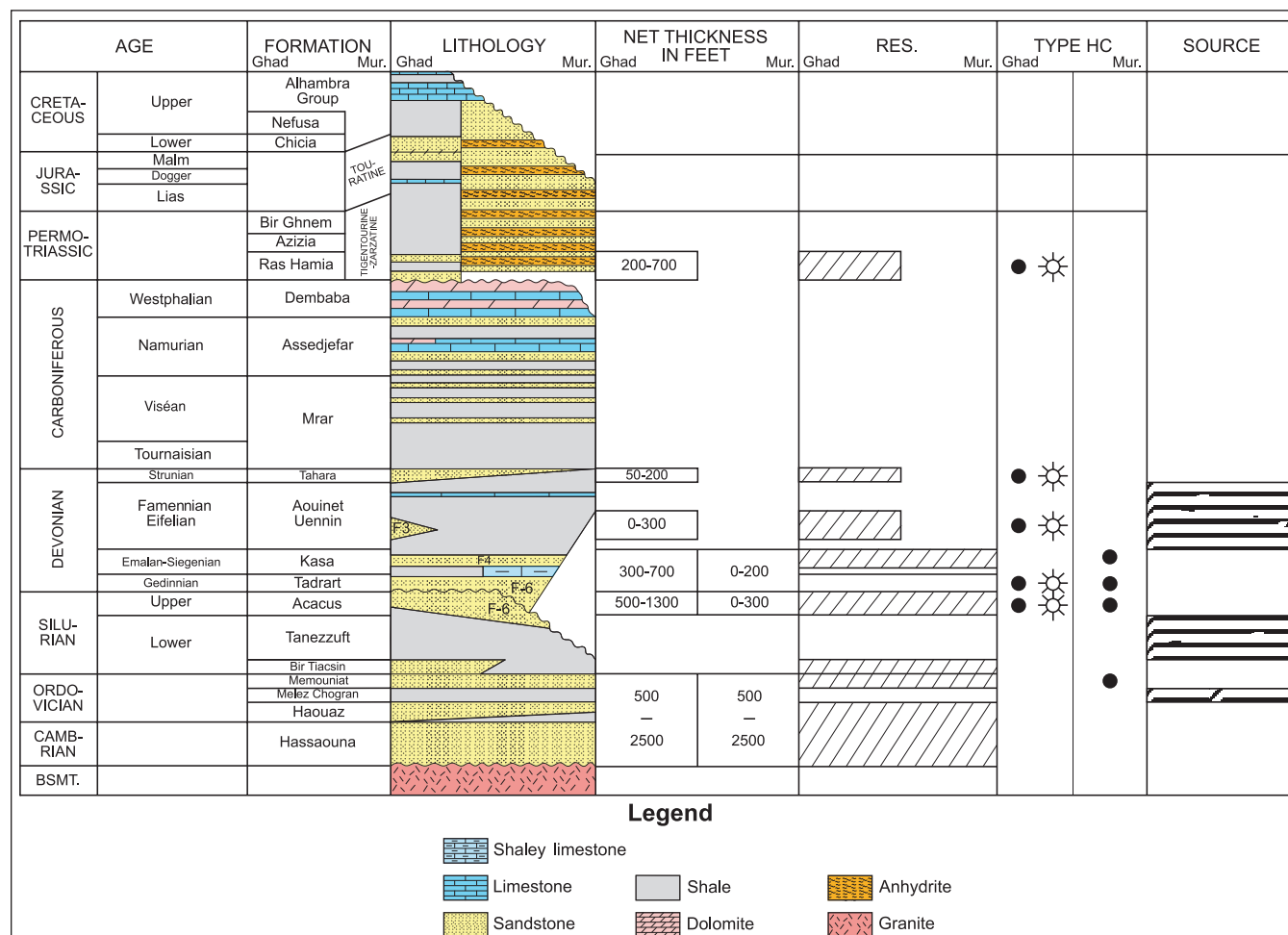


Figure 15. Generalized stratigraphic chart of Ghadamis and Murzuq Basins, showing source and potential reservoir intervals.

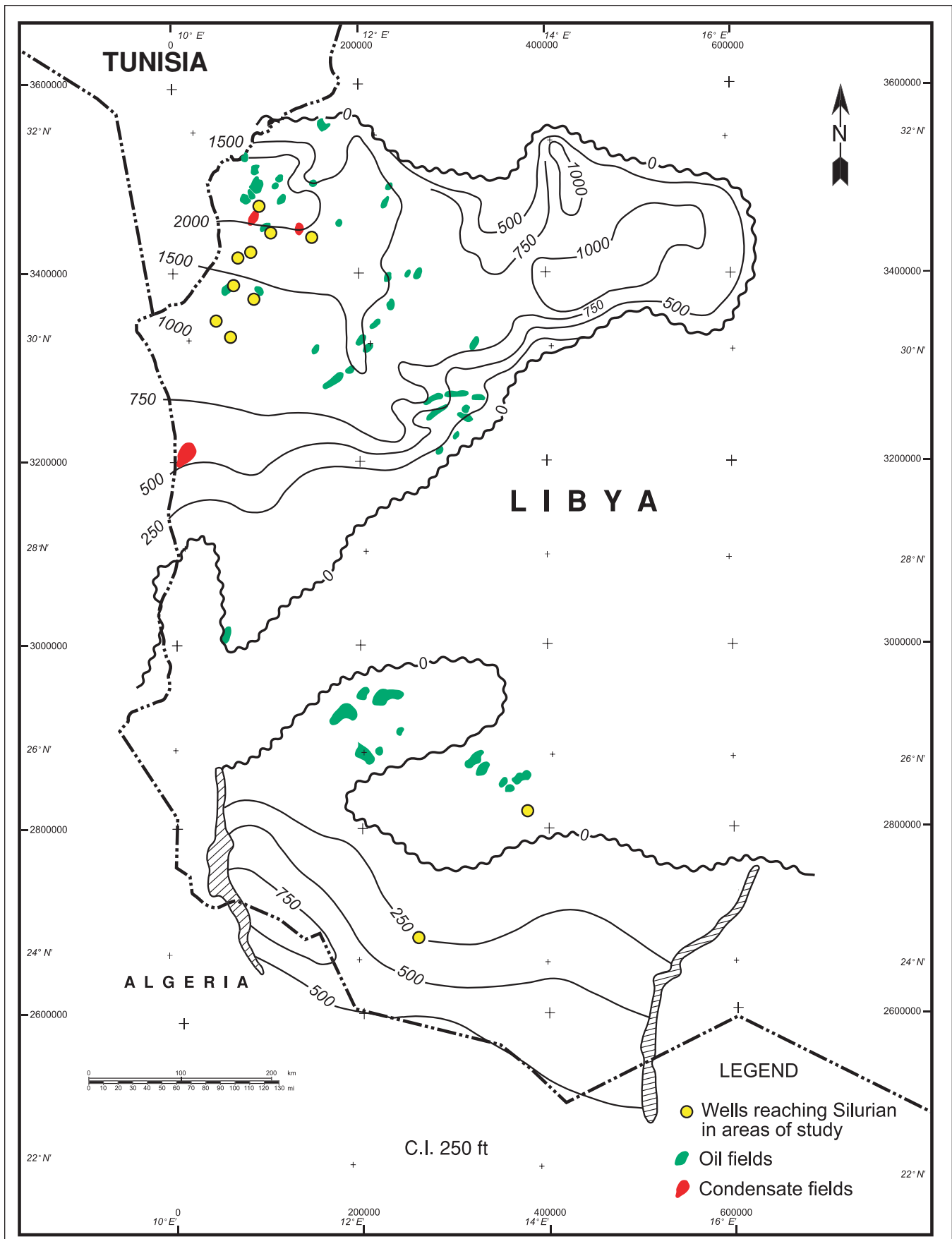


Figure 16. Isopach map of the Acacus Formation, Ghadamis and Murzuq Basins.

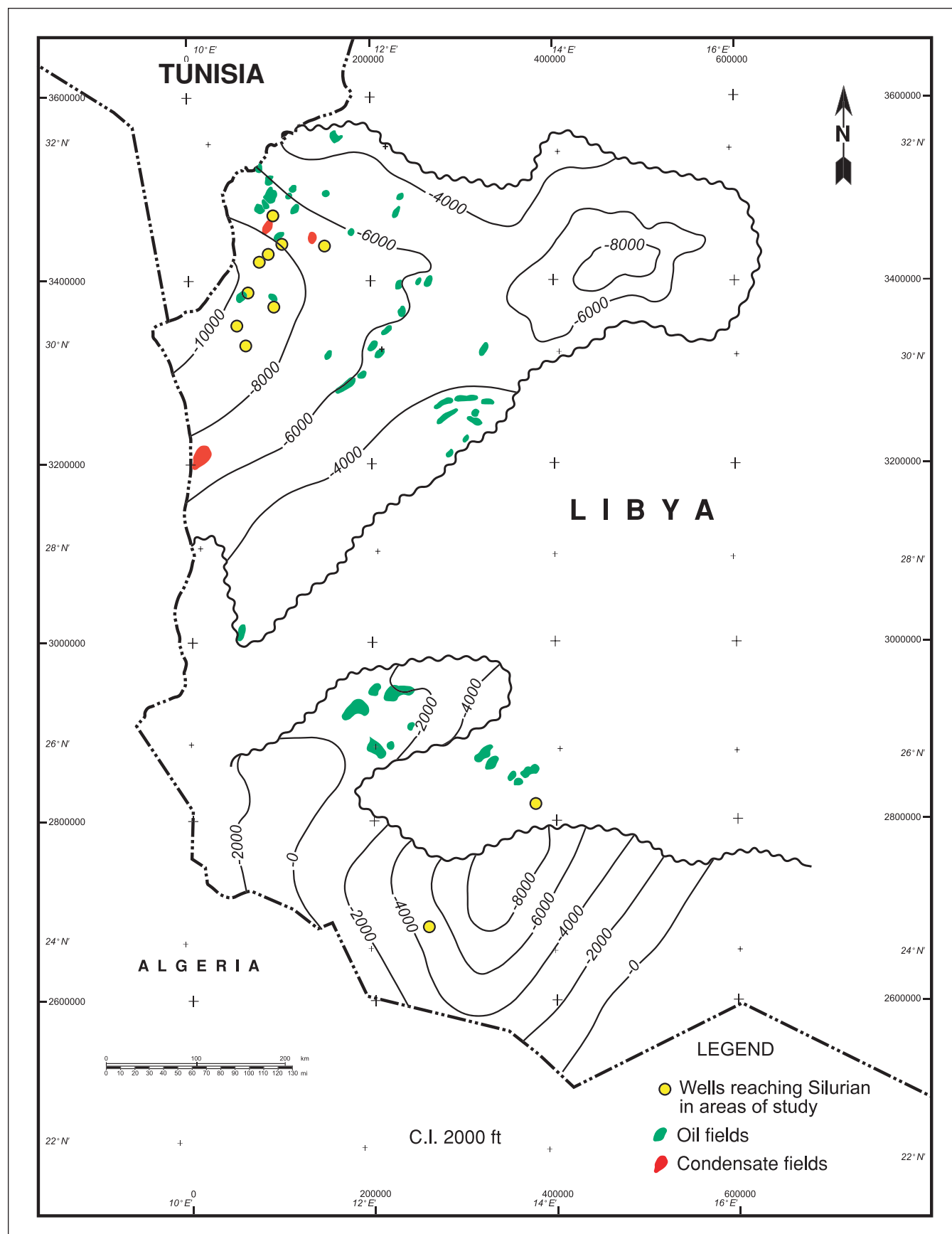


Figure 17. Structure map on the top Acacus Formation, Ghadamis and Murzuq Basins. Modified from Masera Corporation (1992).

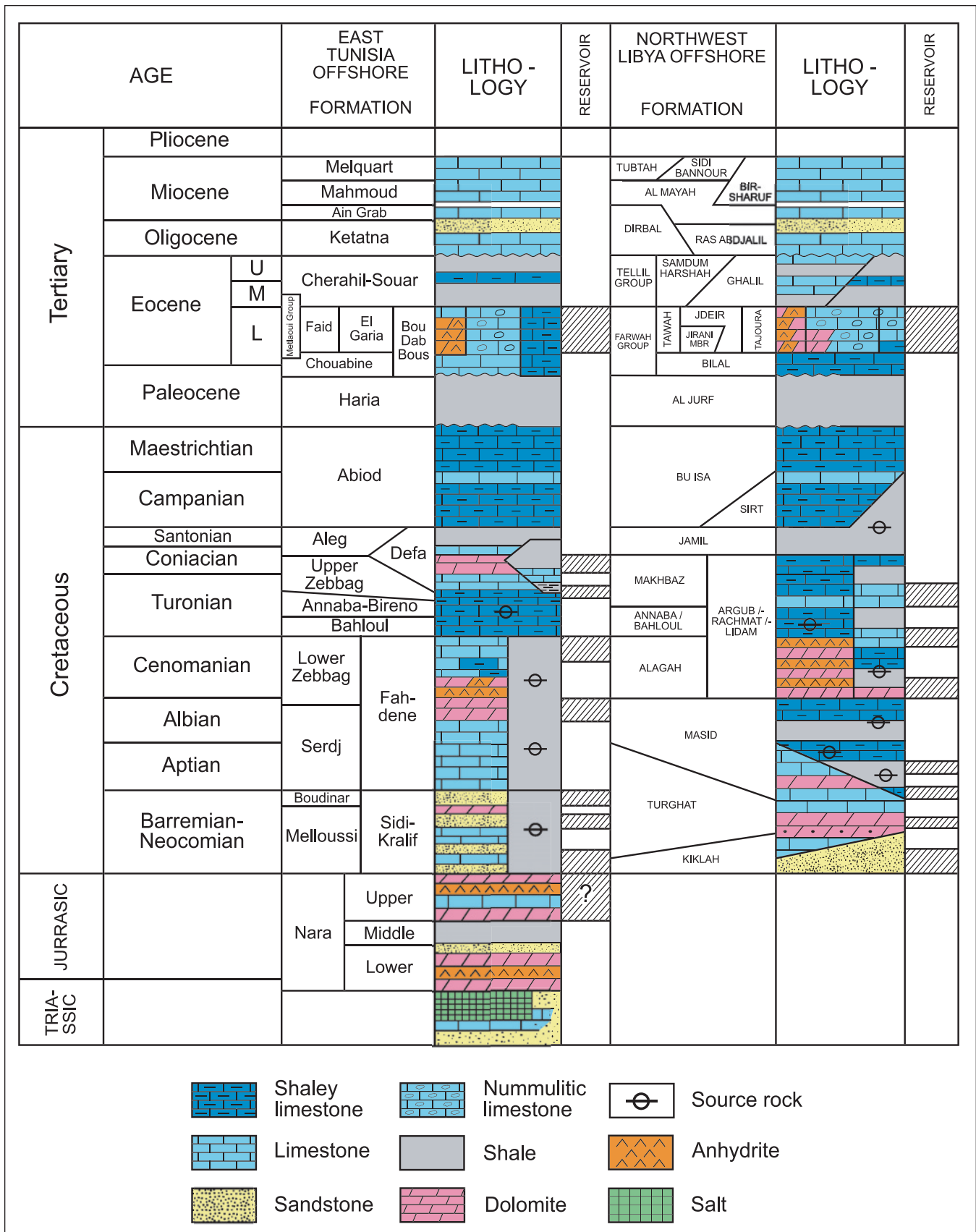


Figure 18. Stratigraphic correlation chart of formations and generalized lithologies of northwest offshore Libya and south offshore Tunisia. Also shown are the main reservoir and source units. Modified from Bishop (1988), Bernasconi et al. (1991), Sbata (1990), and El-Ghoul (1991).

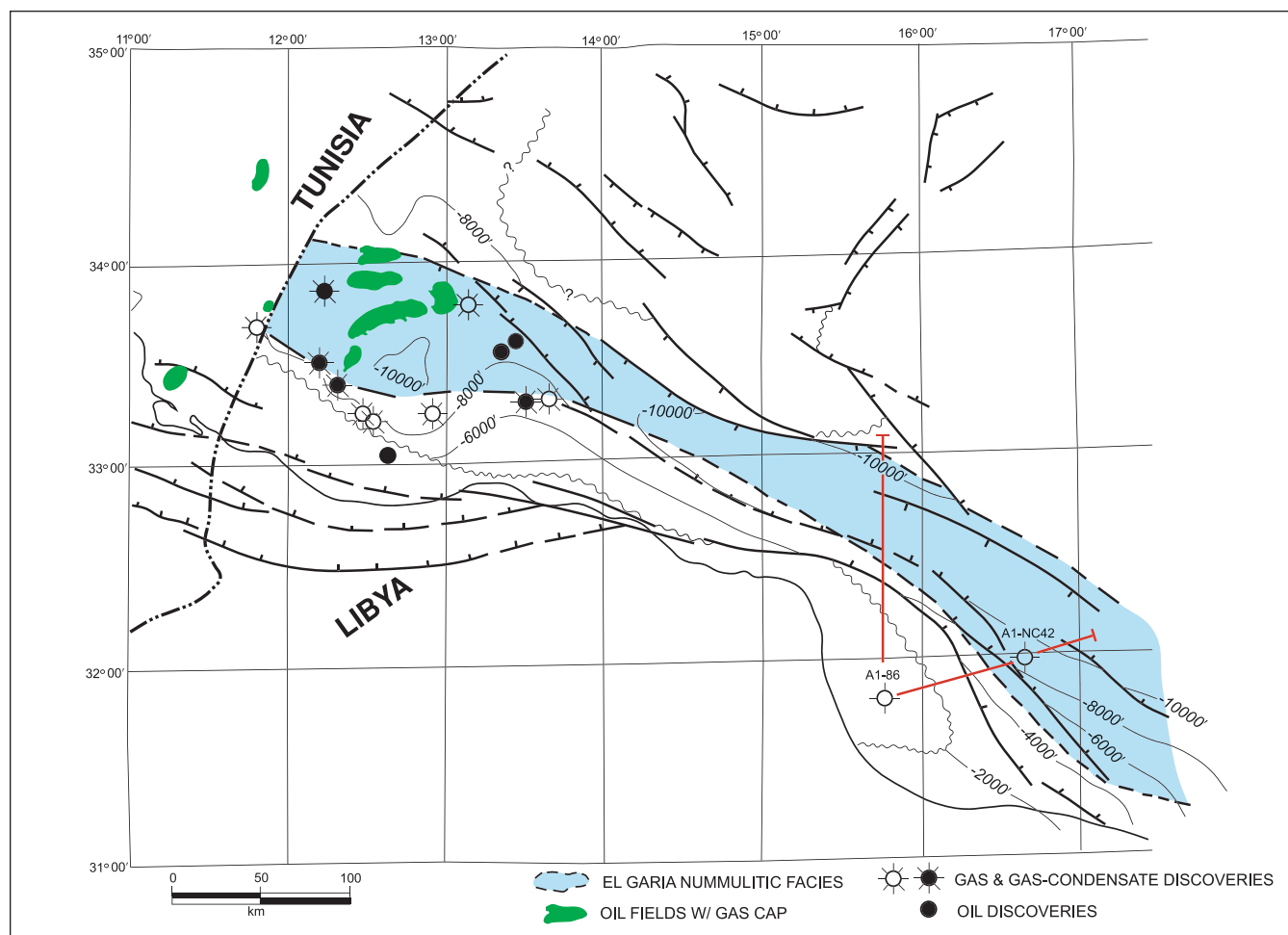


Figure 19. Structure map of the top Metlaoui group, Tripolitania Basin, showing distribution of the El Garia Formation (Jdeir) nummulitic facies.

the west, as much as approximately 400 ft can be expected in parts of the study area.

Along the extreme southwest part of the study area, the Silurian Tanezzuft shale thickens from an erosional edge on the north to more than 1000 ft at the southwest limits of the study area (Belhaj, 1996). It is estimated that Tanezzuft TOC is between 1% and 8%, based on Ghadamis Basin data.

The lower Eocene Chouabine limestone is considered to be an effective source rock in the western part of the Tripolitania Basin, although its area of peak generation is limited and it may not be present in the area of study.

The peak oil-generation-expulsion stage for the Tanezzuft shale probably occurred during the Paleogene. Peak oil generation for the Sidi Kralif-Fahdene and Bahloul Formations probably occurred from the Oligocene to the Miocene in the central part of the eastern Tripolitania Basin.

In the study area, it is likely that secondary migration was vertical or updip directly to reservoirs in some cases, and via carrier beds and faults in other cases.

Even though phases of recurrent faulting occurred throughout the Tertiary, the thick Miocene to Holocene

section, with adequate shale intervals, should have preserved trap integrity in all but the southwestern quadrant. In this sector, which has a very thin Neogene section, there is a risk that late faulting could have caused seals to be breached.

**Traps.**—The trap types expected in the study area include faulted anticlines, horsts and tilted fault blocks, drape anticlines over carbonate buildups or faulted relief, and updip lithology or permeability pinch-outs.

## CONCLUSIONS

The six underexplored basin or trough centers which are the subject of this paper have exceptional potential for major undiscovered petroleum resources.

In each of the six areas, which are peripheral to major oil and gas production, at least one well-defined petroleum system is established. These systems comprise mature, highly organic-rich source rock which provided a voluminous charge to multiple reservoirs by means of a variety of short-distance migration pathways.

In the Sirt Basin study areas, the Upper Jurassic–

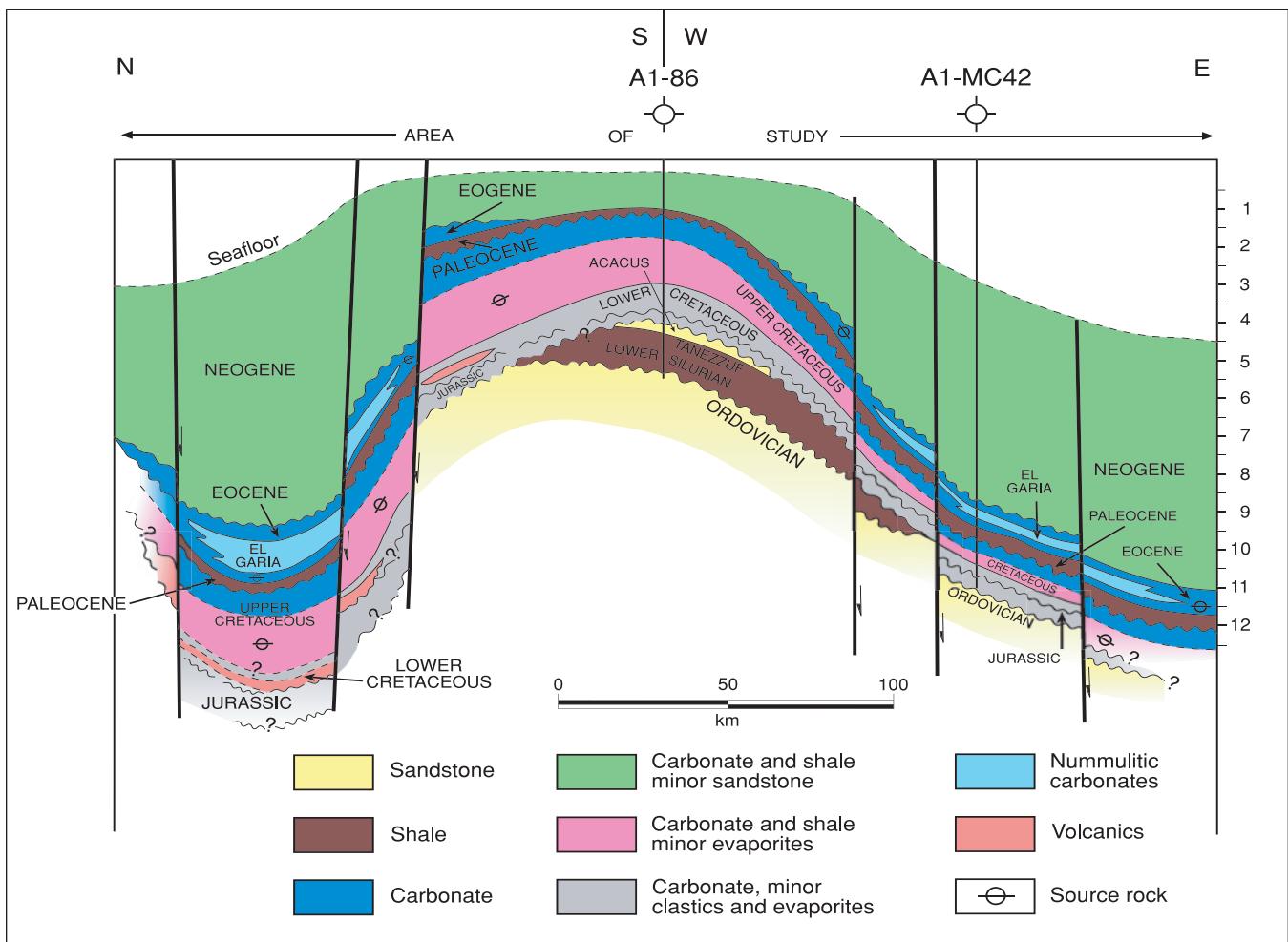


Figure 20. A diagrammatic north-south and west-east structural cross section of the Tripolitania Basin area of study. Adapted in part from Belhaj (1996).

Lower Cretaceous Nubian sandstone members should be considered primary objectives. This thick sandstone series, which is mostly at depths exceeding 12,000 ft, surprisingly has been the subject of minimal exploration to date.

In the Ghadamis and Murzuq Basins, sandstone sequences of the Upper Silurian Acacus and Lower Devonian Tadrart-Kasa Formations are definitely quality objectives, but they have not been priority targets. In the Ghadamis study area, which covers 20,000 km<sup>2</sup>, only eight exploration wells reached the Acacus.

In the eastern Tripolitania Basin, in addition to the lower Eocene El Garia (Jdeir) nummulitic limestone, which is the major producing formation in the western part of the basin, reservoir potential includes numerous dominantly carbonate Lower and Upper Cretaceous formations.

The critical factor in determining future exploration success in the underexplored depocenters will probably be accurate trap definition. In general, at this stage in the exploration history of Libya, it is expected that the ma-

jority of the focus will be on subtle and complex trap types: low-relief faulted structures and drape anticlines, structural-stratigraphic combination traps involving facies pinch-outs, onlap terminations, and unconformity truncation. Identifying specific traps is complicated further by the fact that they are at considerable depths. Therefore, it will be necessary to adopt an integrated, interdisciplinary approach for in-depth, accurate interpretation of the specific trap or prospect. To accomplish this optimum level of trap definition, a detailed geologic database and state-of-the-art tools and methods will be required, including, for example, 3-D seismic, sequence stratigraphy, and basin-modeling concepts.

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