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LIBYA: PETROLEUM POTENTIAL OF THE UNDER-EXPLORED BASIN CENTERS --- A 21ST 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 oil and 40 trillion cubic feet gas. Approximately 80 percent of these reserves were discovered prior to 1970. Since then, a less active and more conservative exploration effort has persisted. Complex, subtle and, in particular, deep plays were rarely pursued during the seventies and eighties because of a lack of definitive imaging technologies, limited knowledge of the petroleum systems, high costs and risk adversity.

Consequently, undiscovered resources remain extensive in Libya. These resources could be accessed, if geological and geophysical knowledge, innovation and advanced technologies were utilized effectively. 3-D 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, under-explored deep areas of the producing basins. Six areas are exceptional in this regard: in the Sirt Basin,the south Ajdabiya Trough, the central Maradah Graben and the south Zallah Trough – Tumayam Trough; and, in the west, the central Ghadamis Basin, the central Murzuq Basin and the offshore eastern Tripolitania Basin. These highly prospective basin sectors encompass a total area of nearly 150,000 sq.km. presently with an average well density, for wells exceeding 12,000 ft., of one well per 5000 sq.km.

INTRODUCTION

The exploration effort in Libya, which commenced in 1957, has been a phenomenal success. In the Sirt basin, the drilling of 1600 new field wildcats resulted in 250 discoveries with recoverable reserves of 45 billion barrels oil and 33 trillion cubic feet gas. These figures include 18 of the 21 giant fields in Libya, which hold reserves of 37 billion barrels oil. In the Ghadamis basin (including the Gheriat and Atchan subbasins), approximately 260 exploration wells yielded 35 oilfield discoveries with an estimated 3 billion barrels of recoverable oil. The 62 wildcats drilled in the Murzuq basin found 11 oilfields with reserves of approximately 2 billion barrels, which include 2 giants. The exploration effort in the offshore Tripolitania basin has been rewarding as well; 14 new field oil and gas–condensate fields have been discovered as result of the drilling of about 50 wildcats. Reserves here are an estimated 2 billion barrels oil and 8 trillion cubic feet gas. The above estimates refer to activities through 1998 and include a number of fields currently categorized as marginal.

In spite of 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. There are: 1) numerous potential areas, proximal to oilfield trends where well density is extremely low, and 2) extensive areas, for most part basin centers, where valid deep objectives were reached by only a few wells.

It is noteworthy that 17 of the 21 giant oilfields and 80 percent of the total recoverable oil and gas were discovered prior to 1970. Since then, a less active and more conservative exploration effort has taken place. Apparently rewards were adequate from the results of field extensions and the drilling of proven, relatively shallow plays. Complex and subtle plays (for example, low relief structural or structural–stratigraphic traps; and deep plays) were rarely pursued prior to the 1990's.

Probably, the main reasons for the absence of a dynamic approach to exploration in the1970 to 1990 period were: lack of definitive imaging technologies (seismic acquisition and processing and other computer – related geoscience technology), limited understanding of the petroleum systems and ineffective use of sequence stratigraphic concepts.

Today, in view of the state-of-the-art technologies available for a wide range of petroleum exploration needs and the relatively low cost to apply them, pursuit of deep plays in Libya should be a top priority. In order to address this objective, I have selected for evaluation six large, under-explored areas with exceptional potential and, for most part, containing deep primary targets (figure 1). It should be pointed out that there are many other promising areas within and near the producing basins of Libya.

Three of the subject areas are in the Sirt Basin: the south part of the Ajdabiya Trough, the Maradah Graben and the south part of the Zallah Trough, including the adjoining Tumayam Trough. The other study areas are in western Libya: the central part of the Ghadamis Basin, the central part of the Murzuq Basin and the extreme eastern part of the Tripolitania Basin.

TECTONIC SETTING

PALEOZOIC

Deposition of mostly continental clastics during Cambrian time and marginally marine to marine clastics during the Ordovician and Silurian, extended 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 clastic deposition during the Devonian and shallow marine to continental deposition in Carboniferous time, the widespread uplift and severe erosion during the Hercynian orogeny, particularly along the Sirt-Tibesti Arch, Qarqaf Arch and the Jefara Uplift, further accentuated the Paleozoic basin margins.

MESOZOIC

A very thick sequence of continental sediments of Triassic to Lower 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 late Permian to 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 Permian to Upper Cretaceous marine clastics and carbonates may exceed 12,000 ft. Tectonic activity in the Tripolitania basin and surrounding offshore areas during Mesozoic time was dominated by east-west oriented dextral transtension related to the 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 Cambro-Ordovician exposed at the Hercynian surface, remained positive until late Jurassic. There were rare exceptions in discrete peripheral areas where Triassic deposition occurred (Maragh Trough, for example). A variable thickness of continental clastics (in the south) and marginally marine clastics (in the north) of Late Jurassic to Early Cretaceous age were deposited on the Hercynian surface. This Nubian deposition was controlled by surface relief and, to some degree, faulting.

In Albian or Early Cenomanian time, extensional and probably, transtensional faulting, followed by uplift and erosion, deformed the Sirt-Tibesti Arch. This activity (the Sirt event) was a prelude to the subsequent collapse of the Arch (El-Alami, 1996; 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 most part, E–W, ESE–WNW and ENE-WSW. Consequently, the subcrop at the Sirt unconformity is a mosaic of Jurassic to Lower Cretaceous clastics in grabens and half grabens, and in depositional or fault contact with basement or Cambro-Ordovician on structural highs. Evidence of this fabric is exhibited in the Faregh, Masrab, Magid, Messlah, Jalu and other areas in the southeast sector and 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 Cenomanian time 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 NNW– SSE, a fabric which persisted throughout the recurrent episodes of faulting during 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 thicken rapidly 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 middle Paleocene to early Eocene, rift tectonics began to have less control on sedimentation, and thickness variation from trough to platform was less pronounced. From early Eocene to 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 the six basin center sectors under study, are extensive and very well established. The multiple systems in the Sirt Basin comprise a wide range of Cretaceous and Paleogene reservoir sequences, which were charged by 3 or 4 Cretaceous source rocks, either singularly or in combination. The Ghadamis Basin petroleum systems involve Ordovician, Silurian, Devonian and Triassic reservoirs charged by Lower Silurian and/or Middle-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 subject under-explored sectors of the Ajdabiya Trough, Maradah Graben and Zallah – Tumayam Trough have a number of important features in common: nearby oil production; only 4 or 5 exploration wells which reached pre-Upper Cretaceous horizons; a world-class source rock, Upper Cretaceous Sirt-Rachmat shale; and large areal extent. The above-mentioned Ajdabiya, Maradah and Zallah-Tumayam areas cover 8,500 sq.km., 10,000 sq.km. and 25,000 sq. km., respectively (figure 3 and 4).

SOURCE ROCK SUMMARY:

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 subject troughs. The total organic carbon (TOC) of this sequence ranges from 0.5 to 8 percent, averaging 1.5 to 4 percent (figure 5) (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's ranging from 0.6 to 6.5 percent in the Hameimat Trough (Alami, 1996). 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; and therefore, they should be considered an effective source in those sectors (figure 6). 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. and the average TOC is approximately 3 percent. It most likely is a minor source in the southern part of the Ajdabiya trough. In the Maradah Graben, based only on 2 wells (El-Hawat, 1996), the Nubian middle variegated shale member attains thicknesses ranging from 200 ft. to 400 ft. This shale sequence was deposited in a partially anoxic, marginally marine environment. It may have contributed some hydrocarbon to the surrounding areas.

The contribution of variable quantities of oil from as many as four different source units, shale or shale and carbonate, at different times of expulsion (during periods from early Oligocene to early Pliocene) has yielded, from place to place, several distinctly different crude oils. One similar characteristic of these oils is the gravity, which ranges from 36 to 40 degrees API. More rock–oil correlation analyses and related studies are needed for more accurate determinations of regional rock-oil-timing associations.

PETROLEUM PLAYS – 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, 1996; Mansour and Magairhy, 1996). Net sand thicknesses are estimated to range from 0, at discrete onlap and truncation limits, to 1200 ft. (figure 7). Depth to the top Nubian varies from 12,000 ft. to 18,000 ft. (figure 8). In spite of these depths, it is expected that average porosities will be 12 to 13 percent, with a maximum porosity exceeding 20 percent. The average porosity, at depths below 15,000 ft., ranges from 12 to 13.5 percent in a number of wells in the nearby Hameimat Trough.

Secondary reservoir objectives are high risk in the area because of limited distribution and poor development. The Bahi (Maragh) sandstone equivalent is absent or very thin in the surrounding areas, with a dominant siltstone and shale lithology, suggestive of the Etel formation. The Lidam dolomite, which is basically 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 in the areas west of the Amal and Jalu highs.

Possible attractive secondary targets are the Paleocene lower and upper Sabil shoal and reef limestones (Spring and Hansen, 1998). The 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 9). 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 accurately imaged 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 would lack a seal. 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 late Eocene to late Pliocene from source beds of the Etel, Rachmat and Sirt formations (Roohi, 1996; Ghori and Mohamed, 1996; Gumati and Schamel, 1988). This 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 rock, the Sirt shale and the Rachmat shale are stratigraphically separated from the Nubian, therefore secondary migration would be via faults or faults in combination with the Sirt unconformity.

Migration from Etel source beds would be accomplished basically by lateral drainage via the Sirt unconformity to underlying Nubian sands.

Oil by means of vertical migration from Sirt source beds reached the Sabil reservoirs via faults and fractures.

TRAPS:

Trap types for Nubian reservoirs are horsts, tilted fault blocks, updip unconformity truncations and updip terminations against basement or Cambro-Odovician quartzite (figure 10). Sabil traps are usually drape anticlines over buildups with lateral permeability barriers.

PETROLEUM PLAYS - 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 7). It is possible that the Nubian is absent on randomly formed Cambro-Ordovician highs, similar to the setting in the southeast Sirt basin, but there are no current data to support this hypothesis. Depth to the top Nubian will vary from 11,500 ft. to 15,000 ft. in the Maradah Graben (figure 8). It is expected that an average porosity will be 12 to 13 percent.

Nubian determinations and estimates in the Maradah Graben are based only on regional projection and partial data from 3 widely separated wells (El-Hawat et al, 1996; Bonnefous,1972). The wells are: D6-NC149, in the Wadi oilfield; P1-16, in the Bazuzi oilfield at the northeast edge of the Zahrah Platform; and V1-59, in the Bilhizan oilfield in the south part of the Bayda Platform.

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. The Zaltan Formation, consistent with the equivalent upper Sabil carbonate to the east, was not controlled by earlier faulting and developed along a shelf edge, which 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. The depth to the top Zaltan is between 7500 to 9000 ft. and because of this shallow depth, it has been subjected to considerably more expl;oration than the Nubian. The basal Upper Cretaceous Bahi sandstone may attain thicknesses exceeding 600 feet in the graben. However, in places, part or all of the so-called Bahi sandstone may be Lower Cretaceous Nubian.

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 of overlying Bahi sandstone or Lidam dolomite. 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 Early Oligocene to Late Miocene for the Etel, Rachmat and Sirt formation source rocks (Roohi, 1996). 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 Sirt shale and the Rachmat shale to the underlying Nubian, Bahi and Lidam reservoirs required an indirect carrier system via faults or faults in combination with the Sirt unconformity. Migration from Etel source beds to the above potential 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. Also, combination traps may be present, involving Nubian sandstone truncated at the Sirt unconformity or updip onlap of Nubian sandstone on the Cambro-Ordovician surface.

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

PETROLEUM PLAYS - 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 sandstone formations; therefore, the following thickness estimates are subject to a degree of change. Nubian net sand thickness is estimated to range from 0, at onlap and truncation limits, to roughly 1000 ft. The Bahi sandstone is expected to be from 0 to 300 ft. thick. Depth to the top Nubian and Bahi ranges from 9,500 ft. to 14,000 ft. It is expected that average porosity will be 12 to 14 percent 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 (Besan et al, 1996; Johnson and Nicoud, 1996; Sinha and Mriheel, 1996). Porosity in the lower and upper Beda members (Farrud sequence) ranges up to 35 percent. The thickness of the Beda formation exceeds 1000 ft. with up to

600 ft. of net porous carbonate (figure 11). Approximately 25 wildcat wells have reached these formations in the area, at depths of less than 9000 ft. However, the well density of one well per 1000 sq. km. indicates the area is still under-explored, even at shallow levels.

The Defa carbonate and the Facha dolomite attain a net thickness of up to 400 ft. in the area.

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 pinchout limits to more than 1000 net feet (figure 12).

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 prevent 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 9,000 ft. and 11,000 ft., the main stage of oil expulsion apparently occurred throughout Miocene time. There is little doubt that the Sirt shale is the only important effective source rock in the area.

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 pinchouts. Northerly oriented pinchouts of the Turonian-Senonian sands, 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.

PETROLEUM PLAYS - CENTRAL GHADAMIS BASIN

GENERAL:

The Ghadamis Basin area of study, which covers more than 20,000 sq.km., is located in the center of the basin bordering Tunisia and Algeria (figures 13 and 14a). The basin is continuous across southern Tunisia and central Algeria, covering an area of approximately 200,000 sq.km. It is particularly noteworthy that during the last 10 years, an estimated 5 to 6 billion barrel of recoverable oil equivalent has been discovered, mainly from Devonian and Triassic sandstone reservoirs in the Algerian sector of the Ghadamis basin. The keys to these discoveries were an understanding of the plays and 3-D seismic. During this same period there has been minimal success in the Libyan sector, although the geologic setting and reservoirs are essentially the same.

In the study area 27 wildcats yielded 1 oil and 3 gas-condensate discoveries with Upper Silurian Acacus sandstone pay, in the north, and 2 oil discoveries, with Triassic and Upper Devonian Tahara sandstone pay, in the central sector.

RESERVOIRS:

The main reservoir targets for the area should be considered both the Acacus and the Lower Devonian Tadrart and Kasa formations (figure 15) (Said, 1974; Masera Corp., 1992; Echikh, 1998). The Acacus net sand thickness ranges from approximately 500 ft. to 1300 ft. (figure 16). The Acacus average porosity is at least 16 percent. The Tadrart and Kasa formations should have a net sand thickness range of 300 ft. to 700 ft. and an average porosity of 14 to 15 percent in the study area. These formations, which are a more or less continuous stratigraphic sequence, are at depths between 8,000 ft. and 12,500 ft. (figure 17). Also, only 8 exploration wells reached these objectives in the study area, most of which were in the north.

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 variation from 0 to 300 ft.; the Upper Devonian Tahara formation with a net sand range from 50 ft. to 200 ft.; and the Triassic Ras Hamia formation with a net sand thickness of 200 ft. to 700 ft. All of these sands have very good porosity, averaging from 14 to 18 percent.

SEALS:

Generally, there is an effective Acacus shale seal above the sand, however, where it is absent, the overlying Tadrart will form a combined objective with the Acacus sand. 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 sand; however, because of a dominant continental clastic facies above the Ras Hamia in the south part of the area, a seal may be lacking.

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 total organic carbon (TOC) between 3 and 5 percent and are approximately 1000 ft. to 2000 ft. thick in this prime study area.

The Peak Oil Generation-Expulsion window (equivalent to vitrinite reflectance (Ro) of 0.8 to 1.3 percent) for both formations is approximately 8,500 ft. to 12,000 ft. The depths to the base of the Tanezzuft and Uennin in the area, are 12,000 ft. to 14,500 ft. and 8000 ft. to 12,000 ft., respectively.

The main stage of oil expulsion from the Tanezzuft source probably occurred from 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, while 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 the Hercynian events, although some early development most likely occurred during the Caledonian orogeny. It is unlikely that the Albian Austrian event or the Eocene Pyrennian 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 relief or faulted structures, unconformity truncation of the Tahara sand in the northern part of the study area and pinchouts of the Uennin F3 equivalent sand.

PETROLEUM PLAYS - CENTRAL MURZUQ BASIN

GENERAL:

This under-explored basin center area covers more than 30,000 sq.km. Only 4 wells have been drilled here; and one well, A1-NC58 , is a marginal oil discovery. Within about 50 km. to the north, there are 7 small, undeveloped oilfield discoveries, with total reserves of about 150 million barrels, and one major discovery, Elephant (N1-NC174), with estimated reserves of 500 million barrels of oil (figure 14b). The Murzuq oil field complex (A, B, C, H and J - NC115 fields) with reserves of roughly one billion barrels of oil, is located approximately 100 km. north of the subject area. In all of these discoveries, the Ordovician Memouniat Formation, a sandstone, is the reservoir (figure 13).

RESERVOIRS:

The main reservoirs for the area should include both the Acacus and the Lower Devonian Tadrart-Kasa sandstones, as well as the main pay in the basin, the Memouniat. The net sand thickness of the Memouniat formation ranges from approximately 500 ft. to 2500 ft. and has an average porosity of 10 to 14 percent. The Acacus net sand thickness is between 0 feet, at the north edge of the study area where it is truncated, and 300 ft. The average porosity of the Acacus sandstone is approximately 15 percent. The Tadrart-Kasa sandstones, undifferentiated, should have a net thickness of up to 200 ft. and an average porosity similar to the Acacus. This sequence pinches out at the Caledonian surface in the northern part of the area.

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

SEALS:

The Tanezzuft shale provides a reliable seal throughout the area for the Memouniat formation. Generally, there are effective shale seals interbedded with Acacus sandstone beds. In a few places, upper Acacus sands are overlain by Tadrart-Kasa sands, which would create a combined reservoir, as in the Ghadamis basin. Uennin shale beds provide adequate seals for theTadrart-Kasa sequence.

SOURCE ROCK, TIMING AND MIGRATION:

The Tanezzuft shale is the only effective oil source of importance in the Murzuq Basin (Hamyouni, 1988). 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.). The Tanezzuft shale is 400 ft. to 1600 ft. thick in the study area. The average TOC is 1.8 percent. The Peak oil-Expulsion window is approximately 6,500 ft. to 9,000 ft. Therefore, because the depth to the base Tanezzuft is between 7,000 ft. and 11,500 ft. in the subject area, the Tanezzuft is in peak oil to wet gas generation stages.

Vertical, updip and fault pathways provided easy, short distance access for migration of oil to the adjacent reservoirs. Migration apparently took place from Early Jurassic to 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 pinchout of the Tadrart-Kasa, in association with dip or fault closure are also potential traps in the area.

PETROLEUM PLAYS - EASTERN TRIPOLITANIA BASIN

GENERAL:

The offshore Tripolitania basin (Gabes-Sabratha 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 sq.km., is essentially unexplored. To date, one dry hole has been drilled here. The concentration of the oil and gas-condensate discoveries in the basin are more than 100km. west of this vast potential area. In general, the 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, there are numerous potential reservoir suites in this basin sector (figure 18). The Lower Eocene Metlaoui Group, El Garia Formation (Jdeir Formation) the main pay in all of the Tripolitania basin discoveries to date, 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 up to 600 ft. in the subject area. The effective porosity range is roughly 5 percent to 30 percent with an average of 17 percent in the western part of the basin. These facies pinchout toward the 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 5,000 ft., in the southwest, to 11,000 ft., in the basin center (Bailey et al., 1989; Sbeta, 1990; El-Ghoul; Bernasconi et al.; Loucks, et al., 1998) (figure 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 Zebbag 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 between 7500 ft. and 15,000 ft. (figure 21).

Also, there are possibilities of beds with reservoir quality of Lower Cretaceous age. The shallow-marine carbonates and marginally marine sandstones of the Meloussi and Boudinar formations, and rudist carbonates of the Serdj Formation (probable equivalents of theTurghat- Kiklah sequence), are potential targets. However, distribution and thickness are matters of speculation. Depths to Lower Cretaceous strata are in the range of 8000 ft. to 16,000 ft.

SEALS:

Shale and argillaceous limestone (mudstone – wackestone) beds provide effective seals for the above 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 range of 1 to 10 percent (Caron, 1999). The Bahloul formation is expected to have an average thickness of 100 feet in the study area. The organic-rich shale beds of the Sidi Kralif-Fahdene sequence, which have a TOC range of .5 to 10 percent in offshore Tunisia, may be as effective as the Bahloul. The distribution and thickness of this sequence in the area of study is relatively unknown. However, on the basis of projection from a few wells to the west, up to approximately 400 feet can be expected in parts of the study area (figure 21).

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

The Lower Eocene Chouabine limestone is considered 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 Tanezzuft shale probably occurred during Paleogene time, and for the Sidi Kralif-Fahdene and Bahloul formations, peak oil probably occurred from Oligocene to Miocene time in the central part of the eastern Tripolitania Basin.

In this 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 there were phases of recurrent faulting throughout the Tertiary, the thick Miocene to Recent 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: 1) faulted anticlines and other upside fault traps; 2) drape anticlines over carbonate buildups or faulted relief; and 3) updip lithology or permeability pinchouts.

CONCLUSIONS

(1) The 6 under-explored basin or trough centers, which are the subject of this paper, have exceptional potential for major undiscovered petroleum resources.

(2) In each of the 6 subject study 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.

(3) In the Sirt Basin study areas, the Upper Jurassic-Lower Cretaceous Nubian sandstone members should be considered primary objectives. This thick sandstone series, which, for most part, is at depths exceeding 12.000 ft., has been, surprisingly the subject of minimal exploration to date.

(4) In the Ghadamis and Murzuq basin areas of study, sandstone sequences of the Upper Silurian Acacus and Lower Devonian Tadrart-Kasa formations are definitely quality objectives. However, these potential reservoirs apparently have not been priority targets to date; in the Ghadamis study area, which covers 20,000 sq. km., only 8 exploration wells reached the Acacus.

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

(6) Most probably, reliable trap definition will be the critical factor in determining future exploration success in the under-explored depocenters. In general, at this stage of exploration in Libya, it is expected that the focus will be on subtle and complex trap types: low relief, faulted structures and drape anticlines, structural-stratigraphic combination traps involving facies pinchouts, onlap terminations and unconformity truncations. The fact that the presumed trap types of the basin center study areas are at great depths, further complicates interpretation. Therefore, it will be necessary to adopt an integrated, inter-disciplinary approach for reliable trap interpretation and prospect evaluation. In order to accomplish this, in addition to a comprehensive synthesis of the available geological data, state-of-the-art tools and methods will be required, including, 3D seismic, sequence stratigraphy concepts and basin modelling.

ACKNOWLEDGEMENT

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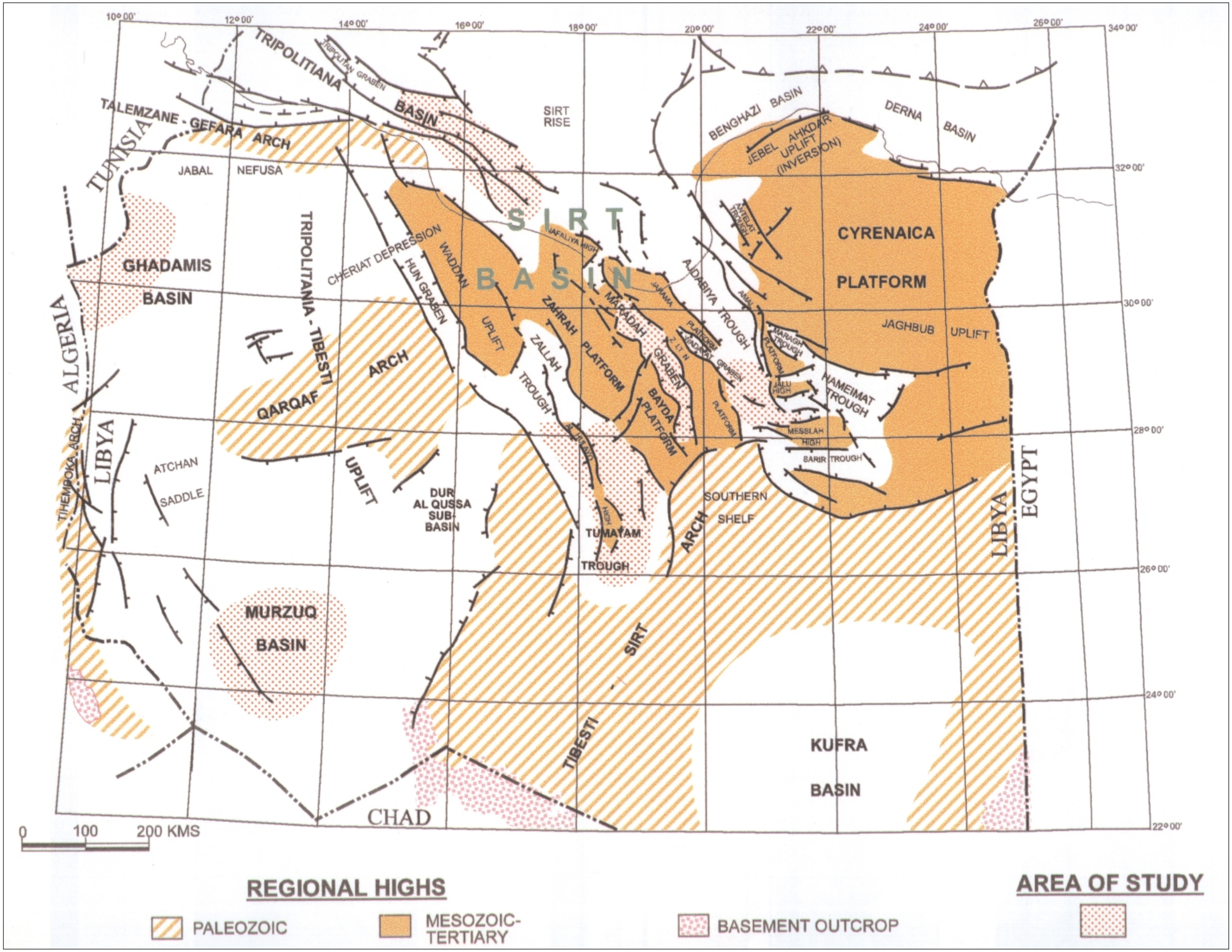
FIGURES

1. Generalized tectonic map of Libya, showing the major structural features. Also shown are 6 under-explored, central basin or trough areas, which are the subject areas of this study.
2. Structural elements of the Sirt Basin, showing the oil and gas fields, the areas of study and the 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 as follows: Ajdabiya Trough – 8,500 sq. km., Maradah Graben – 10,000 sq. km. and South Zallah Trough -Tumayam Trough – 25,000 sq. km.
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.
4. Net shale isopach map of the Sirt and Rachmat formations, Sirt Basin. Modified from Masera Corp. (1992)
5. Net shale isopach map of the Etel Formation, Sirt Basin.
6. Net sand isopach map of the Nubian Formation, Sirt Basin. Areas where the Nubian is absent, due to erosion or non-deposition, are indicated.
7. Structure map on the top Nubian Formation, Sirt Basin. Modified, in part, from Masera Corp. (1992); El-Hawat et al. (1996); Mansour & Mahairhy (1996).
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.
9. North- south structural cross section, extending from the central part of the Ajdabiya Trough to the Faregh oilfield area, depicting actual and inferred (?) Nubian sandstone trap configurations.
10. Isopach map of the Beda Formation, showing the distribution of barrier shoal carbonate facies of the Thalith, Lower Beda and Upper Beda members, south Zallah Trough – Tumayam Trough. After Sinha & Mriheel (1996); Bezan et al. (1996).
11. North-south diagrammatic correlation of the Cretaceous section of wells Y1-59, CC1-71 and D1-72, The well correlation illustrates the probable ralationship of the northward sandstone pinchouts interfingering with Sirt – Rachmat shale sourcebeds. Also shown is the interpreted Nubian sandstone correlation. Datum: top Cretaceous.
12. Location map of the Ghadamis and Murzuq basins, showing the basin center areas of study. The Ghadamis and Murzuq basin study areas cover approximately 20,000 sq.km. and 30,000 sq.km., respectively.
13. Structure map on the top Ordovician, Ghadamis and Murzuq basins, showing oil and gas fields and discoveries. Also shown are the locations of cross sections A-A' and B-B'. Adapted from Masera Corp. (1992).
14. North-south structural cross section A – A', Ghadamis Basin area of study; and, north-south structural cross section B – B', Murzuq Basin area of study. Refer to figure 13 for cross section locations.
15. Generalized stratigraphic chart of the Ghadamis and Murzuq basins, showing source and potential reservoir intervals.
16. Isopach map of the Acacus Formation, Ghadamis and Murzuq basins.
17. Structure map on the top Acacus Formation, Ghadamis and Murzuq basins. Modified from Masera Corp. (1992).
18. A 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), Sbeta (1990, 1991), El-Ghoul (1991).
19. Structure map of the top Metlaoui Group, Tripolitania Basin, showing the distribution of the El Garia Formation (Jdeir) nummulitic facies.
20. A diagrammatic north-south and west-east structural cross section of the Tripolitania Basin area of study. Adapted, in part, from Belhaj (1996).
21. Structure map of the top Cretaceous, Tripolitania Basin, showing the approximate areas of present-day peak oil and wet gas to gas generation of the Fahdene and Bahloul source rocks.



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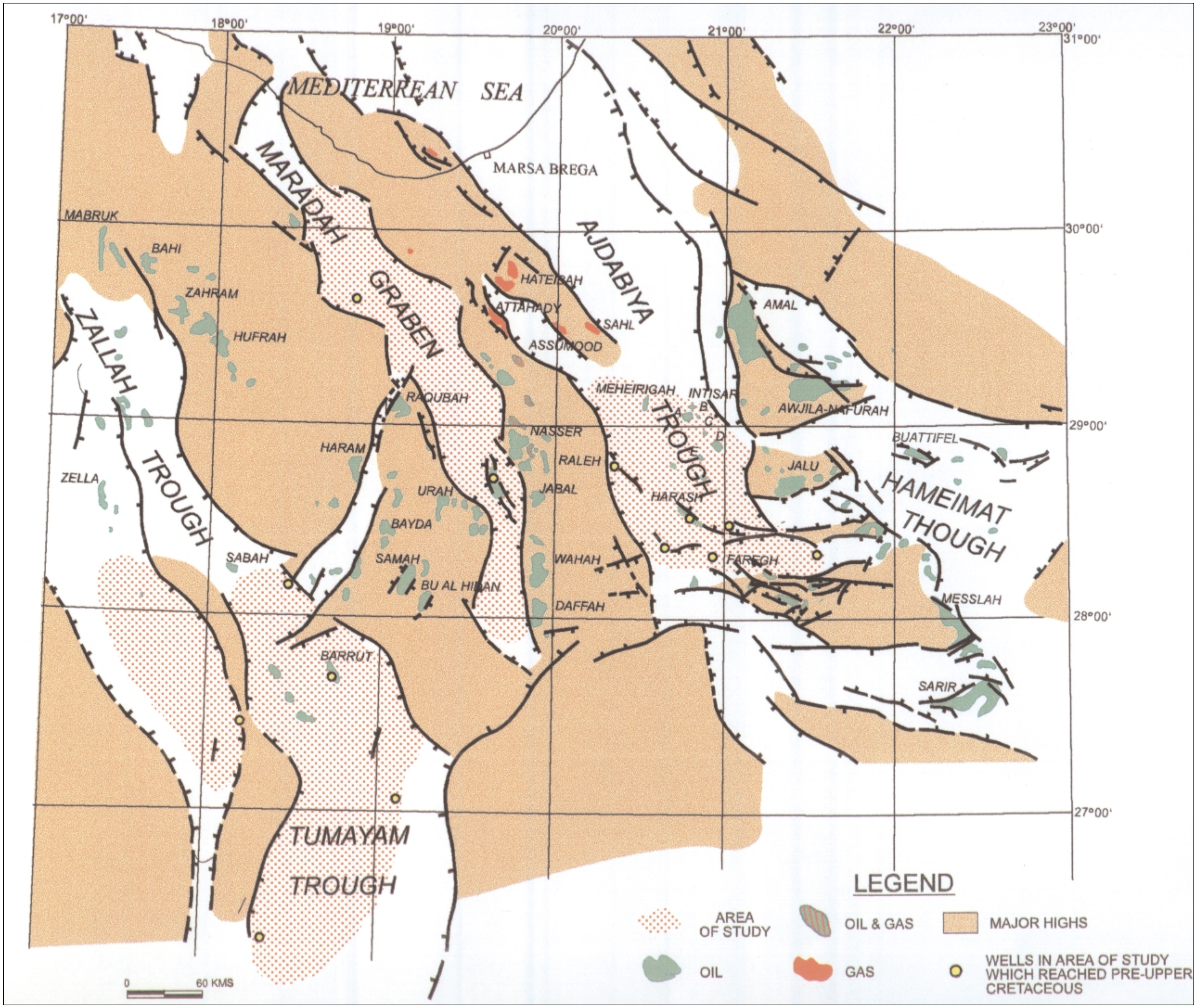

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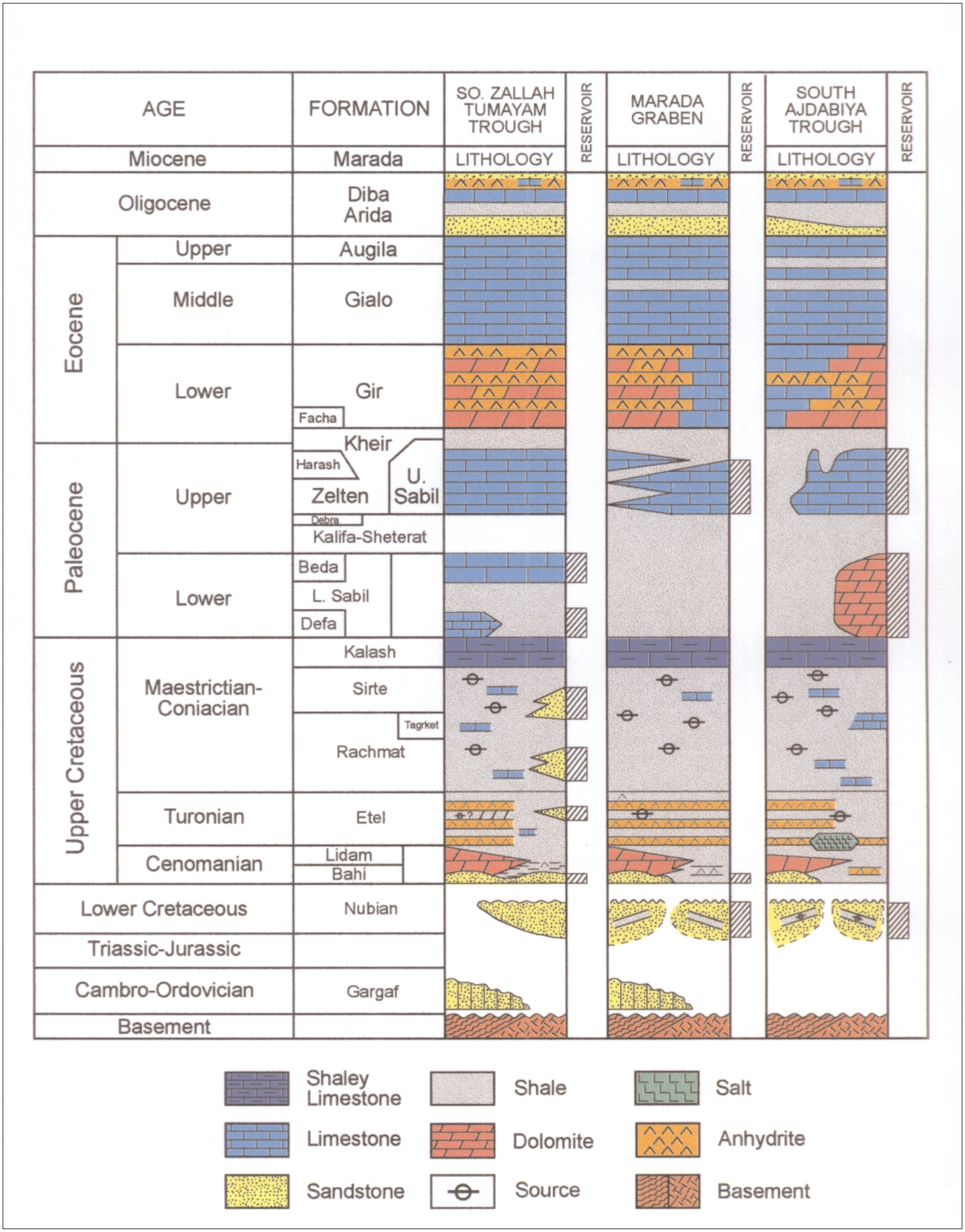

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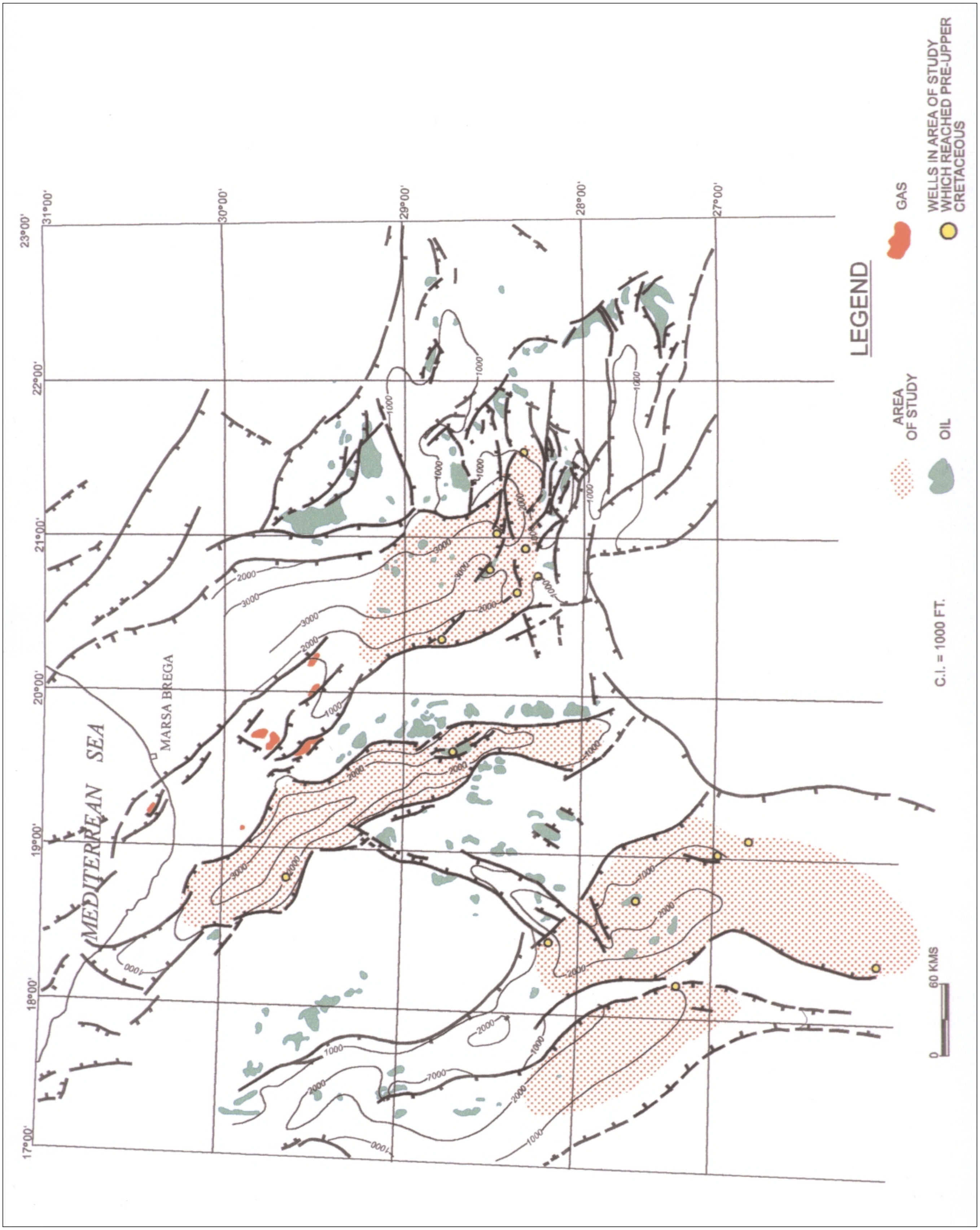


Figure 4. Net shale isopach map of the Sirt and Rachmat formations, Sirt Basin. Modified from Masera Corp. (1992).

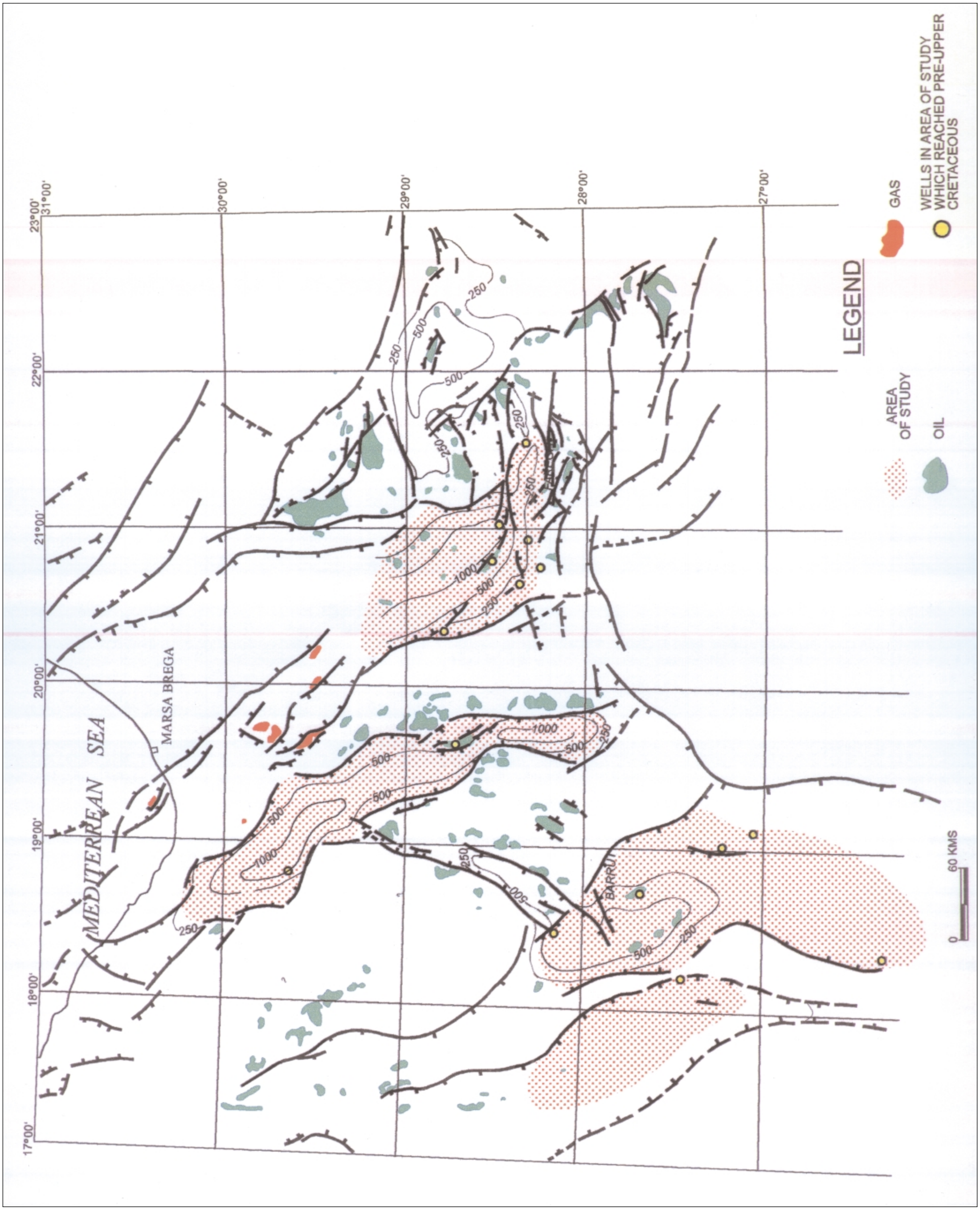
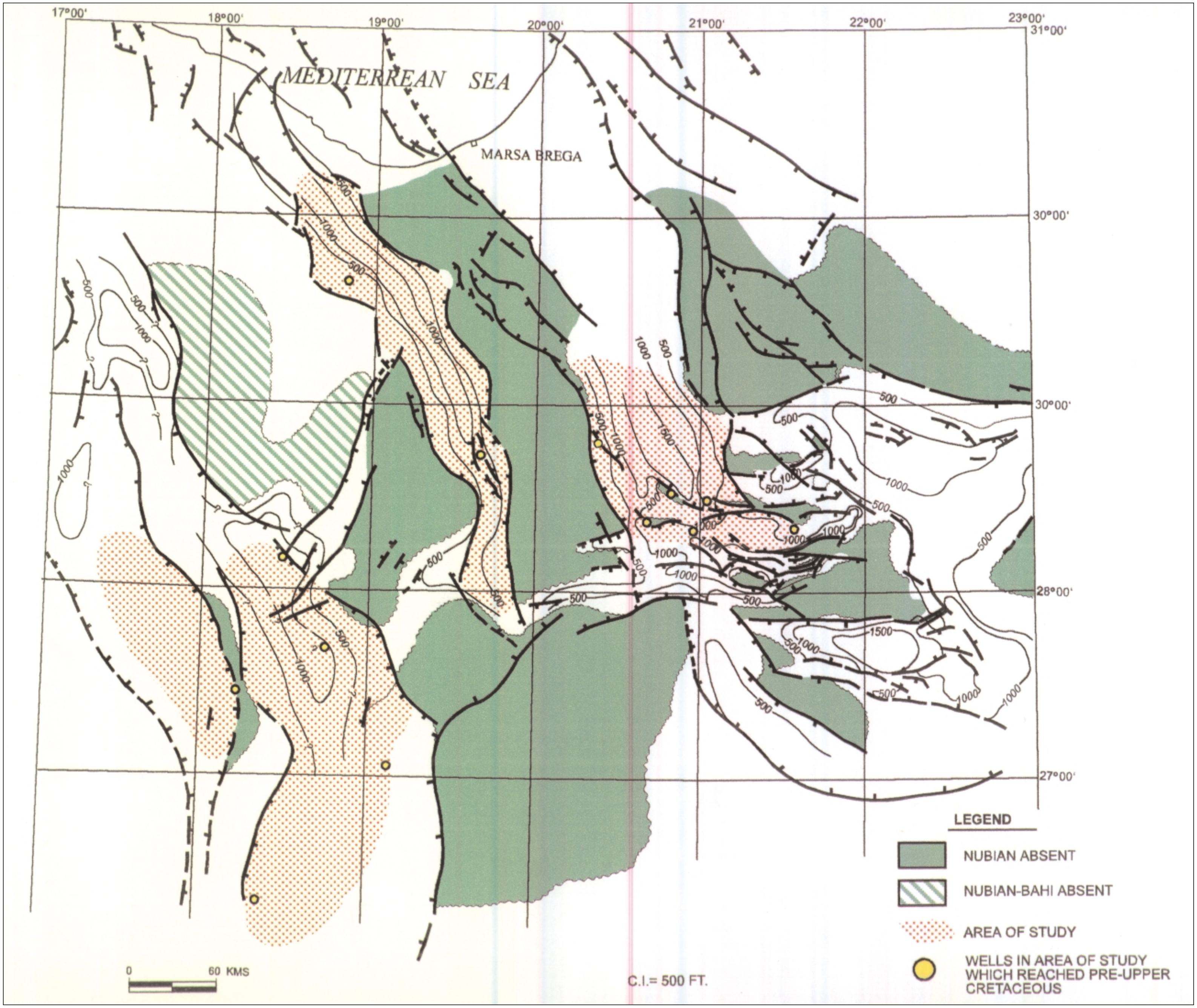


Figure 5. Net shale isopach map of the Etel Formation, Sirt Basin.



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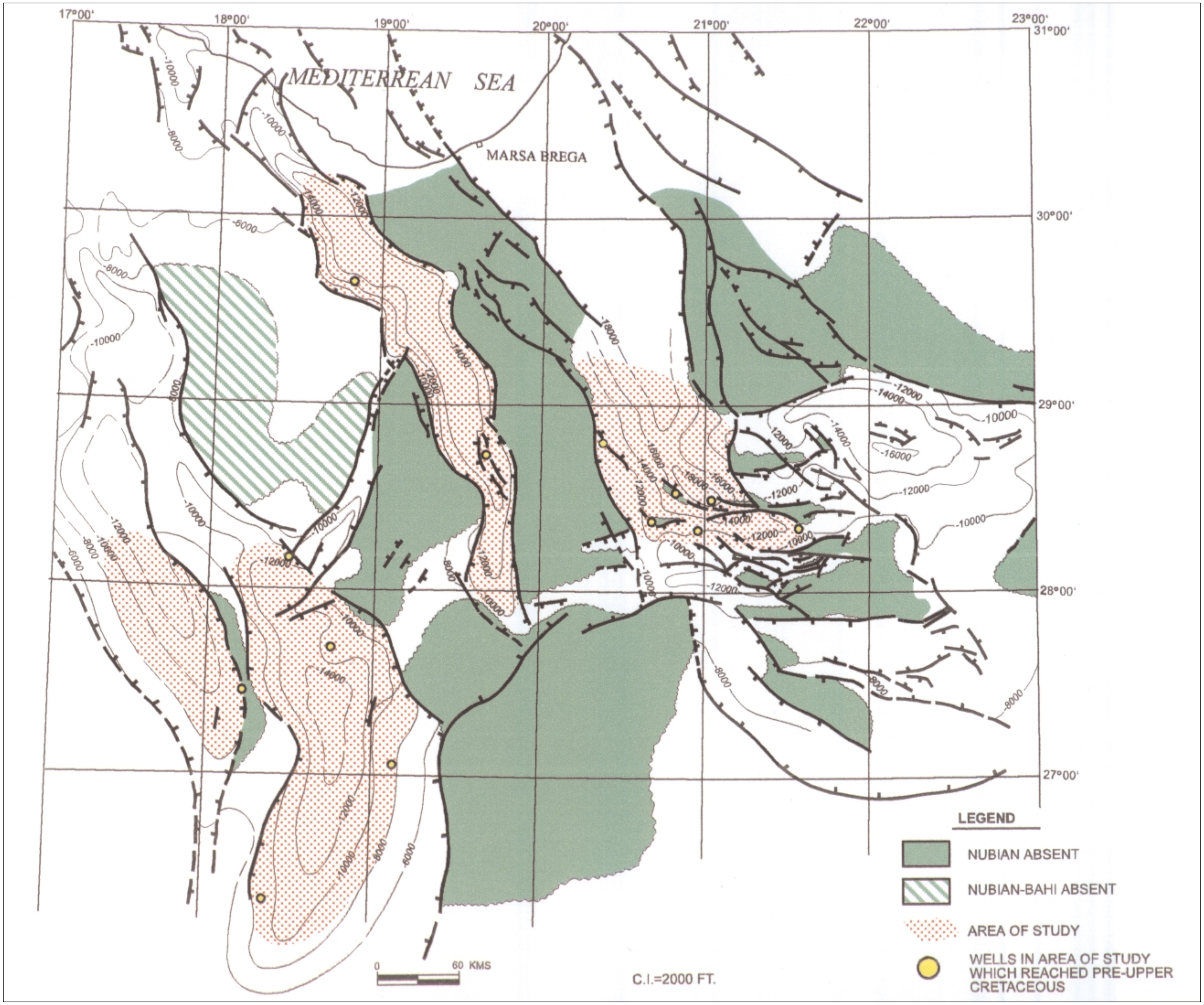


Figure 7. Structure map on the top Nubian Formation, Sirt Basin. Modified, in part, from Masera Corp. (1992); El-Hawat et al. (1996); Mansour & Mahairhy (1996).

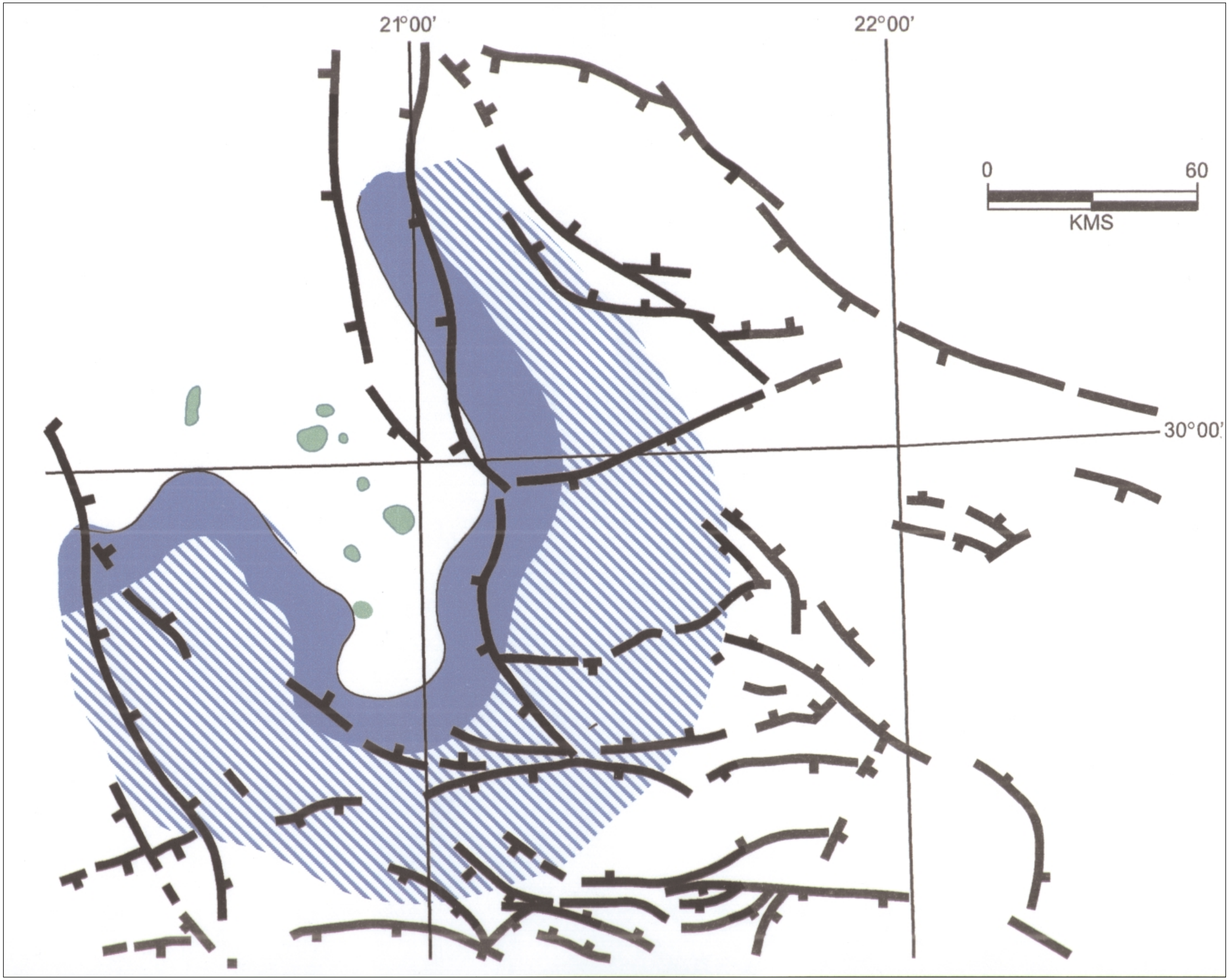


Figure 8. Approximate location of the Paleocene Upper Sabil carbonate shelf edge, Ajdabiya Trough: a zone of potential reef and shoal development. Shelf slope pinnacle reef oil fields are shown.

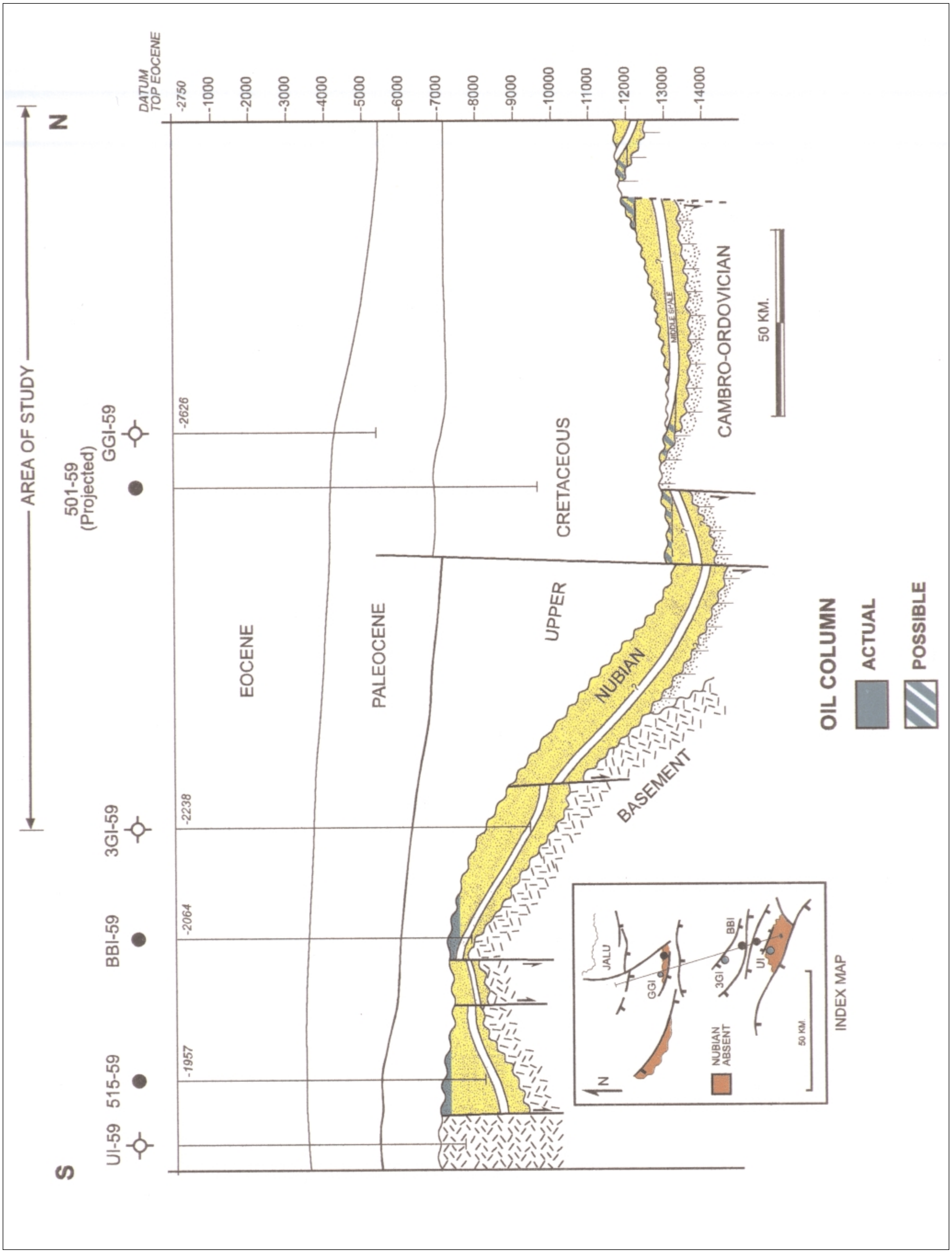
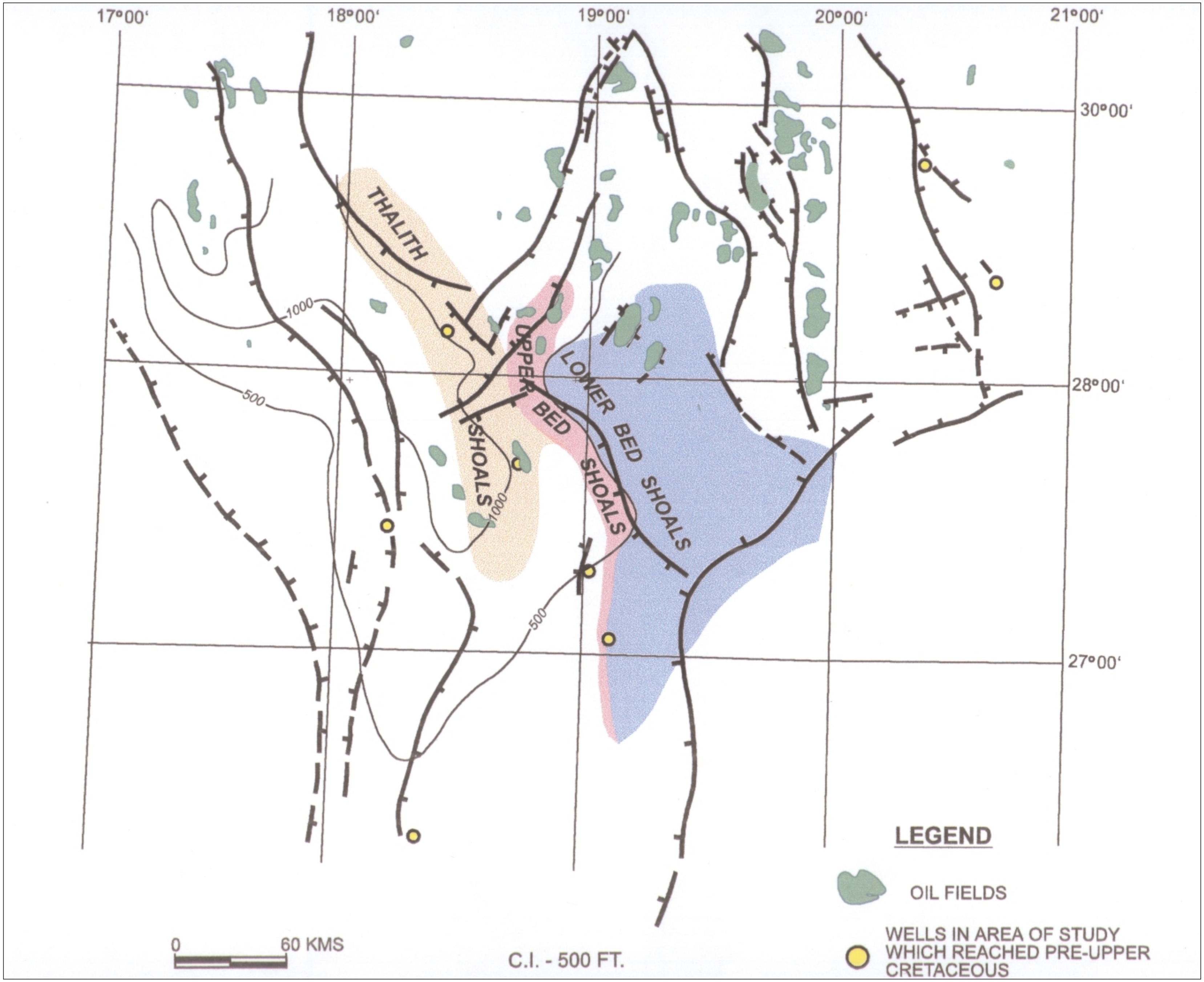


Figure 9. North- south structural cross section, extending from the central part of the Ajdabiya Trough to the Faregh oilfield area, depicting actual and inferred (?) Nubian sandstone trap configurations.



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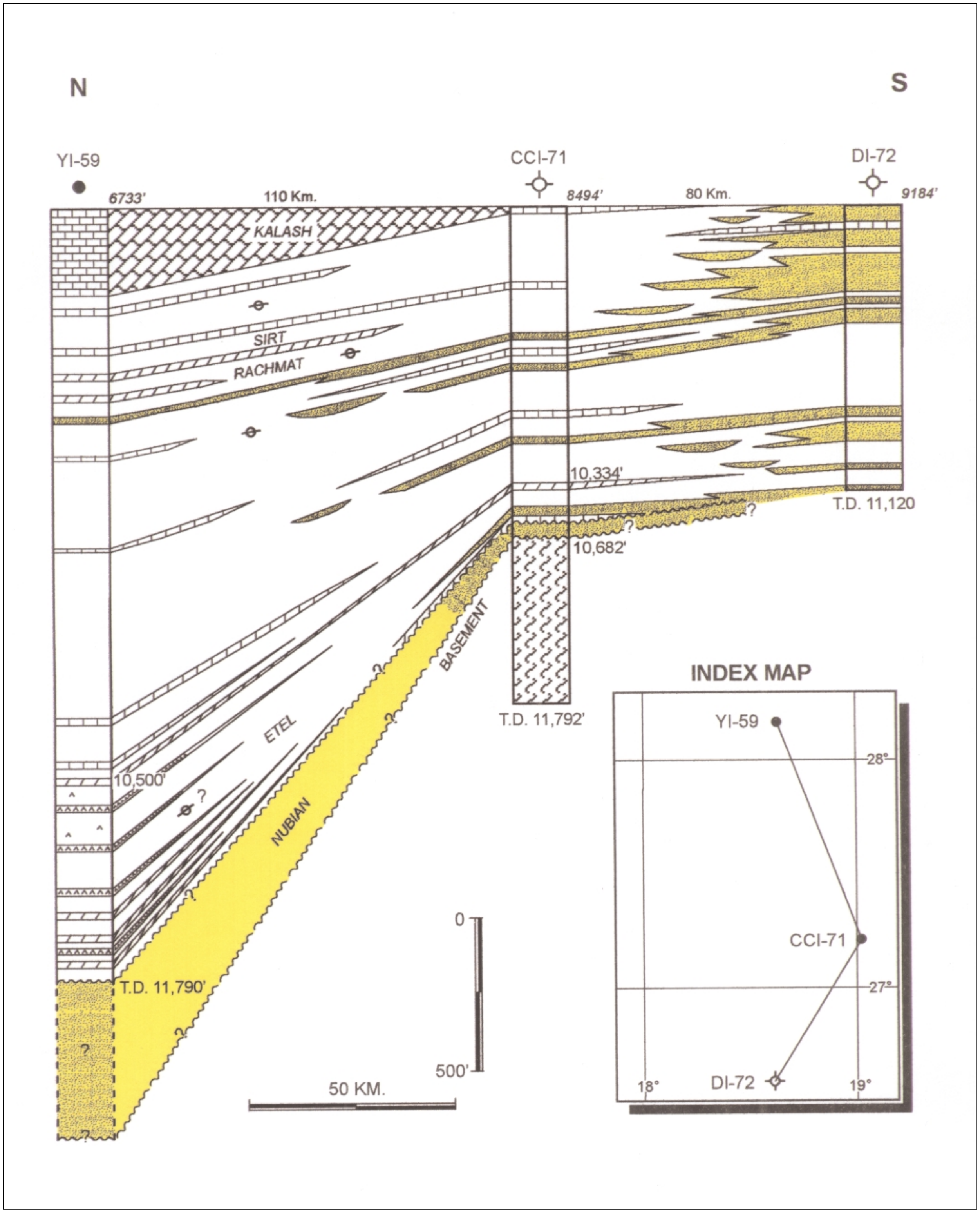
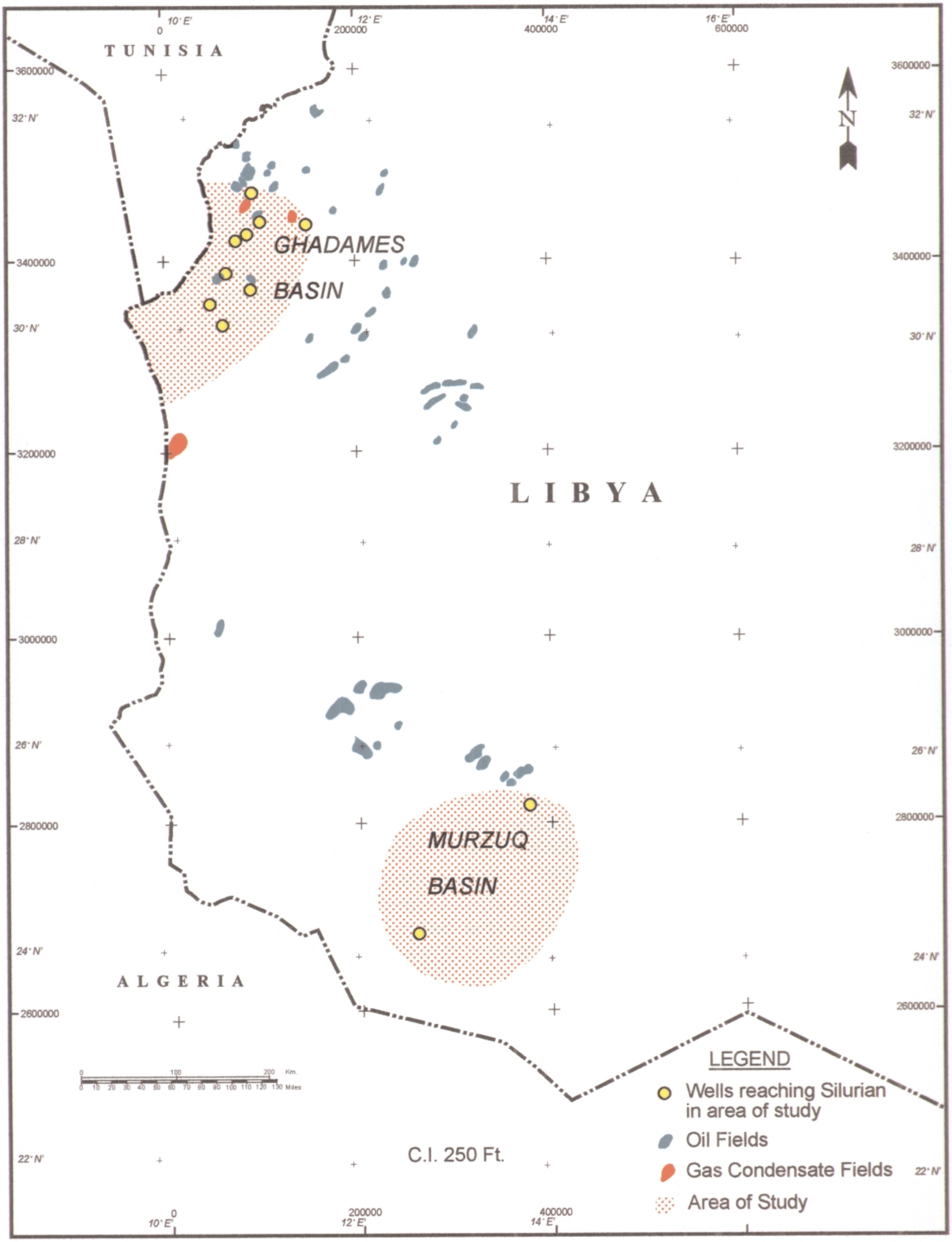


Figure 11. North-south diagrammatic correlation of the Cretaceous section of wells Y1-59, CC1-71 and D1-72, The well correlation illustrates the probable ralationship of the northward sandstone pinchouts interfingering with Sirt – Rachmat shale sourcebeds. Also shown is the interpreted Nubian sandstone correlation. Datum: top Cretaceous.



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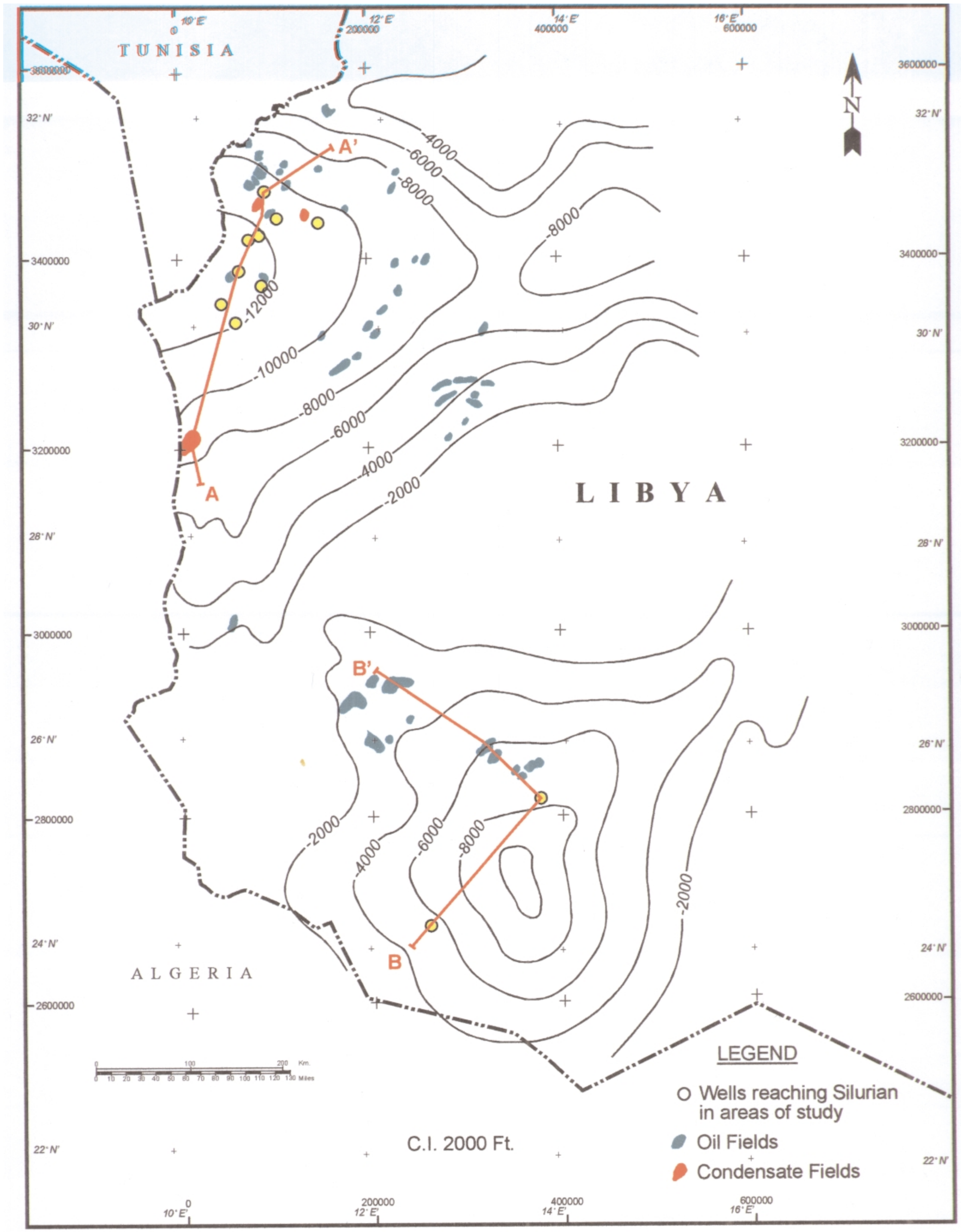

Figure 13. Structure map on the top Ordovician, Ghadamis and Murzuq basins, showing oil and gas fields and discoveries. Also shown are the locations of cross sections A-A' and B-B'. Adapted from Masera Corp. (1992).

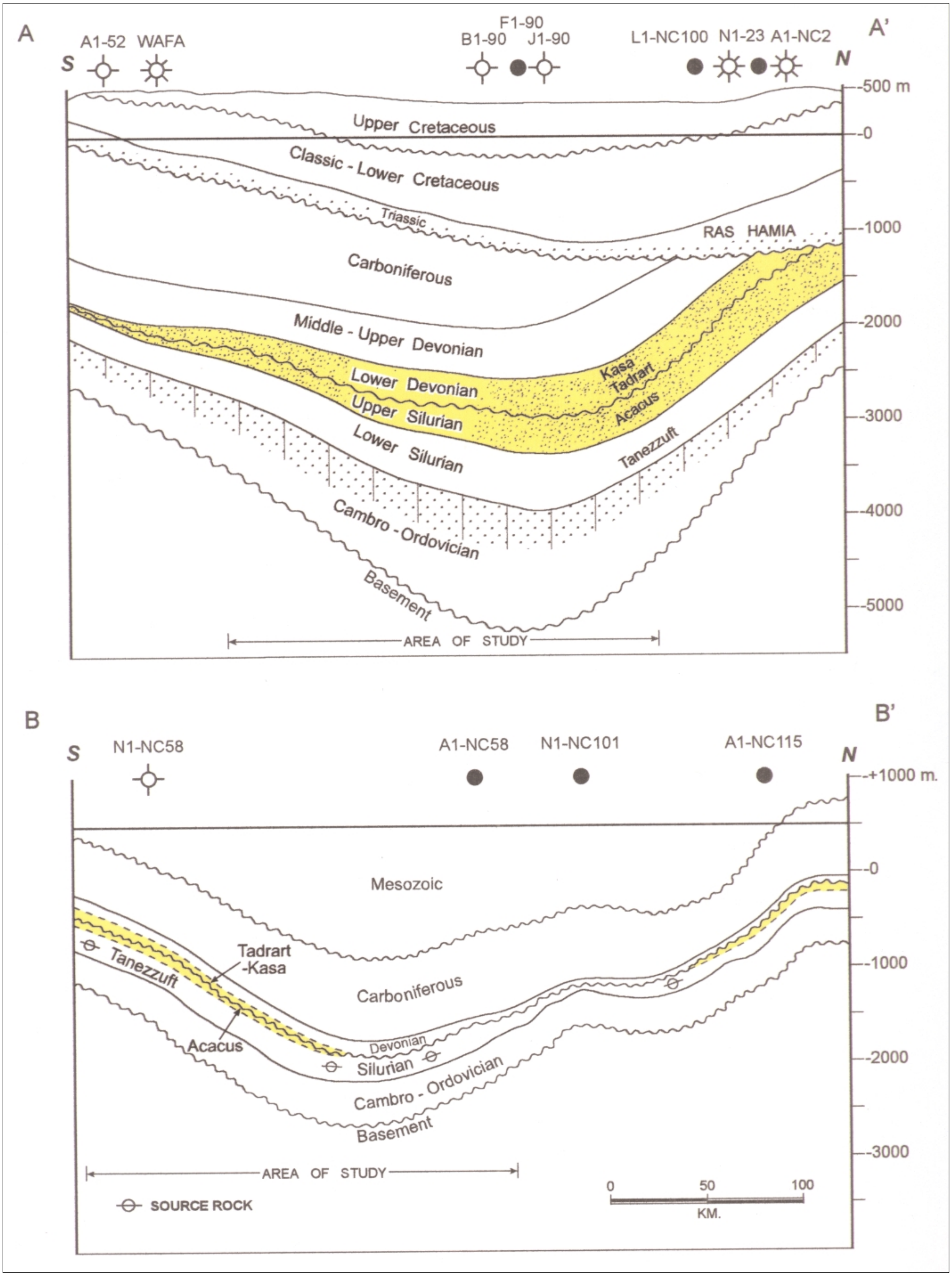

Figure 14. North-south structural cross section A – A', Ghadamis Basin area of study; and, north-south structural cross section B – B', Murzuq Basin area of study. Refer to figure 13 for cross section locations.

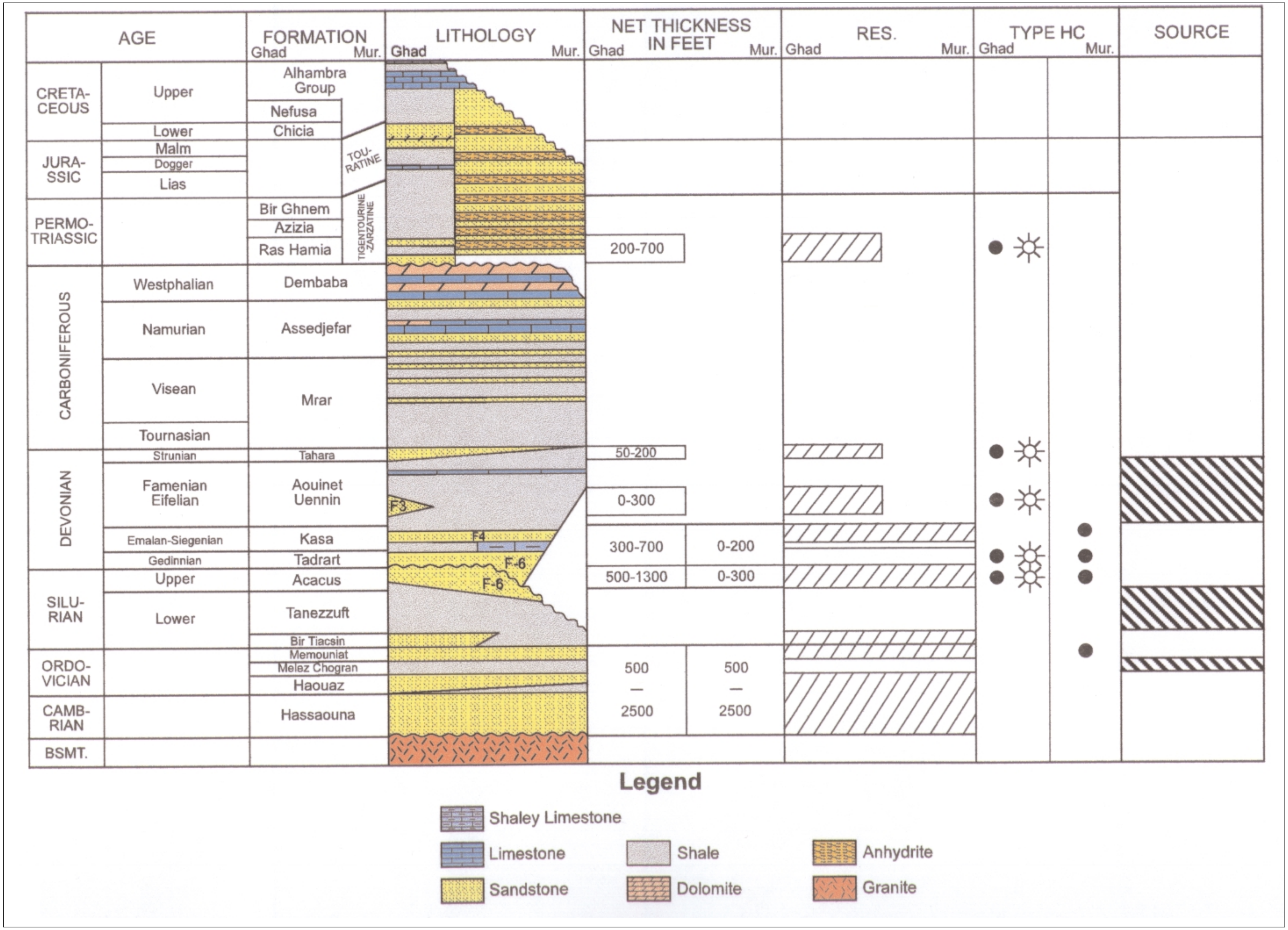

Figure 15. Generalized stratigraphic chart of the Ghadamis and Murzuq basins, showing source and potential reservoir intervals.

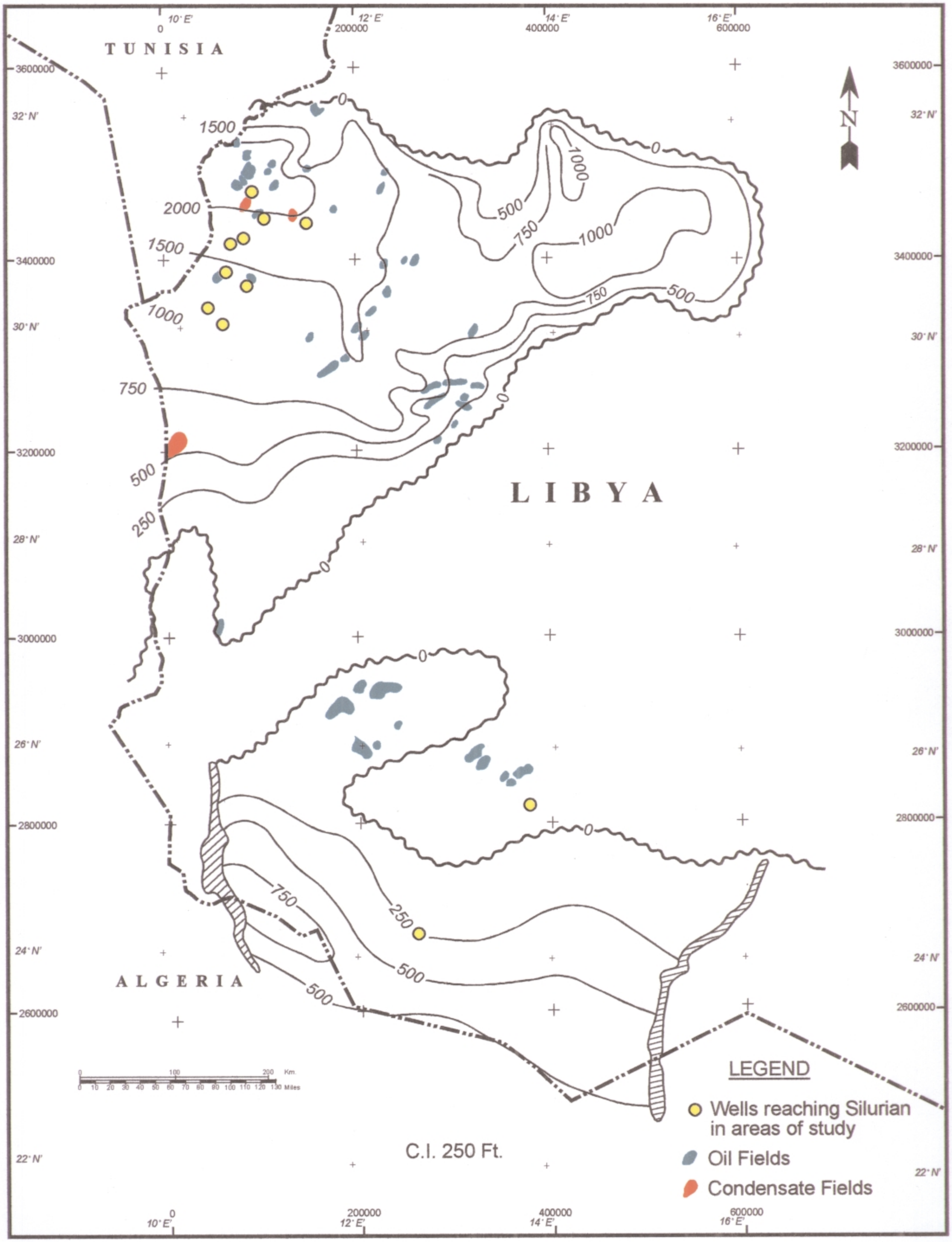

Figure 16. Isopach map of the Acacus Formation, Ghadamis and Murzuq basins.

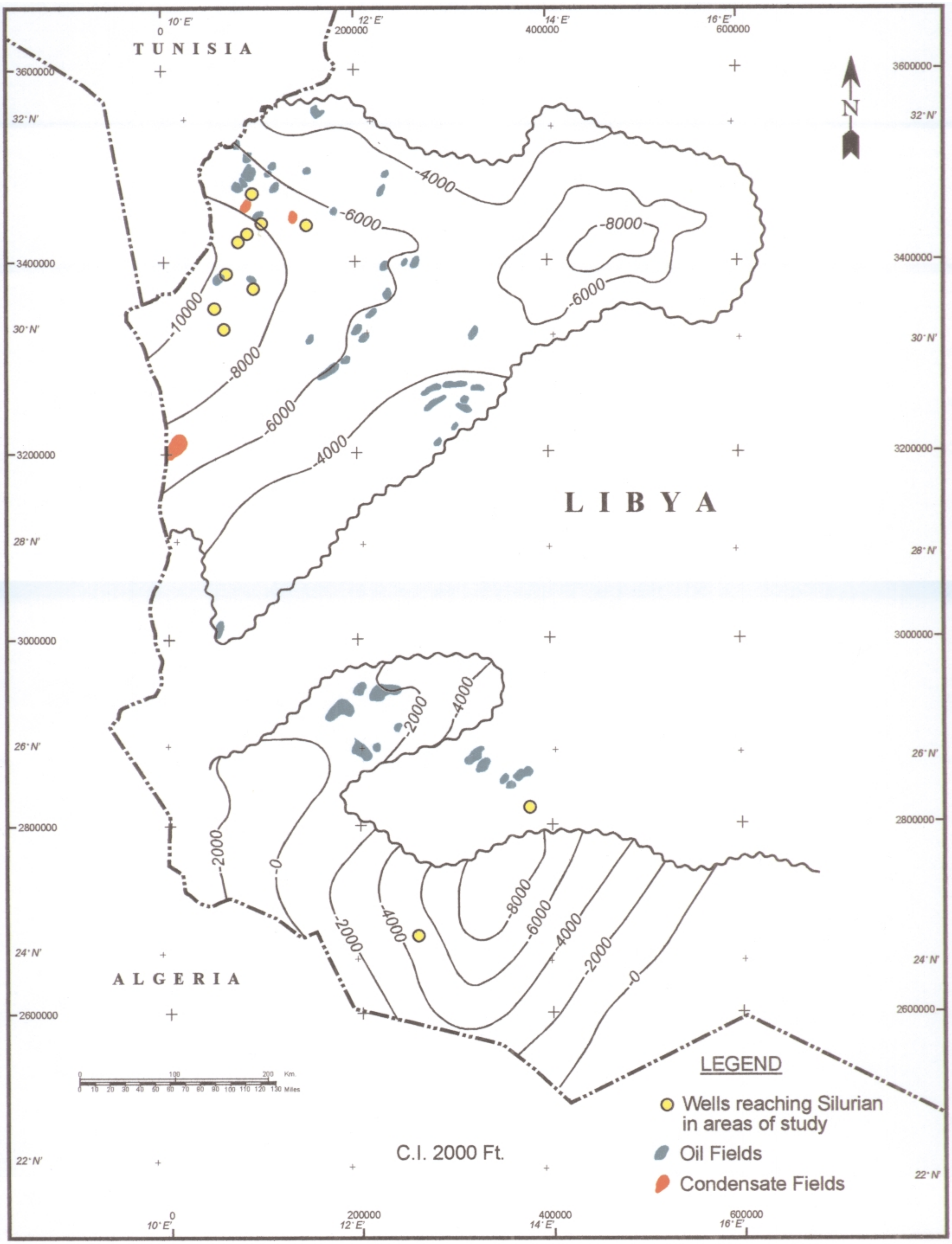

Figure 17. Structure map on the top Acacus Formation, Ghadamis and Murzuq basins. Modified from Masera Corp. (1992).

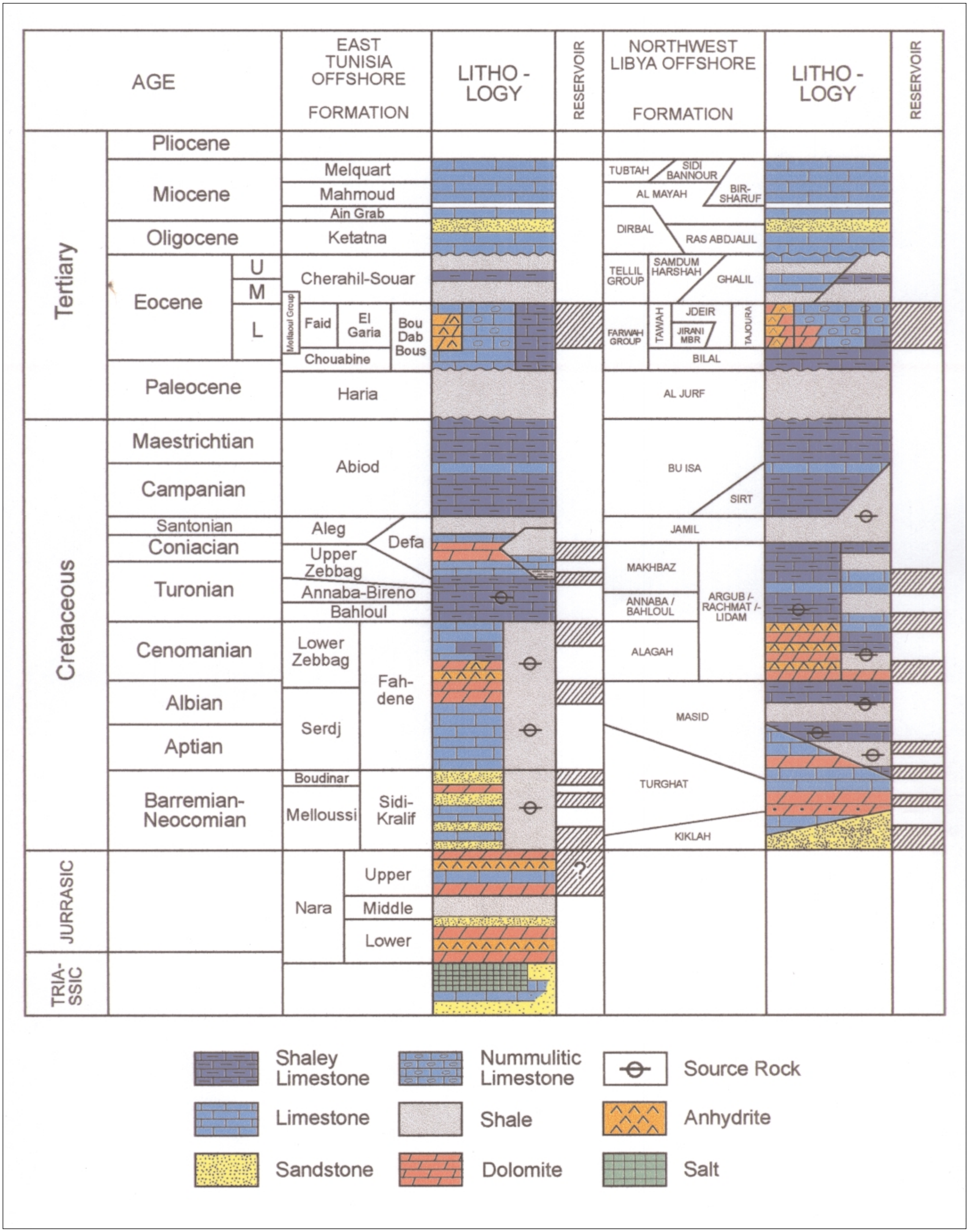

Figure 18. A stratigraphic correlation chart of formations and generalized lithologies of northwest offshore Libya and south offshore Tunisia. Also shown are the main reservoir and source units. Modified from Bishop (1988), Bernasconi et al. (1991), Sbeta (1990, 1991), El-Ghoul (1991).

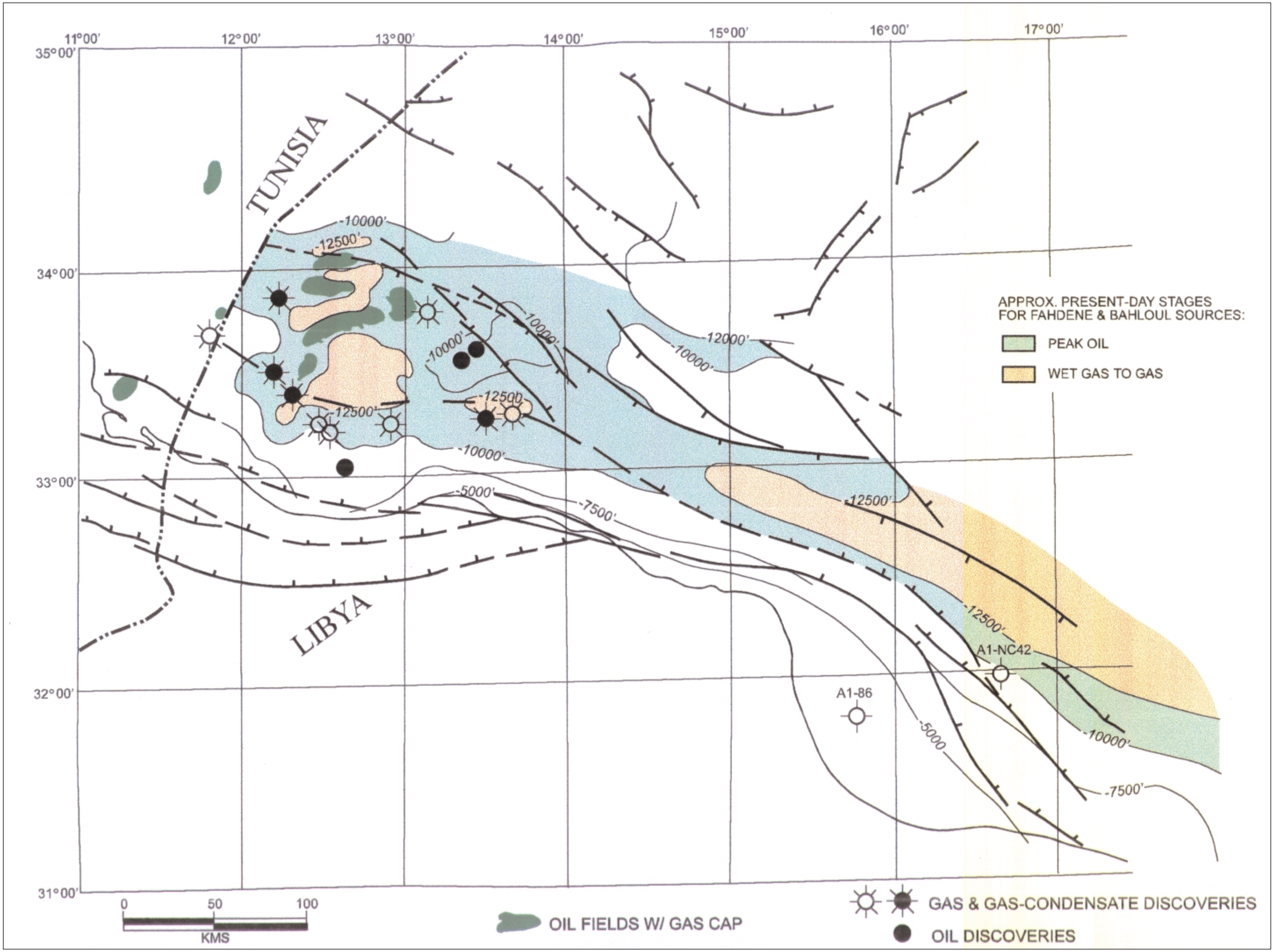

Figure 19. Structure map of the top Metlaoui Group, Tripolitania Basin, showing the distribution of the El Garia Formation (Jdeir) nummulitic facies.

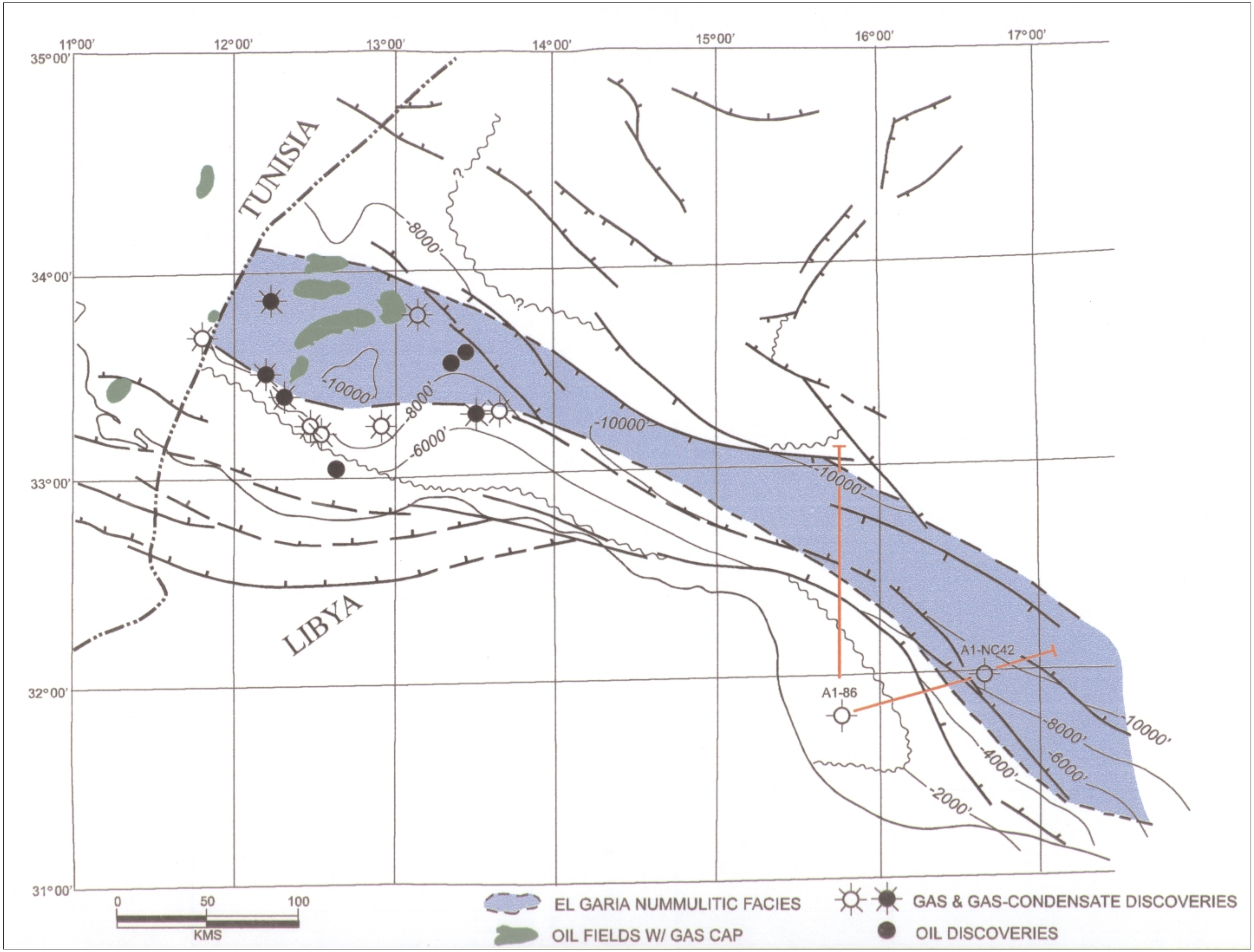

Figure 20. A diagrammatic north-south and west-east structural cross section of the Tripolitania Basin area of study. Adapted, in part, from Belhaj (1996).

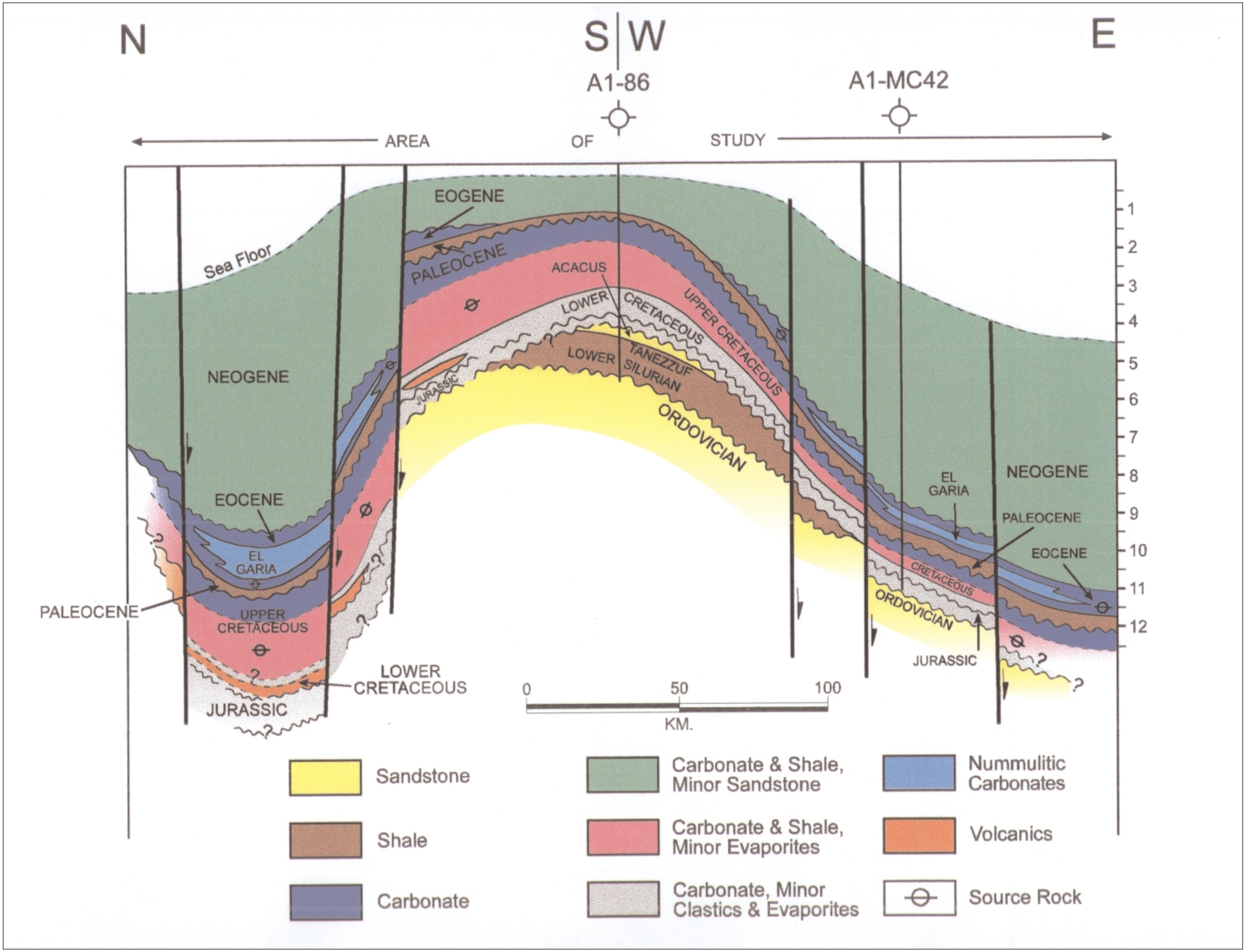

Figure 21. Structure map of the top Cretaceous, Tripolitania Basin, showing the approximate areas of present-day peak oil and wet gas to gas generation of the Fahdene and Bahloul source rocks.