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U.S. GEOLOGICAL SURVEY

REGIONAL GEOLOGY AND HYDROCARBON RESOURCE POTENTIAL, THE MEDITERRANEAN SEA REGION

by

James A. Peterson[1]

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[1]U.S. Geological Survey, Missoula, Montana

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INTRODUCTION

Information Sources

The information and data used in preparation of this report were compiled from many sources, listed in the References. Of particular value were the published books and articles by Stanley and Wezel, 1985; Berckhemer and Hsu, 1982; Biju-Duval and others, 1979; Burollet, 1984; Aubouin and others, 1986; Dercourt and others, 1986; Spencer, 1974; Nairn and others, 1977, 1978; Ager, 1980; Pieri and Mattavelli, 1986; Sonnenfeld, 1985; Neev and others, 1985; May, 1991; and Boriani and others, 1989. Also useful were articles from the Oil and Gas Journal and World Oil, and the annual World Energy Development reports of the Bulletin of the American Association of Petroleum Geologists. An extensive list of literature references is included in several of these published works. Some localities mentioned in the text are not shown on maps included with this report. The reader is referred to the National Geographic Atlas of the World, Fifth Edition, 1981, or other appropriate geographic maps, for location of specific place names.

Geography

The area covered by this report includes (fig. 1): 1) the offshore areas of North Africa beyond the 300 m (1,000 ft) water depth; 2) the entire offshore marine area in the remainder of the Mediterranean; and 3) the onshore areas of Italy, Sicily, Corsica, Sardinia, and the Balearic Islands. U.S. Geological Survey hydrocarbon resource assessments of the onshore petroleum basins of North Africa, and the shelf areas of less than 300 m (1,000 ft) water depth, are included in Peterson (1985, 1986). The latter reports also cover the offshore Pelagian Shelf of Tunisia and northwestern Libya, and the Nile Delta of Egypt. These areas are not included in this assessment.

The Mediterranean Sea covers an area of approximately 2,500,000 km^2 (1,000,000 mi^2) lying between about 30° and 45° North Latitude and 5°W to 35°E Longitude (figs. 1-4). Approximately one-half of the marine area exceeds water depths of 2,000 m (6,500 ft). Large parts of the deep water areas are underlain by oceanic crust. Climate of the region ranges from subtropical ("Mediterranean") with mild, rainy winters and hot, dry summers to semi-arid to arid subtropical climate in the southern and southeastern parts. These regional climatic patterns are greatly modified by topographic effects in the mountainous regions adjacent to the Mediterranean, particularly in the European and northwestern African borders.

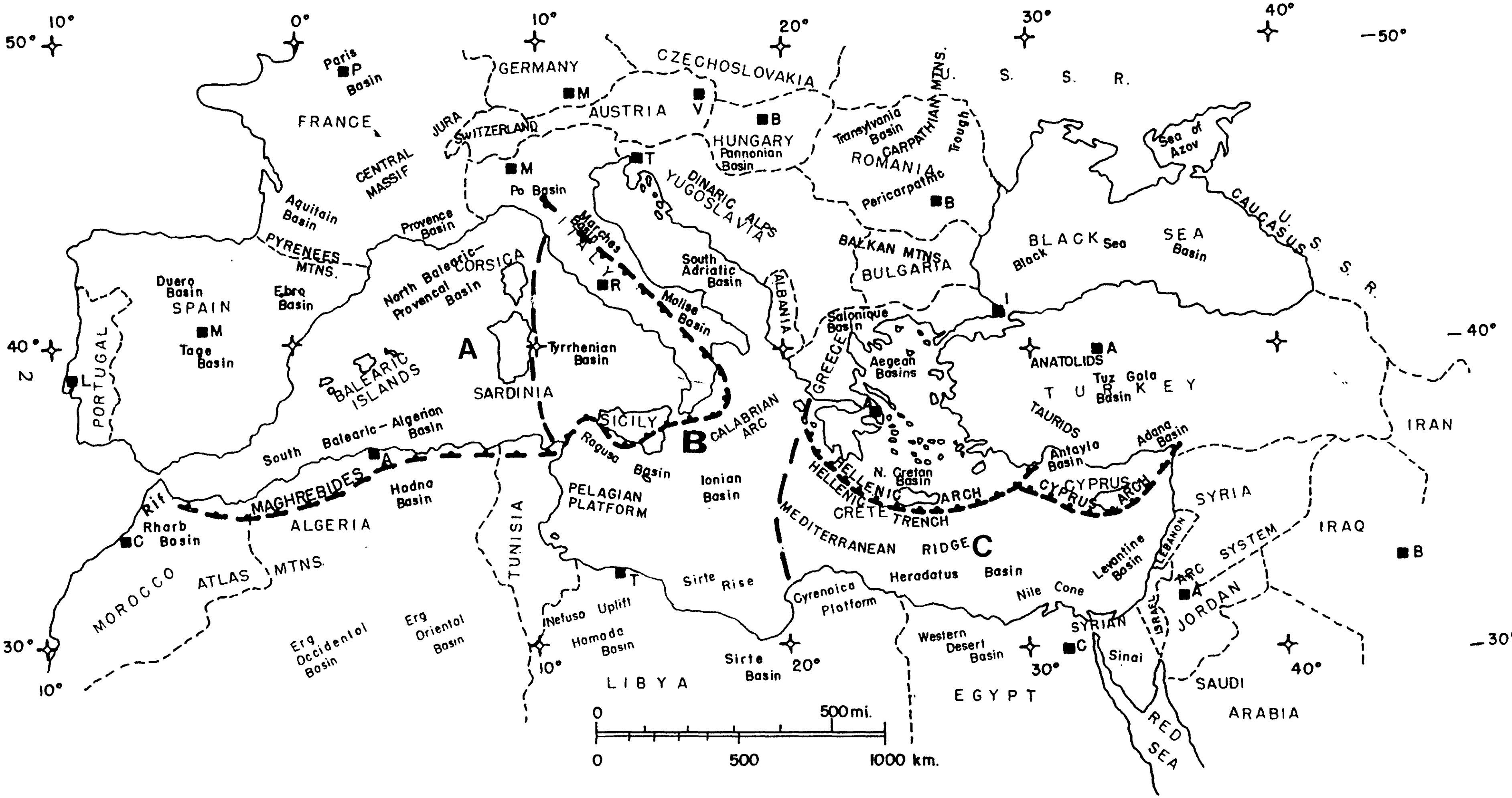


Figure 1. Main basins and uplifts, Mediterranean region. Hydrocarbon assessment areas: A - Western Mediterranean; B - Central Mediterranean; C - Eastern Mediterranean

For purposes of hydrocarbon resource assessment, the region is divided into three parts: western, central and eastern (fig. 1). The Western Mediterranean area (Area A) comprises: 1) the North Balearic-Provencal basin (including the Valencia and Ligurian basins of some authors); 2) the Balearic Islands; 3) the Alboran-South Balearic-Algerian basin (these three areas occupy approximately 675,000 km^2 or 260,000 mi^2); 4) the islands of Corsica and Sardinia (together occupying approximately 90,000 km^2 or 35,000 mi^2). The Central Mediterranean (area B) includes the Tyrhennian Sea basin (approximately 135,000 km^2 or 52,000 mi^2); 2) Italy, Sicily and the Adriatic Sea (approximately 600,000 km^2 or 240,000 mi^2); and 3) the Ionian Sea basin (approximately 300,000 km^2 or 110, 000 mi^2). The Eastern Mediterranean region (area C) includes: 1) Greece and Crete (approximately 225,000 km^2 or 90,000 mi^2); and 2) the deep eastern Mediterranean, including the Hellenic trench, Mediterranean Ridge, Herodotus basin, Nile Cone, Cyprus basin, and offshore Turkey (approximately 475,000 km^2 or 175,000 mi^2). The bordering lands of the south-central and southeastern Mediterranean include the tablelands, plateaus, hills or low mountains of the Nefusa, Cyrenaica, Western Desert, Sinai, and Israel-Lebanon-western Syria areas, and the intervening relatively flat basin areas of Egypt, Libya, and Tunisia. Elevations in this coastal belt are generally less than 350 m (1,000 ft). The east-west trending mountain ranges of the Atlas orogenic belt occupy the steep border lands of the southwestern Mediterranean where elevations rise to more than 2,000 m (6,500 ft) in many places. The northern Mediterranean is bordered in part by the high-standing Alpine Mountain ranges, including the Apennine chain extending southward through Italy (figs. 5-9).

This study was conducted as part of the U.S. Geological Survey World Energy Resources Program. The purpose of the work is to summarize the geologic background of the area, emphasizing those aspects related to the potential for generation, accumulation and preservation of hydrocarbon resources in the Mediterranean region. An extensive listing of references pertinent to the assessment of the region is included with the report.

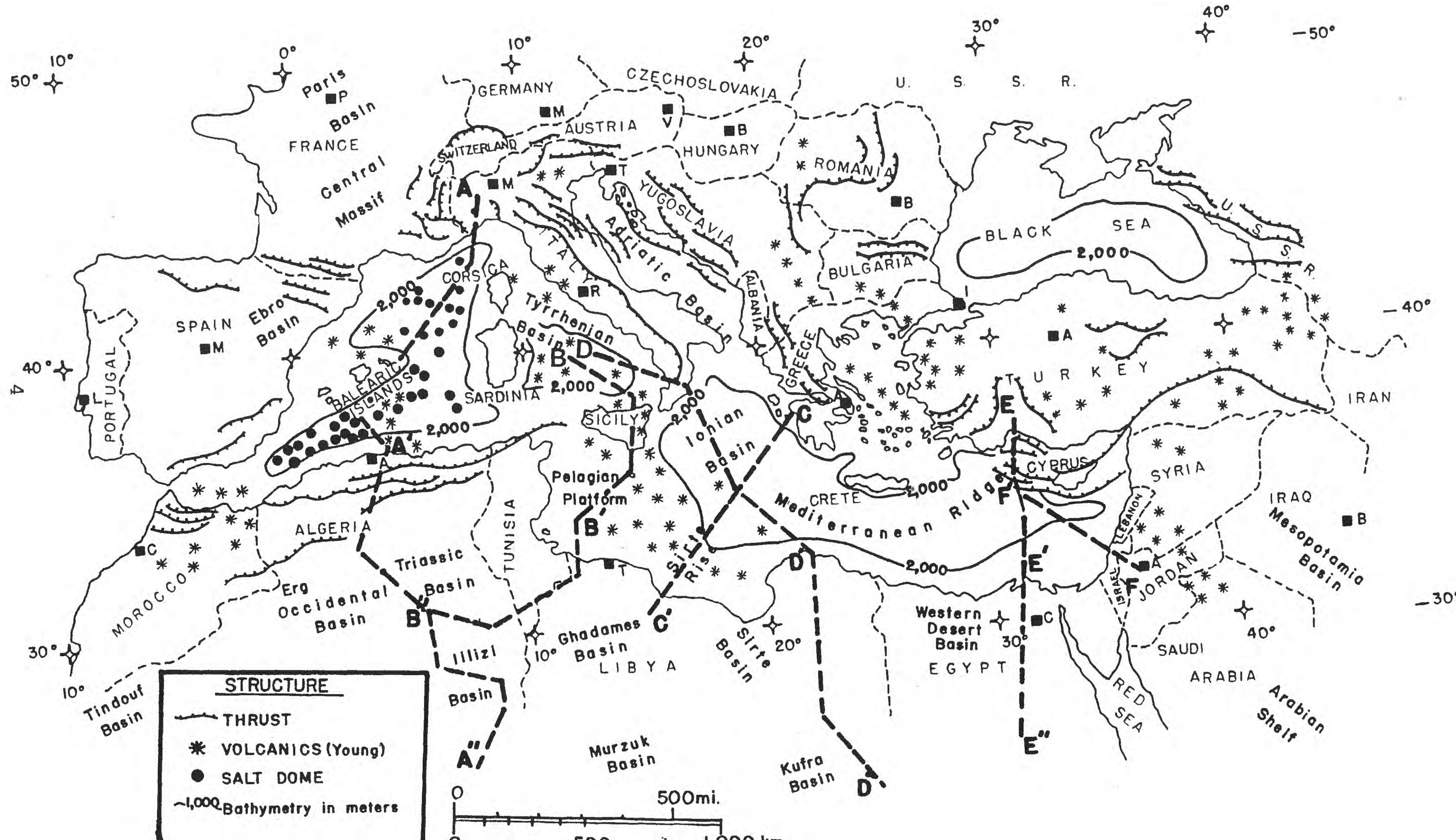
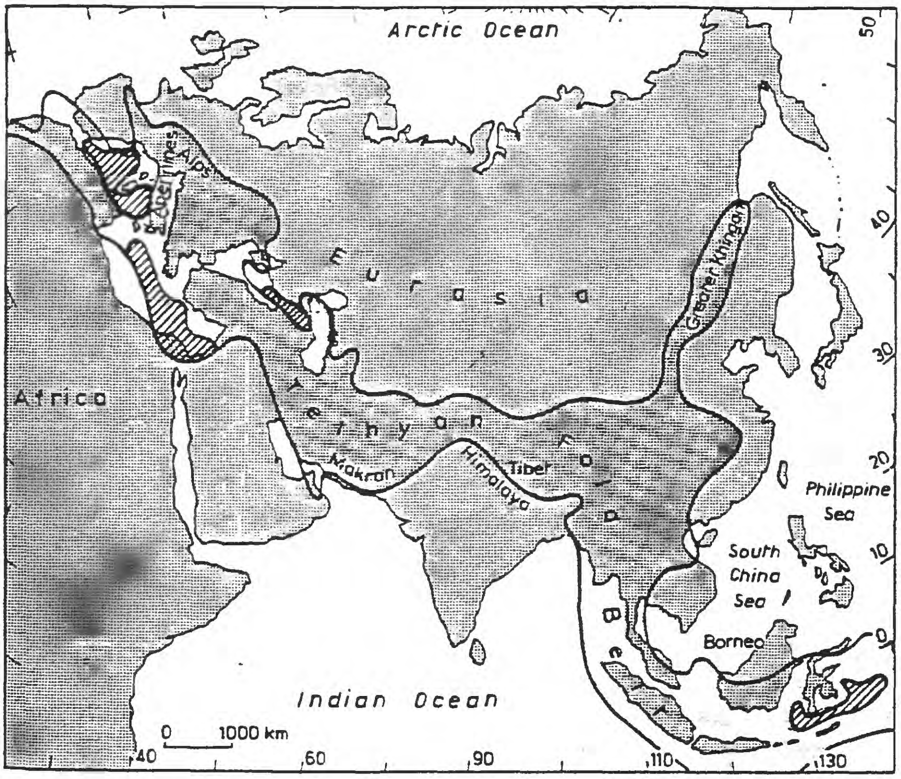
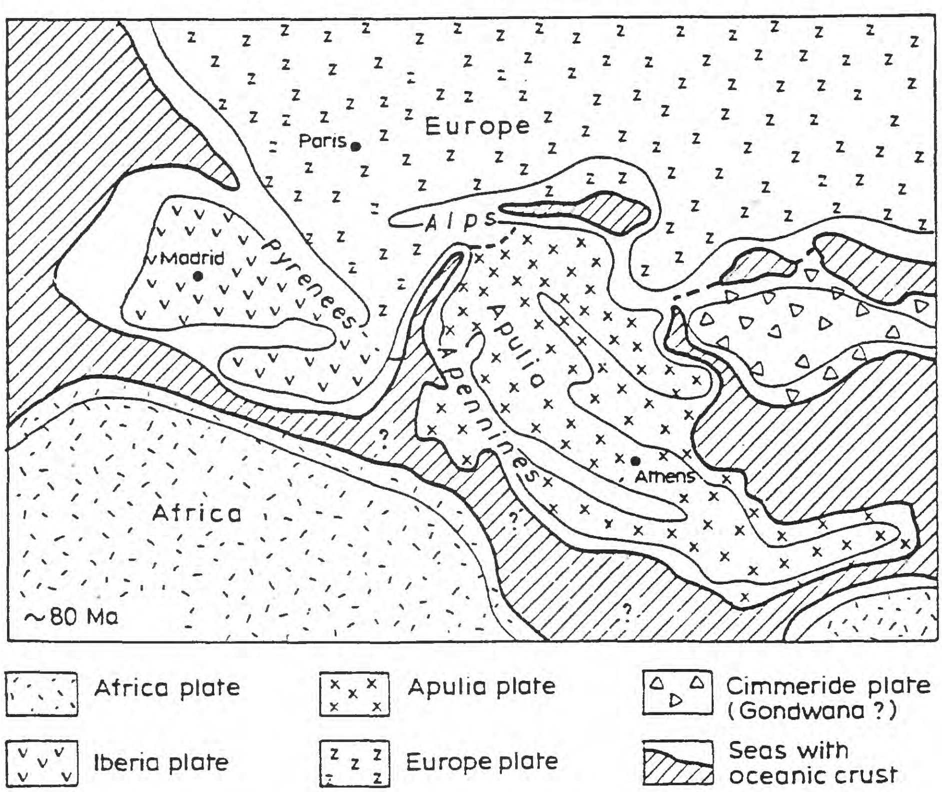


Figure 2. Map of main Alpine structure, Mediterranean region, showing areas of young volcanics and salt domes. Lines of cross-sections A-A' - A'', B - B' - B'', C - C', D - D' - D'' E - E' - E'', and F - F' of figures 11-15 and 53 are shown



A. General outline of the Tethyan foldbelt that extends from Indonesia in the southeast to the Atlas Mountains of Africa in the northwest. All crust south of the northern limit of this foldbelt is suspect with regard to kindred relations to Eurasia. The belt constitutes a complicated history of both accretion of continental fragments originating either along the northern edge of Gondwana or within the ancient Tethyan realm as continental plateaus, and translational movement of terranes effecting the large-scale dispersion within the belt. The hashed areas represent trapped or juvenal ocean crust. (Modified from Sengor (1987))



B. Speculative paleogeographic map of Europe for the period around 80 Ma depicting the general distribution of marginal seas, areas of oceanic crust, and distinct continental crustal fragments. The future sites of the Pyrenees, Alps, and Apennines are also indicated; these mountain systems reflect varying manifestations of the collision between Africa and Europe. (Figure modified from Dercourt *et al.* (1986))

Figure 3. A - Regional extent of Tethyan foldbelt; B - Paleogeographic map of Europe, approximately mid-Cretaceous time, from Howell (1989)

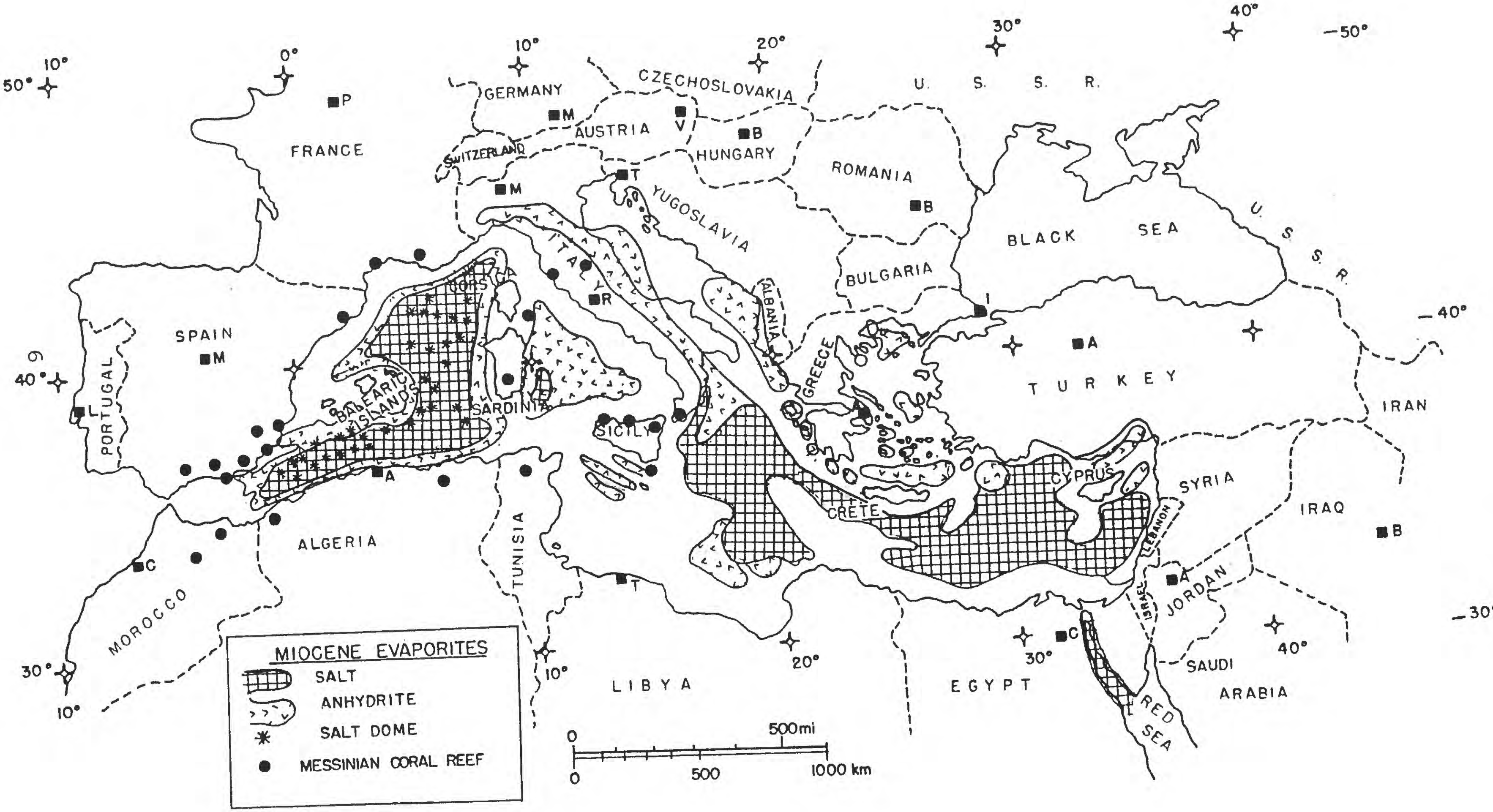
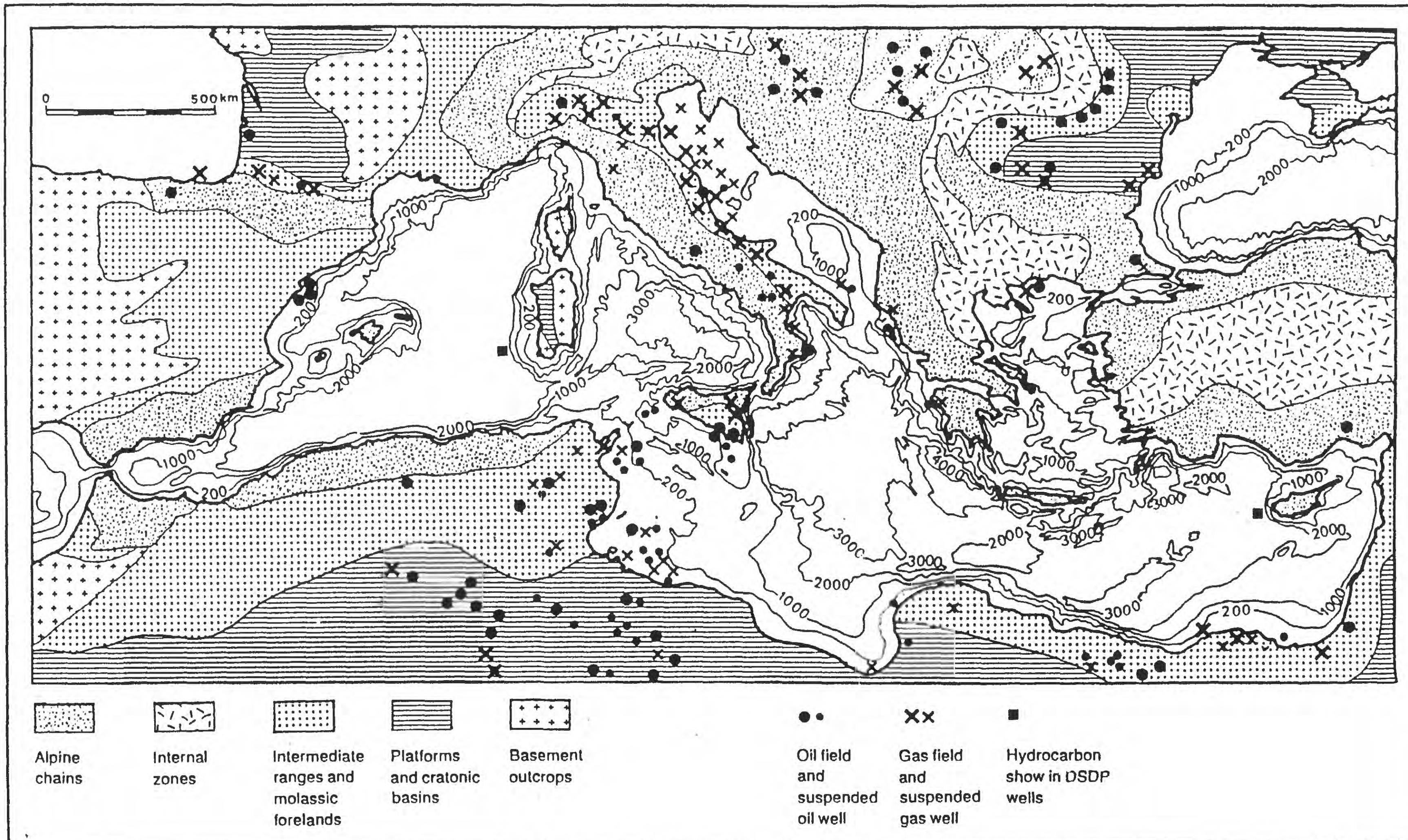
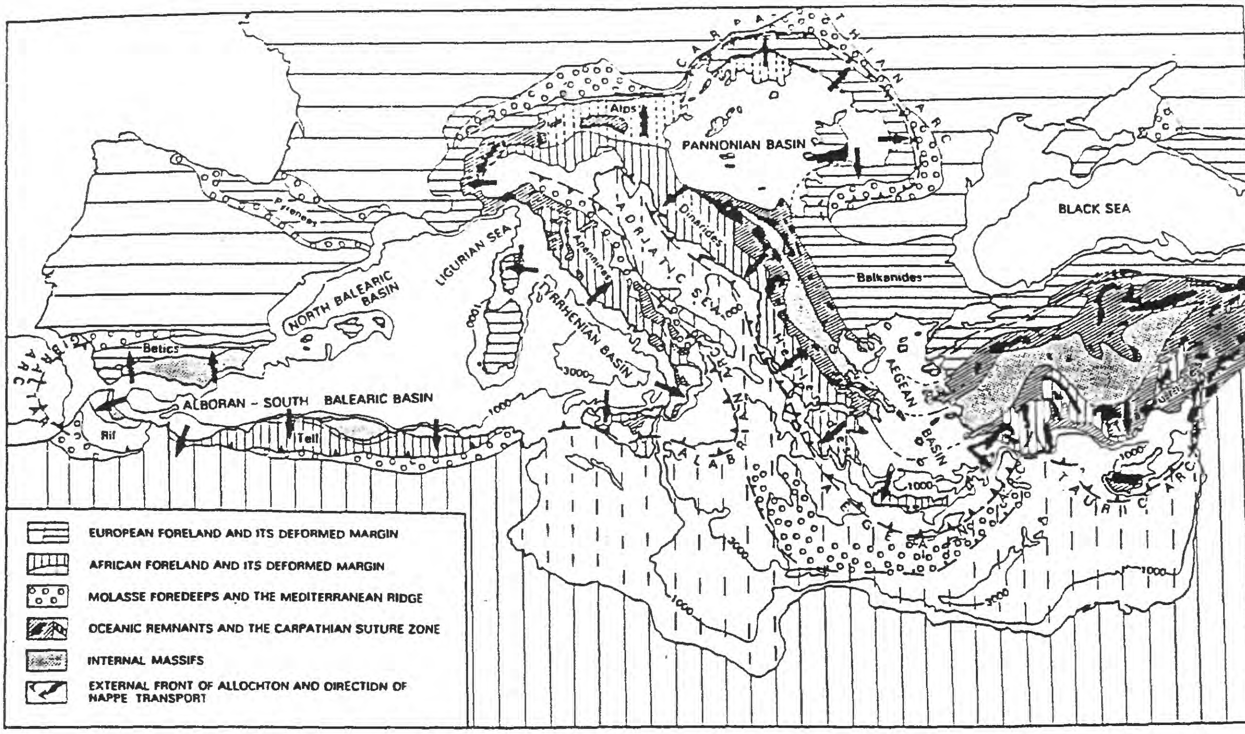


Figure 4. Areas of Miocene (Messinian) evaporites, Mediterranean regions. From Sonnenfeld (1985).

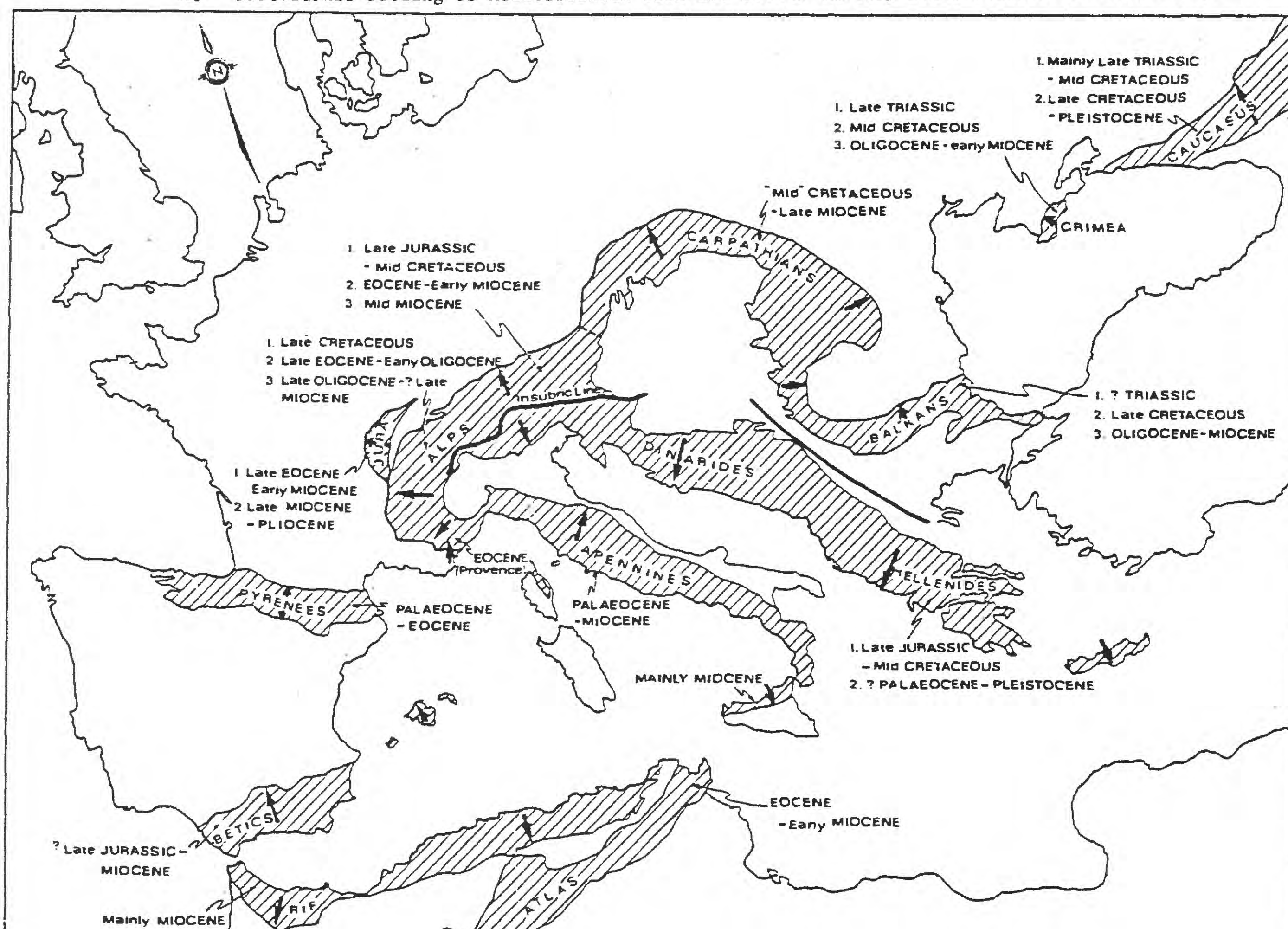


The Mediterranean Sea in the Alpine system.

Figure 5. Map of the main Alpine system of the Mediterranean region, showing main areas of hydrocarbon occurrence. From Burollet (1986)

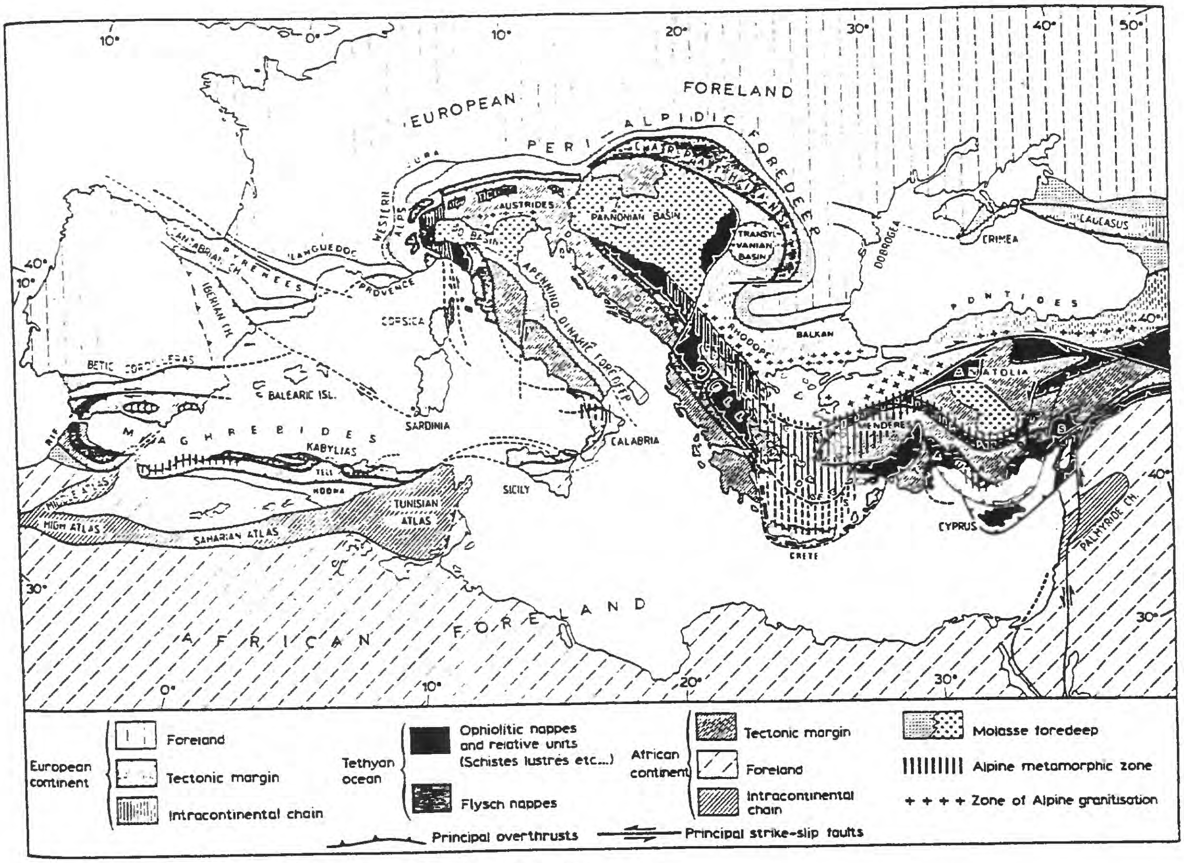


A. Geotectonic setting of Mediterranean back-arc basins (mainly after Channell et al., 1979).

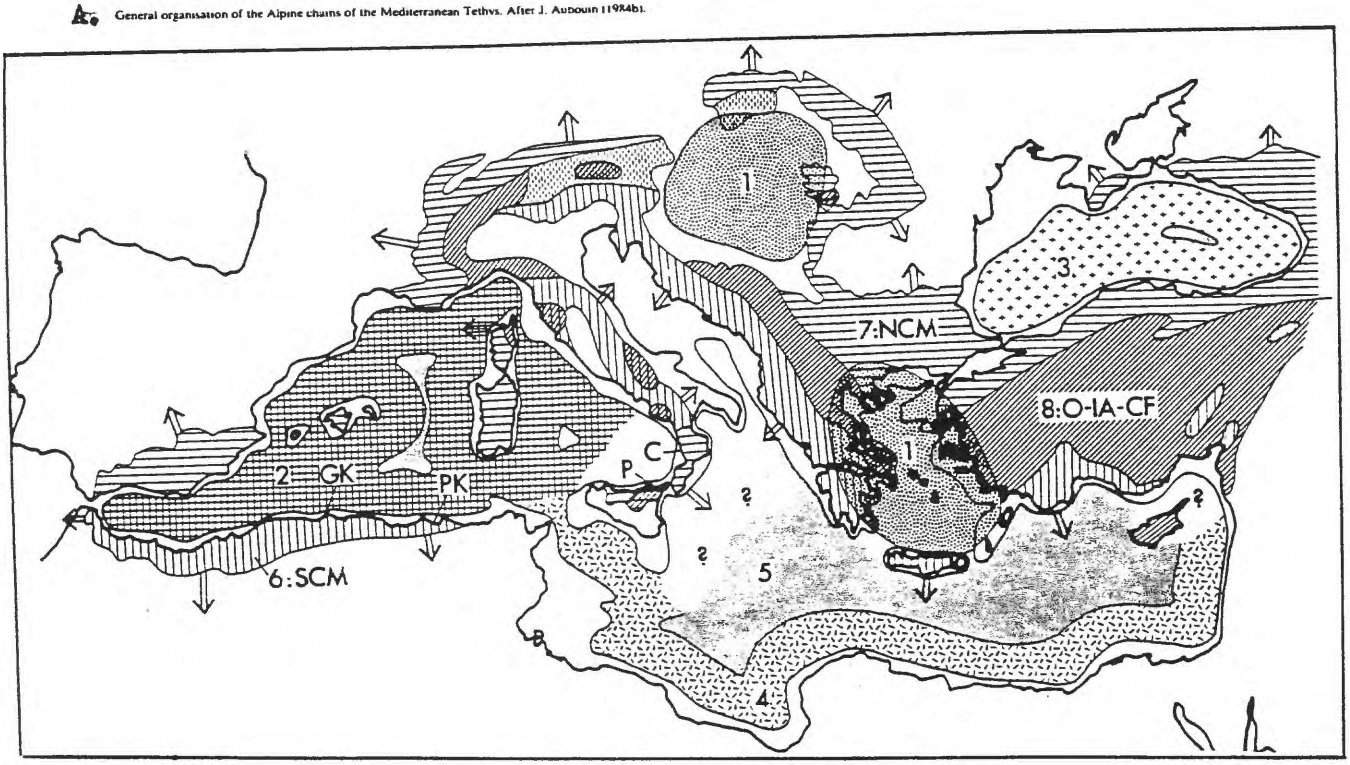


B. *Direction and age of the main Alpine movements in Europe*

Figure 6. Map of the Alpine system: A - Geotectonic map, from Horvath and Berckhemer (1982), B - Age of Alpine movements, from Ager (1980)

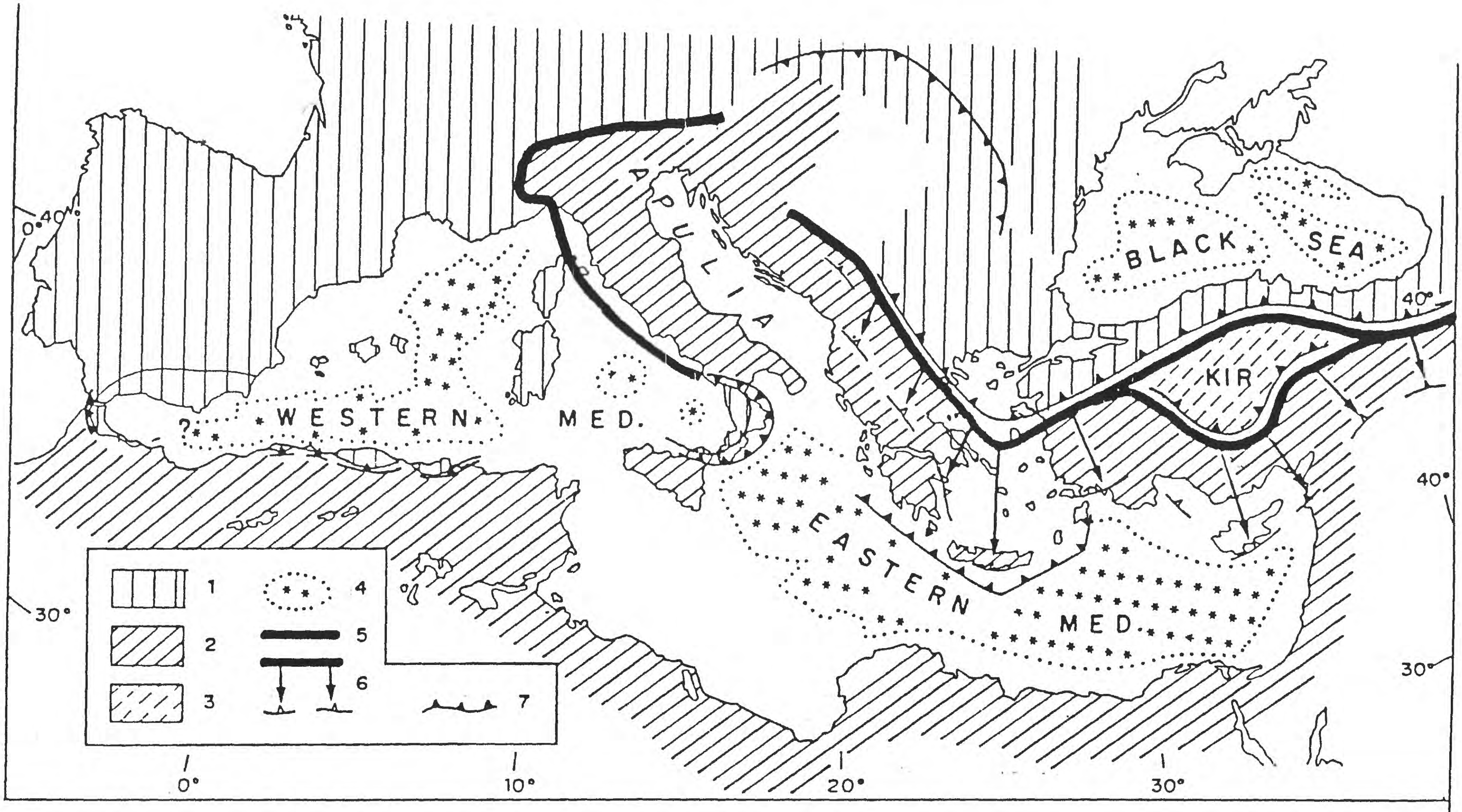


A. General organisation of the Alpine chains of the Mediterranean Tethys. After J. Aubouin (1984b).



B. Extensional zones in the circum-Mediterranean region. 1: probably Recent/late Cenozoic; 2: probably mid- to late Cenozoic; 3: probably late Cretaceous/early Cenozoic; 4: possibly Mesozoic; the strip shown lies about 150 km from the 200 m submarine contour; 5: Cenozoic/Mesozoic areas lying more than 150 km offshore from the 200 m submarine contour. These areas are most likely to be oceanic; 6: SCM = Mesozoic southern continental margin complex; 7: NCM = Mesozoic northern continental margin complex; 8: O-IA-CF = ophiolites and pelagic sediments/island arcs/continental fragments. The ophiolites, pelagic sediments and island arcs are mostly Mesozoic in age. Based partly on Channell et al. [1979]. GK = Grand Kabyle; PK = Petit Kabyle; P = Pelitoran massif; C = Calabrian massif: all four are continental slivers which may have migrated southwards from the southern edge of Europe to Africa and Sicily. Arrows show direction of tectonic transport of thrust sheets.

Figure 7. Circum-Mediterranean region: A - general organization of Alpine chains, from Auboin (1984); B - extensional zones and ages, from Smith and Woodcock (1982)



Classified continental and oceanic components of the Tethyan system. 1 = Eurasian continent and dependencies; 2 = African continent and dependencies; 3 = Kirsehir block; 4 = present oceanic basins; 5 = suture zones of the Mesozoic oceans; 6 = idem plus the major ophiolitic nappes (arrows) issued from them; 7 = past and present subduction trenches.

Figure 8. Continental and oceanic components of the Tethyan system, from Ricou and others (1986)

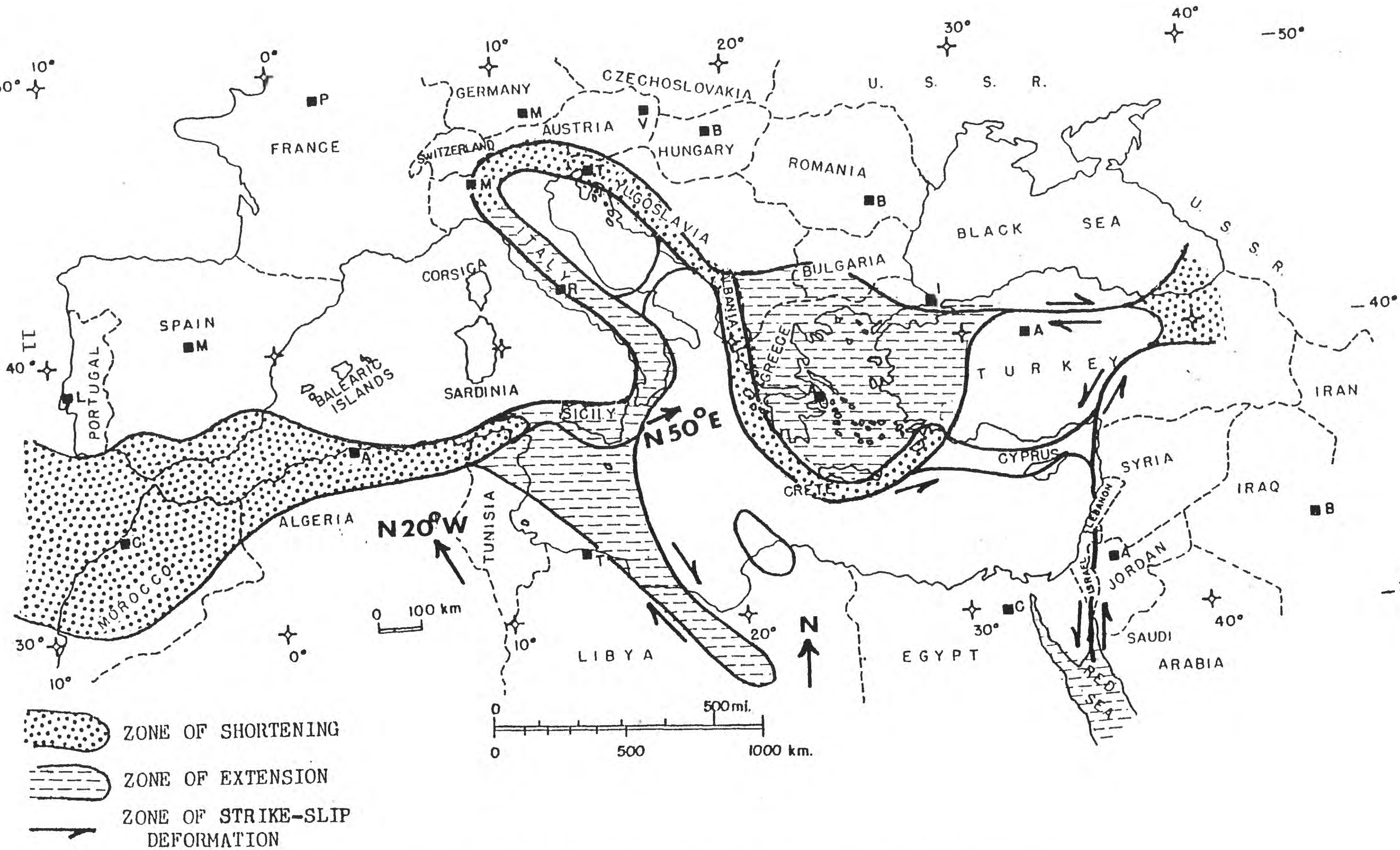


Figure 9. Present-day zones of shortening, extension, and strike-slip deformation, Mediterranean region, modified after Westaway (1990)

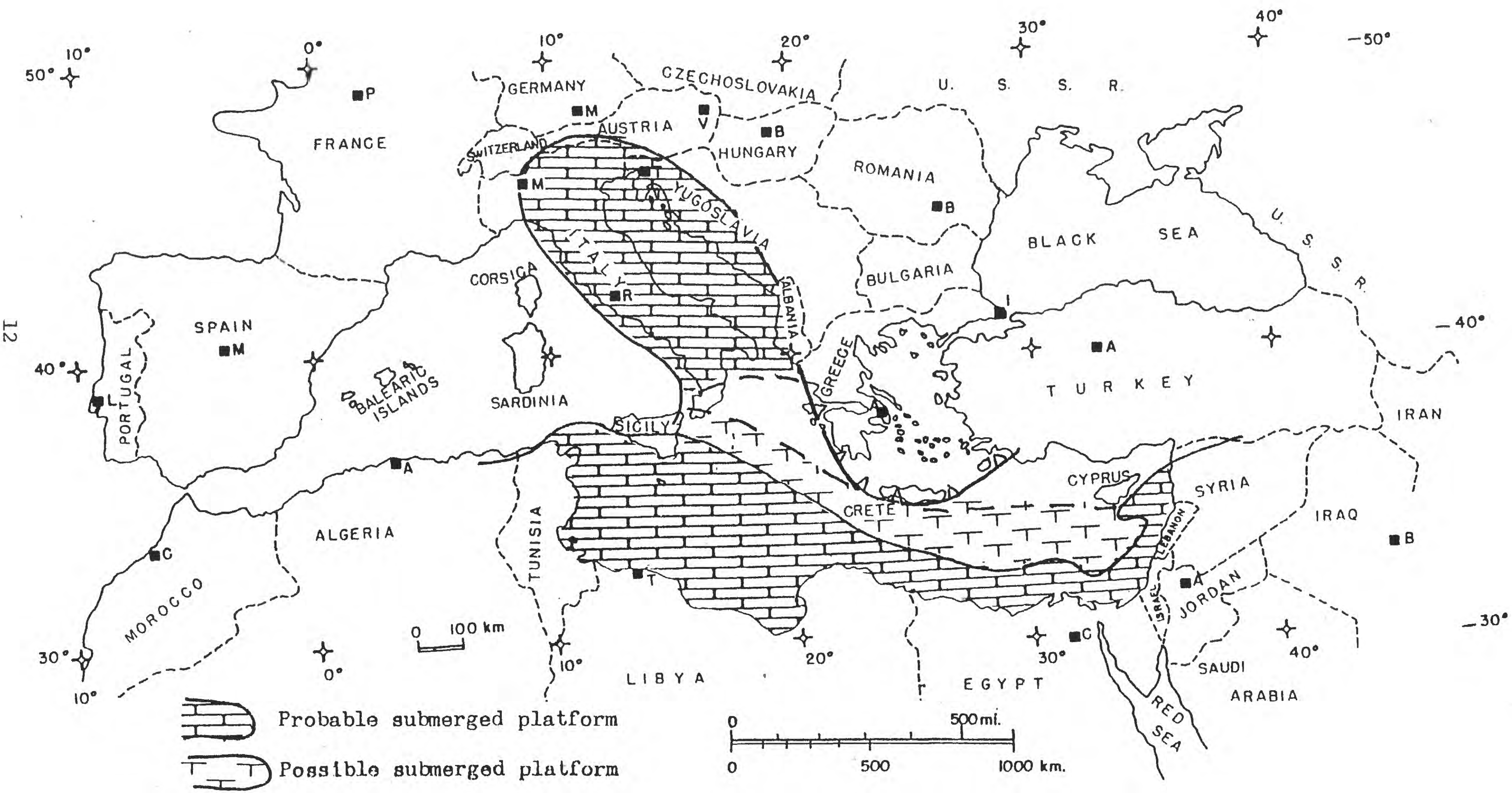


Figure 10. Mesozoic-early Tertiary north African platform distribution. Information from Byramjee (1975), Malovitskiy (1975), Biju-Duval and others (1979), Morelli (1985), Westaway (1990), and others

REGIONAL GEOLOGY

Introduction

The Mediterranean region is part of a long-lived continental collision zone characterized by several openings and closings. During Paleozoic time, the stable platform of North Africa-Arabia was part of the southern hemisphere continent, Gondwana. Continental plates which now make up the European side of the Mediterranean were part of a group of separated continental blocks, many of them far removed from the African-Arabian platform until approximately late Paleozoic time, when they became assembled into Eurasia as part of the supercontinent Pangea. Assembly of Pangea probably began with the Hercynian (Variscan) orogeny in Carboniferous time and was completed in Permian to Early Triassic time. The various continental plates which now make up the southern European-Asian continental mass came together at this time, and the first major collision between the European and African continents also occurred. During the Late Permian and Triassic, crustal compression relaxed and crustal stretching, associated with rifting and development of extensional basins, occurred as part of the early breakup of Pangea. At this time, the African and European plates began to drift apart, resulting in the initial opening and general subsidence of the Tethys ocean (fig. 3). By Early Jurassic time, coincident with strong rifting in the western region associated with counter-clockwise rotation, the Apulian (Adria) plate began to separate from Africa and drift northward. At this time, the wedge-shaped paleo-Tethys ocean occupied the eastern region, separating Asia from the Arabian plate. General subsidence began in the west during the Lower Jurassic and ended during the Upper Jurassic. The Tethys ocean is commonly divided into two phases: 1) paleo-Tethys, a pre-middle Mesozoic (Jurassic) phase, which separated Laurasia from Gondwana to the east, and 2) a neo-Tethys post-middle Mesozoic phase (fig. 3). The present Mediterranean is bordered by continental margins of Jurassic and younger age. The floor is of Middle Jurassic and younger oceanic crust, or is of African or European continental crust, which subsided and stretched in Middle Jurassic and later time. This process was controlled by relative motions between Africa and Europe, primarily related to regional crustal movements during the opening of the Atlantic Ocean basin.

Structural Summary

North Africa

The main North African petroleum basins are on the North African or Sahara platform, which lies between the uplifts in southern Algeria, Libya, and Egypt on the south and the Mediterranean Tethys geosyncline on the north (Peterson, 1985). Pertinent works on the structural geology and structural history of north Africa include the following: Said (1981), Conant and Goudarzi (1967), Klitsch (1968), Sander (1968), Youssef (1968), Goudarzi (1970, 1980), Burollet (1971), Burollet and others (1971, 1978), Schurmann (1971), Bishop (1975), El Shazly (1977), Salaj (1978), Brown (1980), El-Etr and Moustafa (1980), and Parsons and others (1980).

North Africa was affected by several episodes of tectonic activity including: 1) late Precambrian, 2) Caledonian (early Paleozoic), 3) Hercynian (late Paleozoic), 4) Laramide (Late Cretaceous-early Tertiary), and 5) Alpine (late Tertiary).

The Precambrian basement, which is exposed in several uplifts to the south and has been penetrated in numerous deep wells, consists of schist and gneiss as well as some granite and volcanic rocks (figs. 11-15). The basement rocks apparently were extensively folded and faulted in Precambrian time (Said, 1981; Bishop, 1975; El Shazly, 1977). At least three Precambrian orogenic cycles are described which determined the basic structural grain of north Africa. During this structural phase, much of the tectonic lineation was oriented northwest-southeast, particularly in Egypt where early block faulting occurred (El Shazly, 1977).

Caledonian (Ordovician to Early Devonian) tectonic activity was characterized by general northwest-southeast and east-west belts folding and faulting, which further consolidated the pattern of earlier platform basins and uplifts (Goudarzi, 1980; Klitsch, 1968; El Shazly, 1977; Bishop, 1975). At this time, Paleozoic basins and uplifts were delineated, such as the Hamada, Murzuk, and Kufra basins, and the Gargaf arch and Sirte high in Libya, the Illizi, Erg Oriental, and Erg Occidental basins and the Amguid spur in Algeria, and the Western Desert basin in Egypt, possibly the ancestral Suez-Red Sea trough, and numerous smaller trough and high trends extending southeast from the Mediterranean.

During the late Paleozoic Hercynian tectonic cycle, general uplift of the Sahara platform took place, coupled with superimposed, generally west-east folding trends related to early development of the Tethys geosyncline. Mild tectonic activity continued in most Paleozoic basins and uplifts at this time; also several west-east uplifts were initiated, including the Nefusa uplift and Algerian anticlinorium in northwest Libya, southern Tunisia, and eastern Algeria. Evidence of sagging in the Suez Graben at this time also is documented (Said, 1981; El Shazly, 1977). Widespread erosion of the platform took place at the close of Hercynian activity, and Permian rocks are generally absent or very thin on the platform, but are markedly thicker north of the Nefusa uplift into the Jefara trough segment of the Pelagian platform (figs. 1, 12).

During Mesozoic and Tertiary time, most of Africa was above sea level (Kennedy, 1965), and marine deposition took place only in the marginal shelf basins associated with the breakup of the Pangea supercontinent. In north Africa, the Mesozoic and Tertiary basins were initially formed by vertical and sinistral strike-slip tectonic movements associated with separation of the European and African cratons and opening of the Mediterranean Tethys ocean. In early Mesozoic time, active subsidence and northward tilting of the Sahara platform, accompanied by marine transgression, took place during the early formative phases of the southern Tethyan shelf margin. The general orientation of tectonic units at this time continued the northeast-southwest or west-east Hercynian trends. Subsidence was greatest in the Pelagian platform region

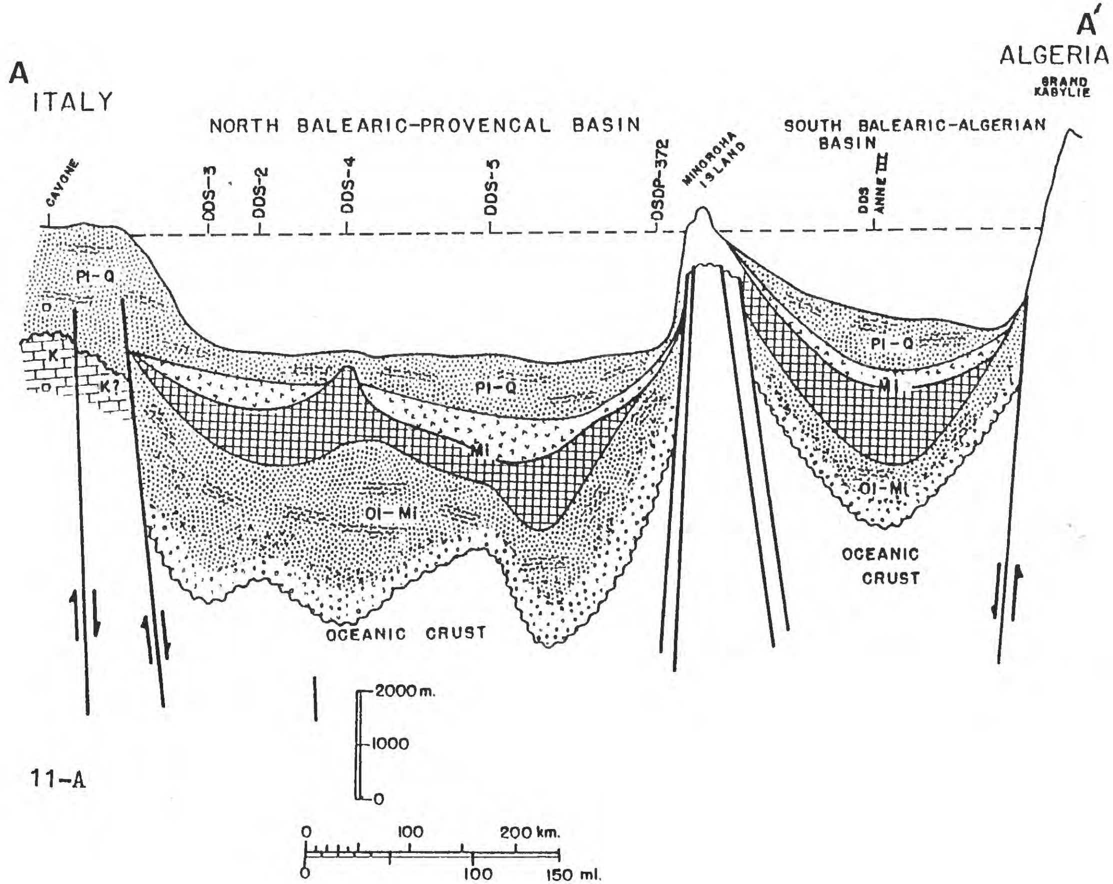
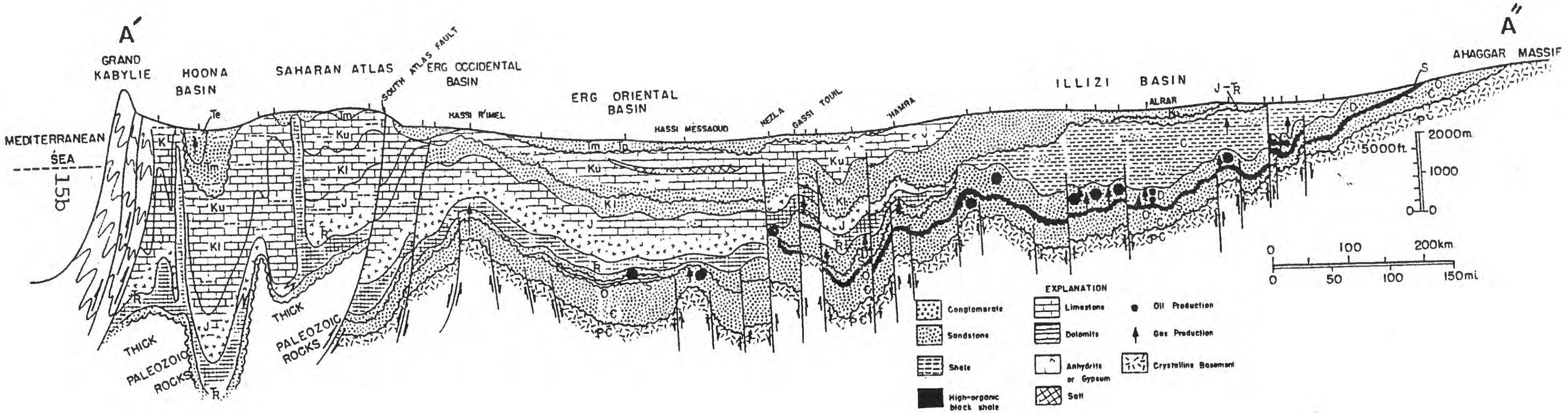


Figure 11. North-South structural-stratigraphic cross-section A - A' - A'', north-western Italy to southeastern Algeria. Line of cross-section shown on figure 2



A´
A˝
GRAND KABYLIE
HOONA BASIN
SAHARAN ATLAS
SOUTH ATLAS FAULT
ERG OCCIDENTAL BASIN
HASSI R'MEL
ERG ORIENTAL BASIN
HASSI MESSAOUD
NEZLA
GASSI TOUIL
HAMRA
ILLIZI BASIN
ALRAR
AHAGGAR MASSIF
MEDITERRANEAN SEA
15b
THICK PALEOZOIC ROCKS
THICK PALEOZOIC ROCKS
5000ft.
2000m.
1000
0
0
0 100 200km
0 50 100 150mi
EXPLANATION
Conglomerate
Sandstone
Shale
High-organic black shale
Limestone
Dolomite
Anhydrite or Gypsum
Salt
Oil Production
Gas Production
Crystalline Basement

11-B

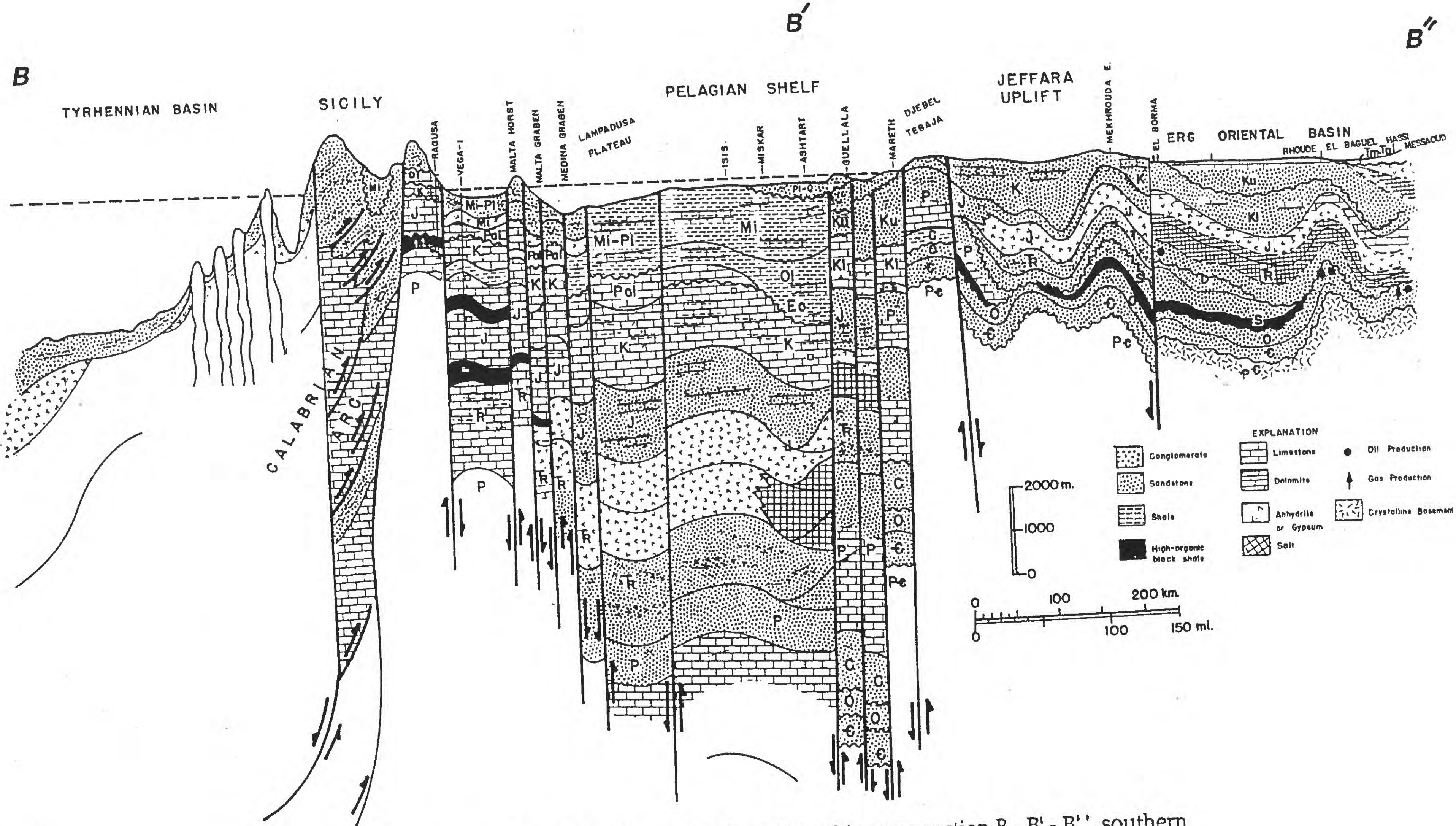


Figure 12. North-South structural-stratigraphic cross-section B - B' - B'', southern Tyrrhenian Sea to central Algeria. Line of cross-section shown on figure 2

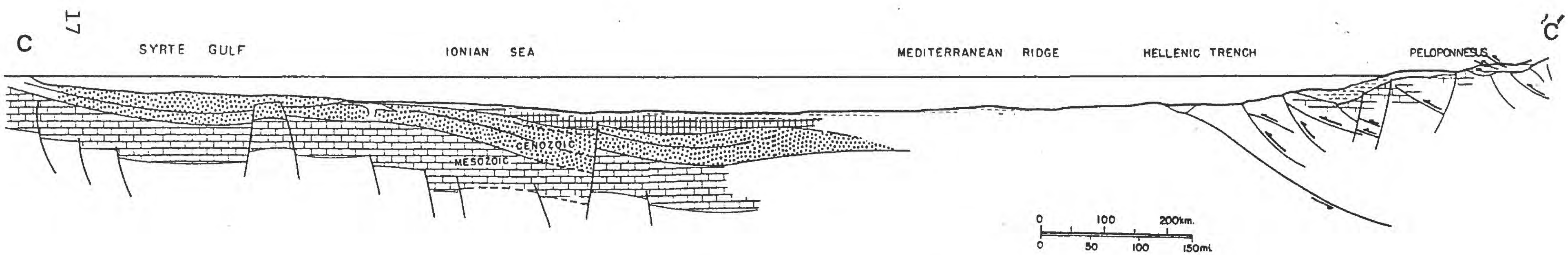


Figure 13. Schematic southwest-northeast structural-stratigraphic cross-section C - C', Libya to Greece. Modified after Biju-Duval (1979)

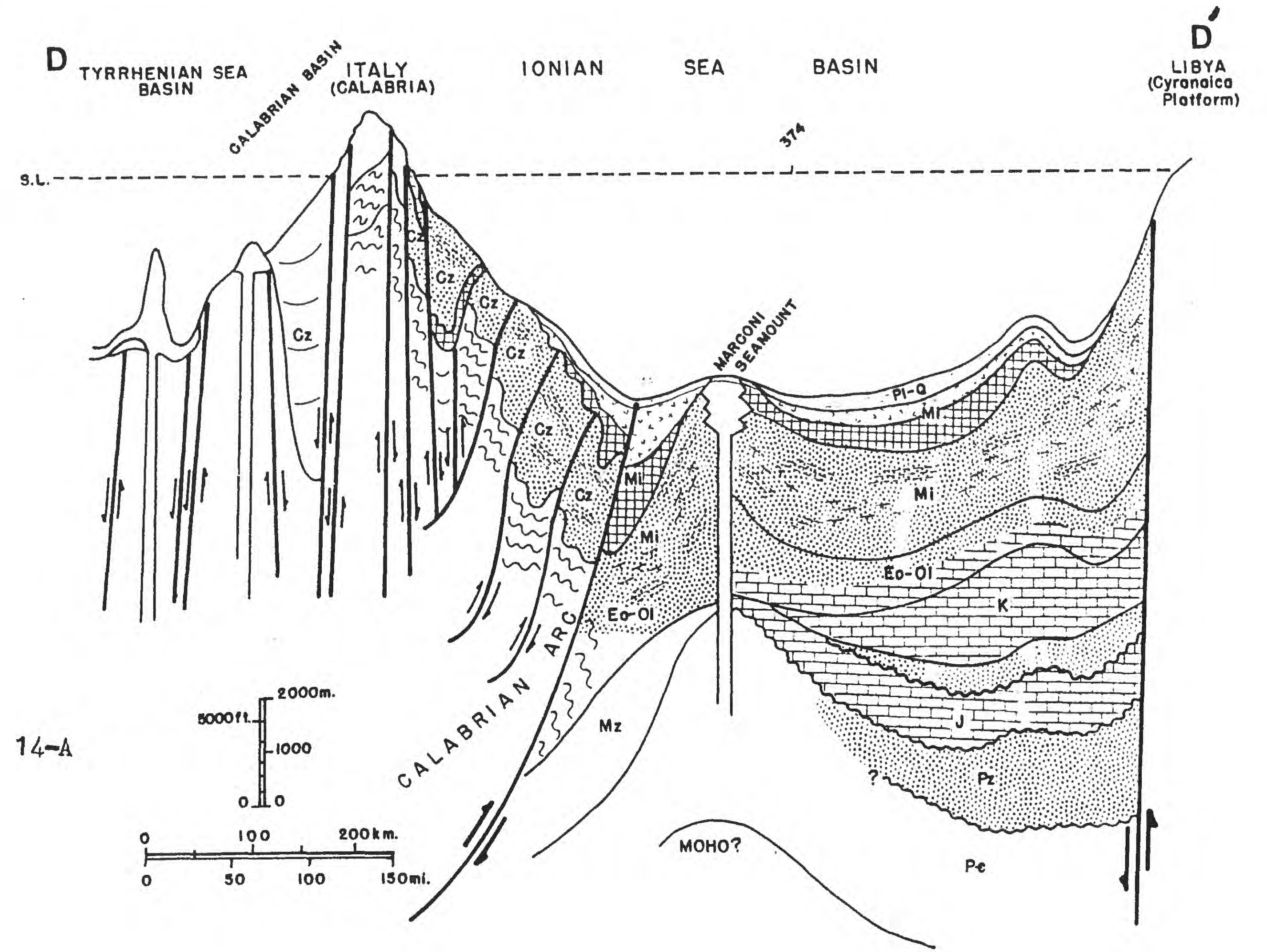
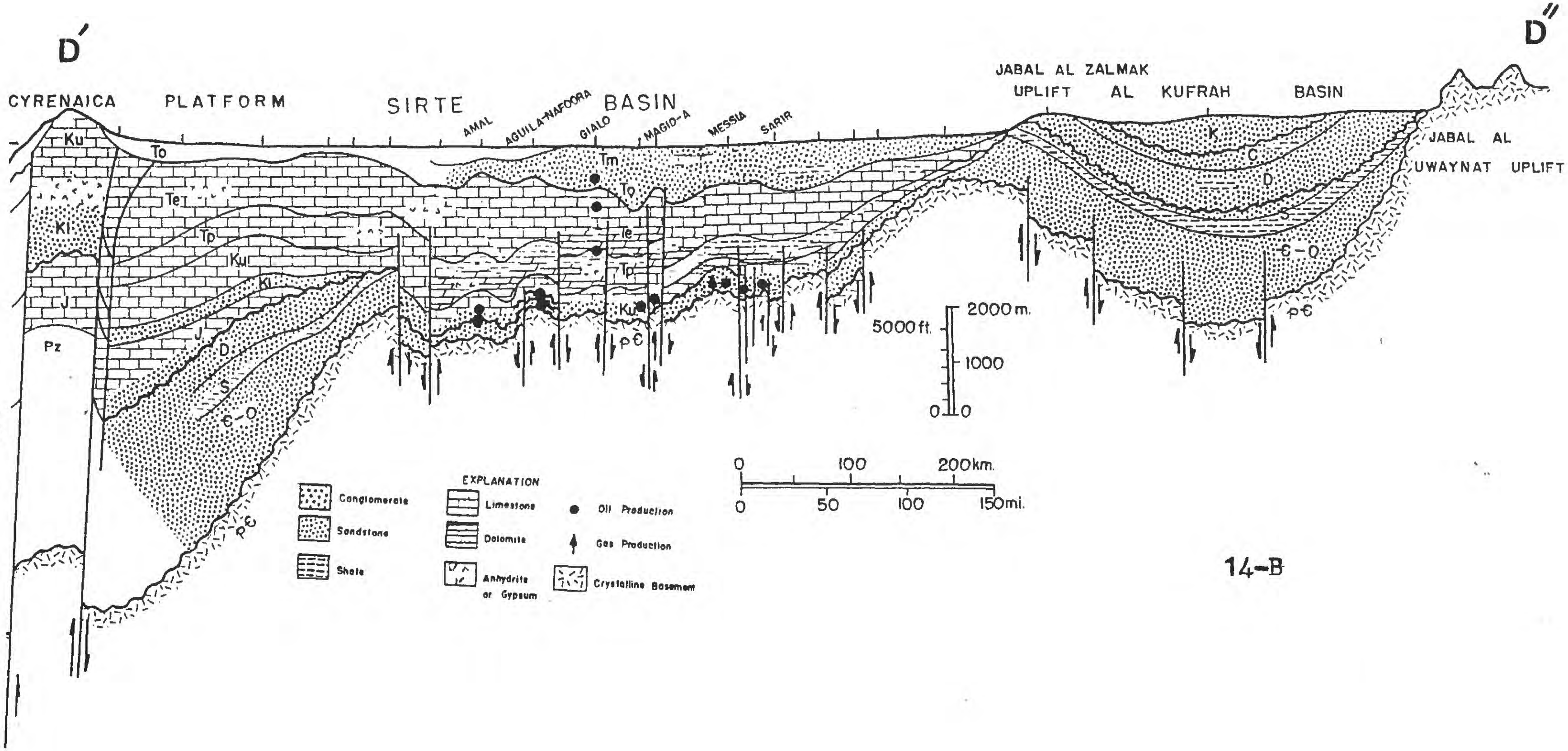


Figure 14. North-South structural-stratigraphic cross-section D - D' - D'', southern Tyrrhenian Sea to southeastern Libya. Line of cross-section shown on figure 2


D′
D″
CYRENAICA PLATFORM
SIRTE BASIN
AMAL
AGUILA-NAFOORA
GIALO
MAGID-A
MESSLA
SARIR
JABAL AL ZALMAK UPLIFT
AL KUFRAH BASIN
JABAL AL UWAYNAT UPLIFT
Ku
Kl
J
Pz
To
Te
Tp
D
S
Є-O
pЄ
Tm
K
C
5000 ft.
2000 m.
1000
0
0
100
200km.
50
150mi.
EXPLANATION
Conglomerate
Sandstone
Shale
Limestone
Dolomite
Anhydrite or Gypsum
Oil Production
Gas Production
Crystalline Basement

14-B

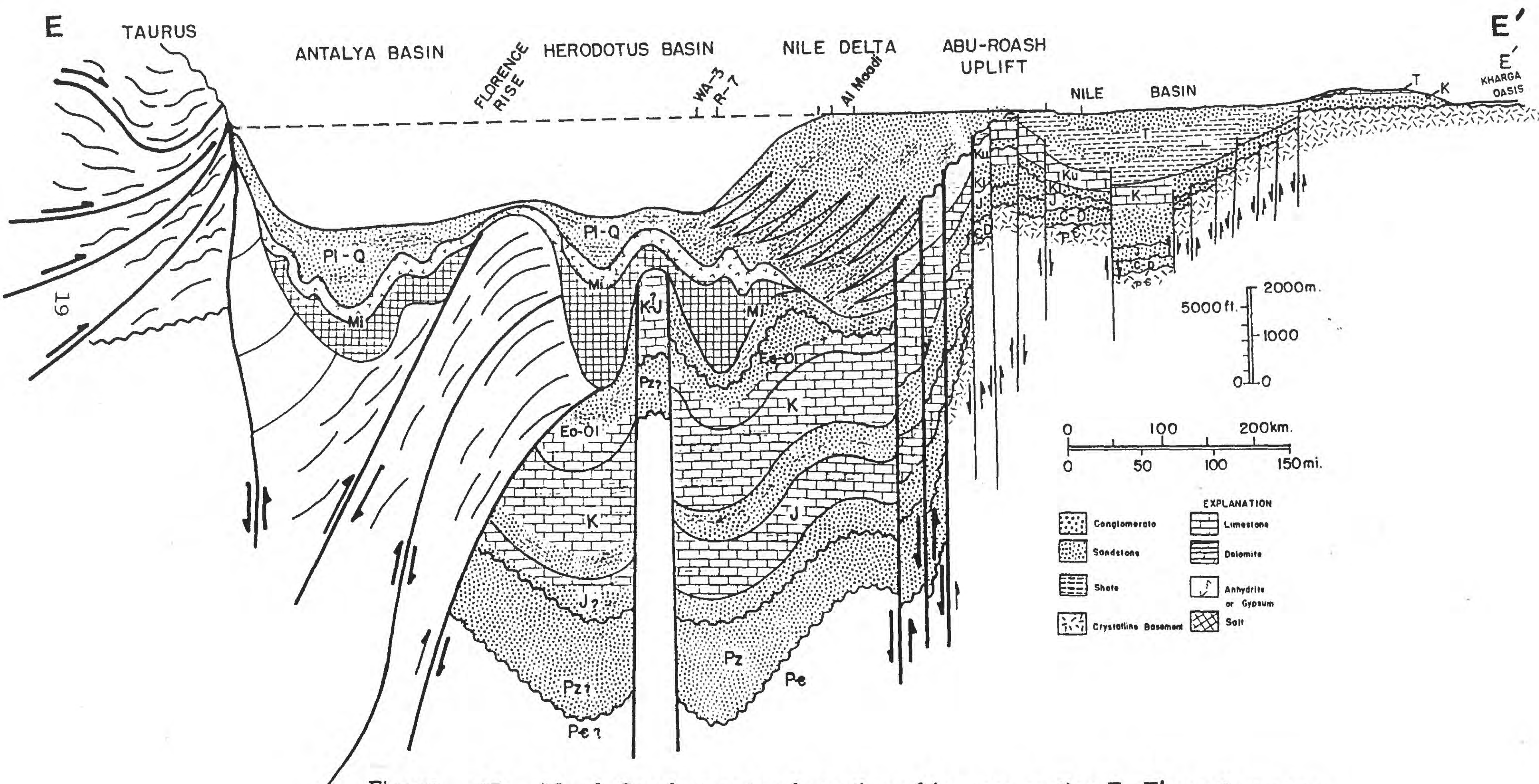


Figure 15. North-South structural-stratigraphic cross-section E - E' southwestern Turkey to southeastern Egypt. Line of cross-section shown on figure 2

and in central and northern Algeria where substantial thicknesses of Triassic and Early Jurassic red beds and evaporites, including salt, were deposited on eroded middle and late Paleozoic beds (figs. 11, 12). Most of central and eastern Libya and Egypt remained high at this time, except for the northern margin adjacent to Tethys.

During Late Cretaceous and early Tertiary time, maximum southward transgression of the Tethys ocean occurred in North Africa and was accompanied by northwest-southeast horst and graben block faulting. This event was followed by regional northward tilting of the Sahara platform which continued into Miocene time. Fold and fault trends in northern Egypt at this time were generally northeast-southwest and were accompanied by the development of numerous local small basins and uplifts (El Shazly, 1977). Active subsidence continued during the late Mesozoic and early Tertiary in the Pelagian and Cyrenaica platform regions (fig. 1), and several thousand meters of Cretaceous and lower Tertiary carbonate and clastic deposits accumulated (figs. 12-14). Late in Cretaceous or early Tertiary time, however, the Cyrenaica platform was faulted and uplifted, perhaps in conjunction with block faulting of the Sirte basin. The Pelagian and Cyrenaica platforms and the Western Desert basin were parts of the once continuous northern margin of the Sahara platform before its breakup by Sirte basin block faulting and northward tilting in mid-Mesozoic time. Deeply buried blocks of the original platform border most likely are present in northern and offshore parts of the Sirte basin. Late Cretaceous folding in Egypt, trending northeast-southwest, resulted in development of the "Syrian Arc" system (Fig. 1) which extended across northern Egypt and to the northeast into the Syria region (El Shazly, 1977). Early Tertiary tectonic trends, however, were controlled by northwest-southeast or north-south faults in eastern Egypt associated with early development of the Nile Valley and the Suez and Red Sea grabens.

Alpine tectonic activity of late Tertiary age did not greatly affect the northern African platform except for broad epeirogenic movements. Present tectonic trends on the platform tend to be oriented north-south or northwest-southeast, although some prominent features have generally west-east trends. Increased tectonic activity in the Pelagian platform region and general northward regression of the Mediterranean seaway occurred at this time. During the Miocene, the Algerian Sahara remained generally stable, and block faulting ceased in the Sirte basin. In Egypt, regional uplift took place during the Oligocene and was followed by early to middle Miocene transgression and continued development of the Nile, Suez, and Red Sea grabens. Regional uplift, folding, and rifting occurred in late Miocene, continuing into the early Pliocene, at which time the Nile River system began to develop within the Nile graben, followed by rapid northward migration of the Nile Delta into the Mediterranean region. Active subsidence of the Suez graben continued into the Pliocene, at which time the Red Sea became connected with the Indian Ocean.

Several episodes of igneous activity in north Africa are recorded, including those of Paleozoic age in southeastern and southwestern Egypt and Libya, Mesozoic age in Libya and Egypt, and late Tertiary to Holocene age in Egypt and Libya. The most extensive deposits are the Oligocene-Miocene basaltic volcanic rocks in the Sinai, Suez, Red Sea, and Western Desert regions of Egypt and the late Tertiary-Holocene basaltic volcanics in central and south central Libya.

Reconstructions of the geologic history of the northwestern Africa region are given by several authors, including Klemme (1958), Dillon and Sougy (1974), Caire (1978), Bronner and others (1980), Hinz and others (1981), Seibold (1982), and others, some of which are listed in the references. The geologic history of this region follows a sequence of closely related tectonic and sedimentologic events. The sedimentary cover of onshore northwest Africa ranges in thickness from 3 km (10,000 ft) or less in Algeria to probably as much as 10 km (30,000 ft) or more in the western basins, and is considerably greater than 10 km (30,000 ft) in the Atlas folded belt (figs. 16-19). The sedimentary section to the north is primarily marine, while substantial thicknesses of continental clastics are present to the south.

The Alpine zone of northwestern Africa includes the complex of uplifts and basins adjacent to the Mediterranean Sea, separated from the southern region by the South Atlas fault (fig. 2). This complex structural region is generally separated into several structural provinces, in the Atlas Range province of Morocco, Northern Algeria and Tunisia.

The Atlas Range underwent a series of strong orogenic movements during the Tertiary, although the Moroccan Meseta in northeastern Morocco apparently remained as a relatively stable block (Stets and Wurster, 1982). Early Tertiary activity continued the inversion movements of the Late Cretaceous accompanied by folding episodes and deposition of conglomerates and other clastics in downwarped areas. Cherty limestone, marl, phosphatic and shell beds and sandstones formed in the Tellian trough of northern Algeria and the High Atlas regions at this time. In middle and late Eocene time, folding, uplift, and erosion occurred in these areas. Folding also occurred in the Rif region (fig. 1) at this time, forming arcuate structures open to the north, and the Kabylia zone of northern Algeria (fig. 11) was overthrust to the south. Tectonic activity diminished in the Oligocene, when coarse orogenic clastics were deposited in low areas. Thick shale deposits (Numidian flysch) formed north of the Atlas Mountains in northeastern Algeria and northwestern Tunisia.

The major tectonic phase of the Atlas Mountains region occurred in the early Miocene (Caire, 1971, 1978; Dillon and Soughy, 1974; Klemme, 1958). At this time, a foredeep subsided between the northern and southern Atlas chains and filled with marls and sandstones. A complex system of tight folds, nappes and sedimentary klippe formed in the Atlas, Kabylia and Rif regions (figs. 1, 2, 7, 11). Folding, overthrusting, and wrench faulting also occurred. Vertical movements began in middle Miocene time, forming the combination of uplifts and intermontane basins characteristic of the modern Atlas mountains province.

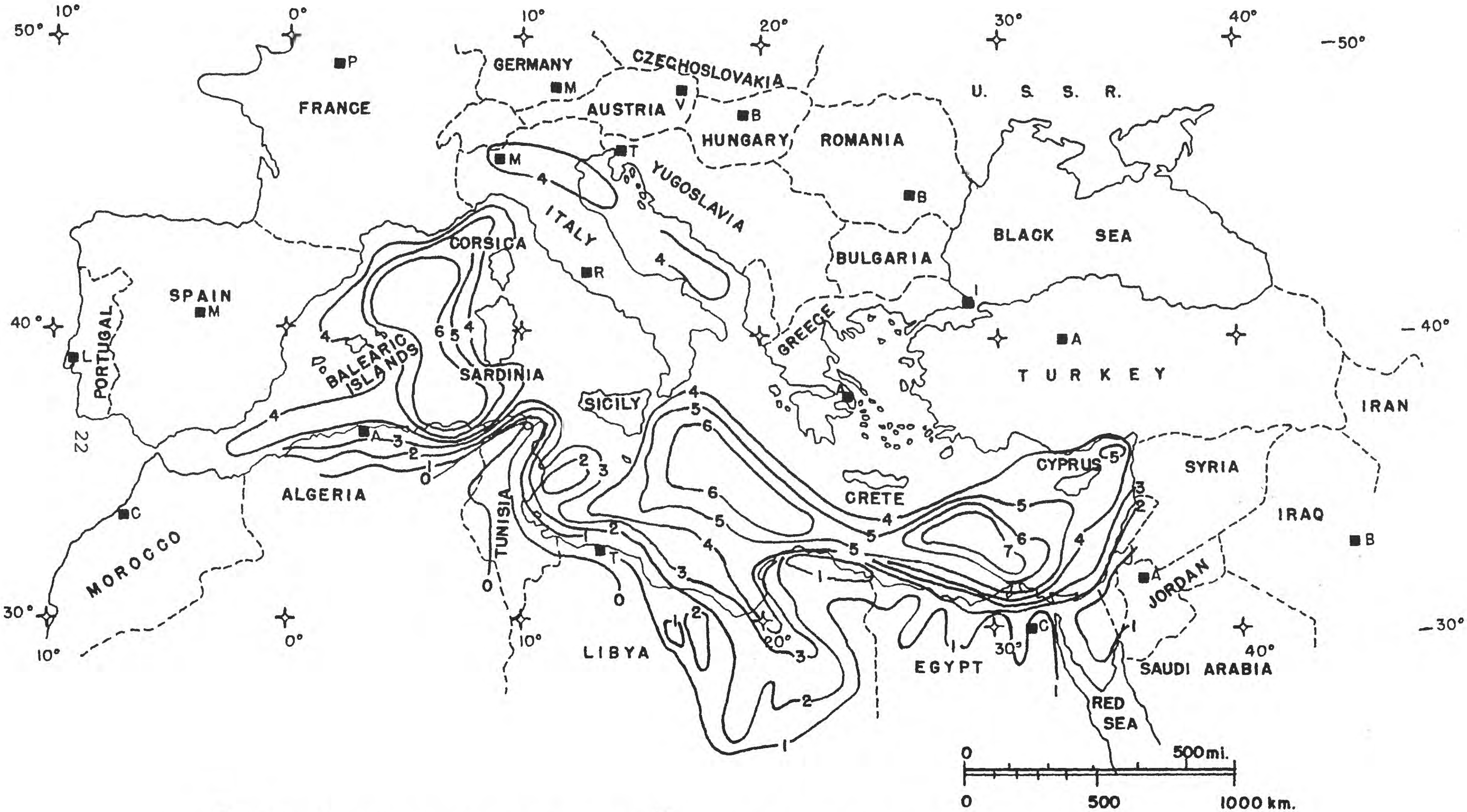


Figure 16. Approximate thickness in thousands of meters, Cenozoic rocks, partly restored where erosion has occurred, northern Africa and adjacent Mediterranean Sea. Compiled from numerous sources. Modified from Peterson (1985, 1986)

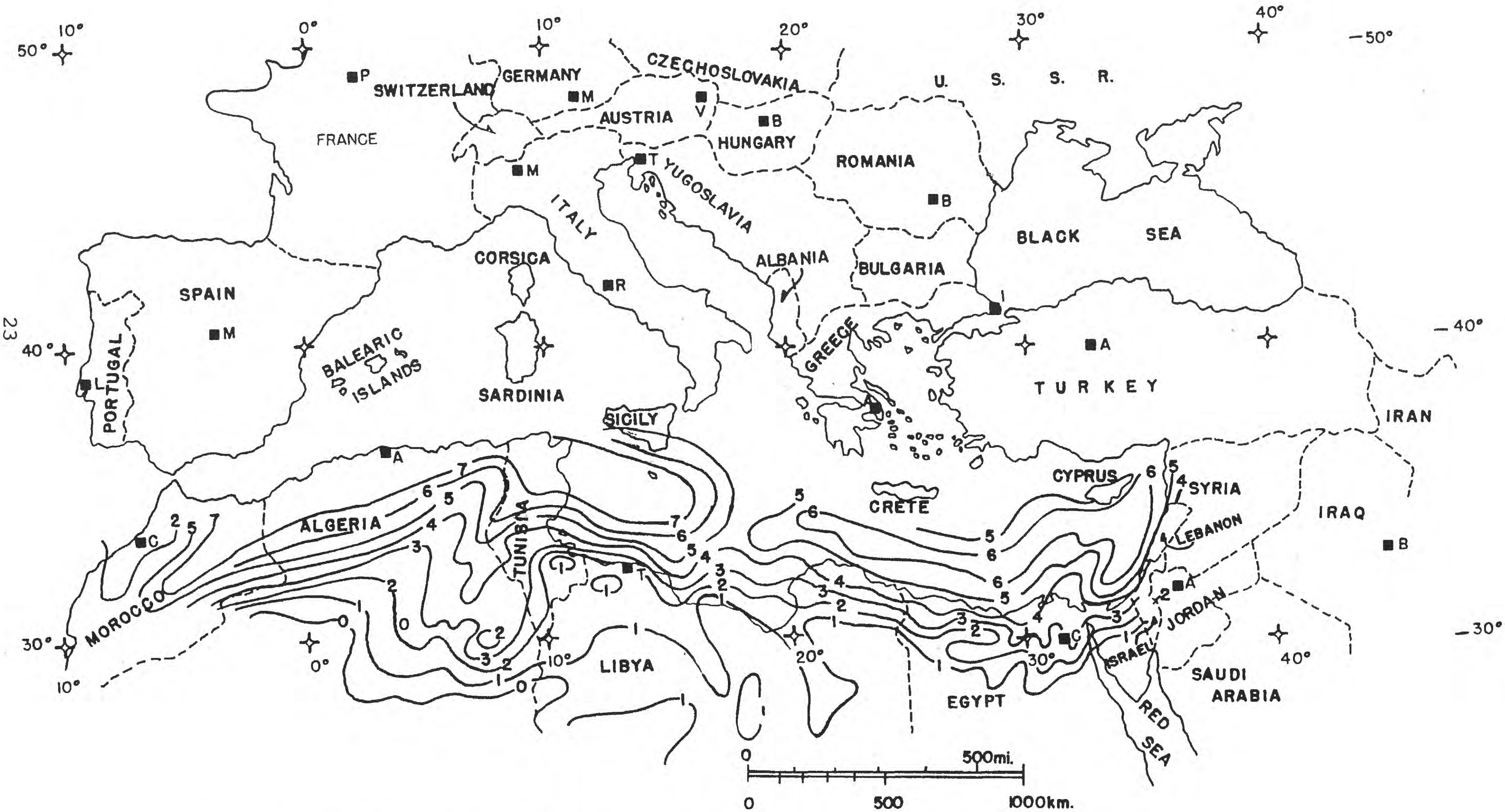


Figure 17. Approximate thickness in thousands of meters, Mesozoic rocks, partly restored where erosion has occurred, northern Africa and adjacent Mediterranean Sea. Compiled from numerous sources. Modified from Peterson (1985, 1986)

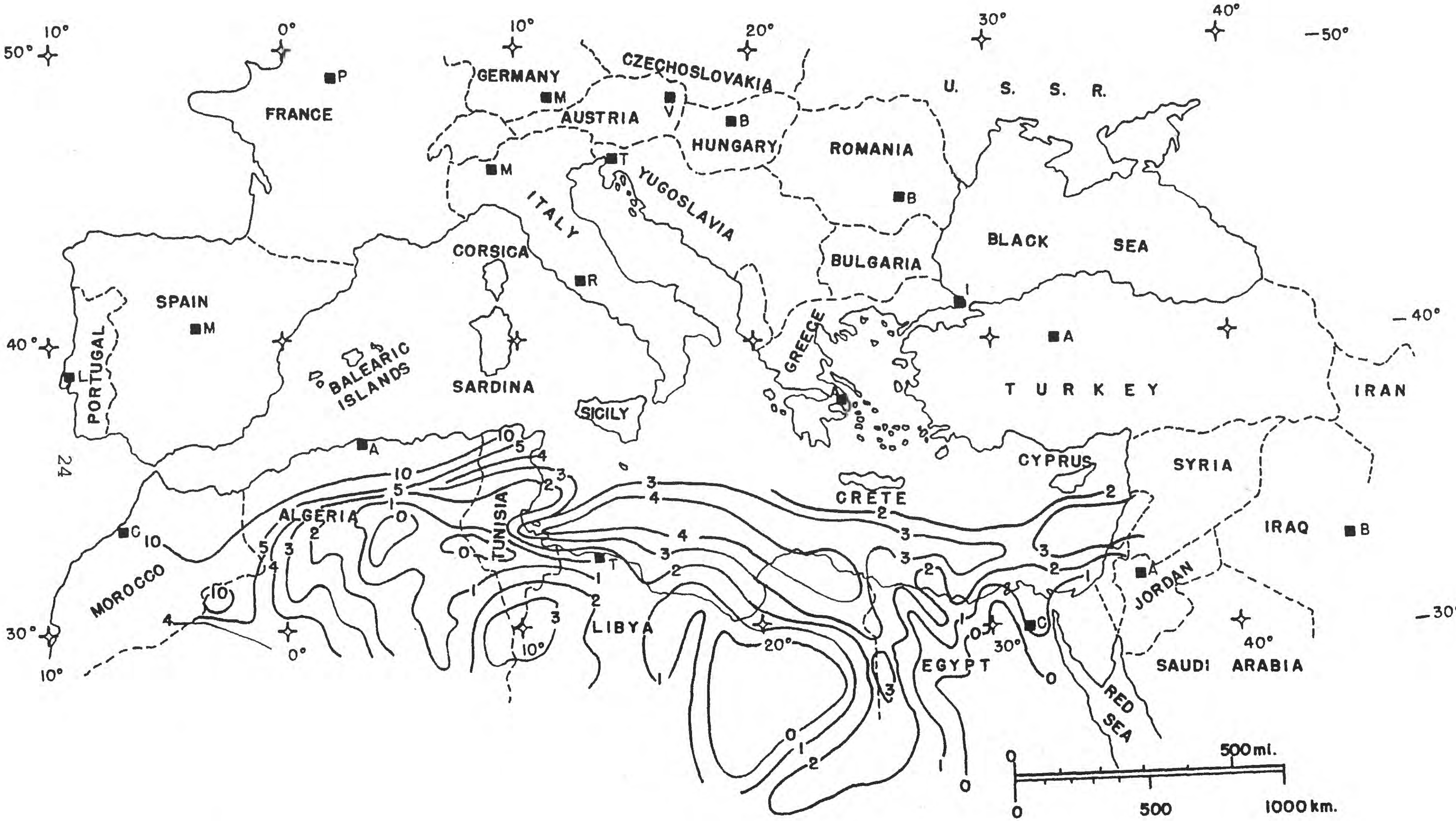


Figure 18. Approximate thickness in thousands of meters, Paleozoic rocks, partly restored where erosion has occurred, northern Africa and adjacent Mediterranean Sea. Compiled from numerous sources. Modified from Peterson (1985, 1986)

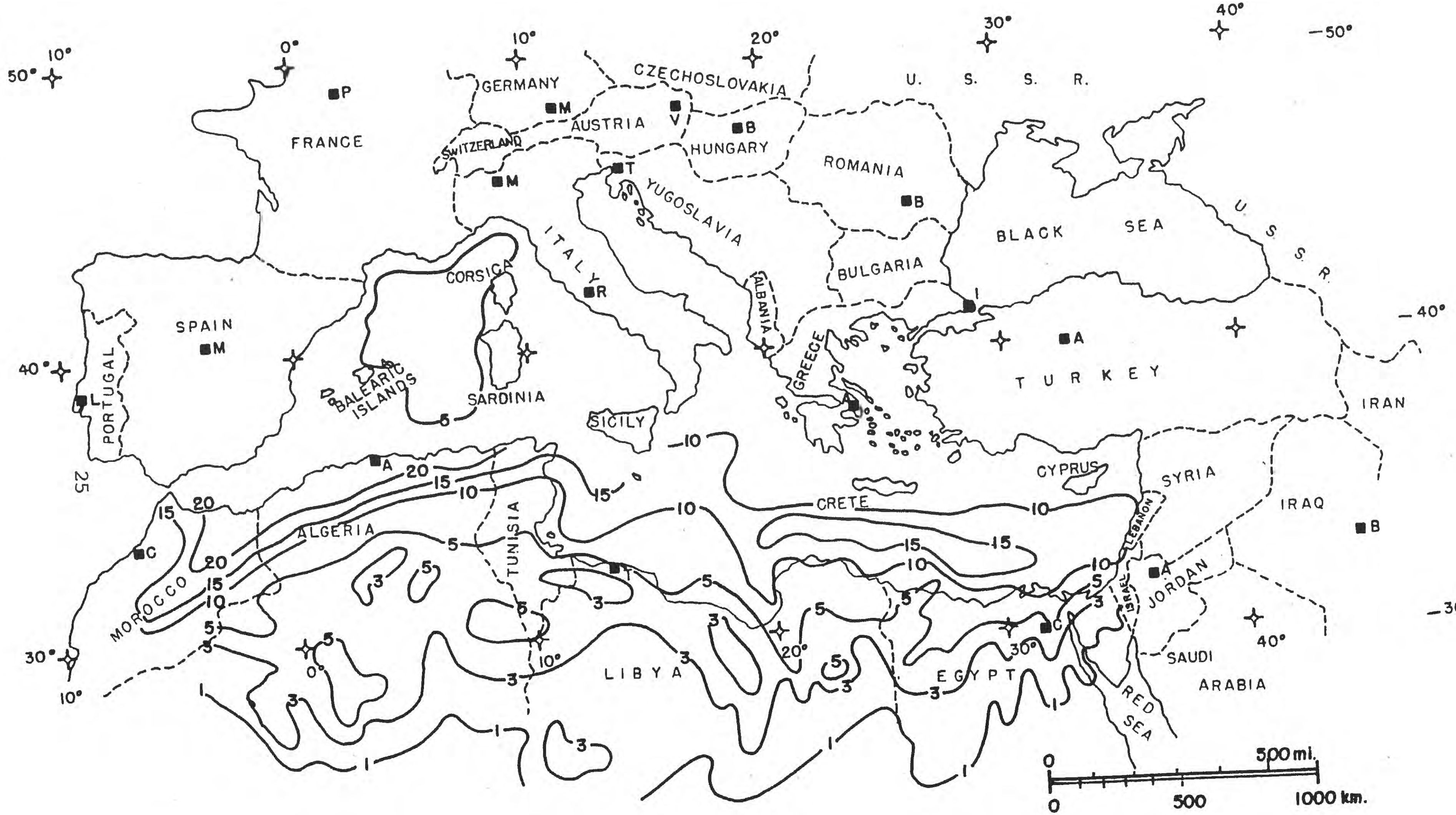


Figure 19. Approximate thickness in thousands of meters, sedimentary cover, partly restored where erosion has occurred, northern Africa and adjacent Mediterranean Sea. Compiled from numerous sources. Modified from Peterson (1985, 1986)

Southern Europe

The general organization of the Alpine chains in southern Europe is shown on figures 2 and 5-8.

Precambrian - In the Alpine region, Precambrian rocks are highly metamorphosed and intruded by Precambrian and younger igneous rocks.

Paleozoic - The Caledonian orogeny mainly affected northern and northwestern Europe and created the Caledonian mountain ranges in the Fenno-Scandian region. To the south, the subsiding "European geosyncline" received a substantial thickness of marine and continental sediments, primarily sourced from the Fenno-Scandian region. At the close of the Caledonian orogeny, in late Silurian time, the Old Red continent of northwestern Europe was formed and was bordered on the south by the subsiding Variscan geosyncline, which occupied essentially all of south-central and southern Europe and extended into what is now northern Africa.

The Hercynian (Variscan) orogeny extended through Carboniferous and Permian time. Folding and mountain building occurred throughout northern Europe, and granitic intrusions were emplaced in the region of the Italian Alps, southern Italy, Sardinia, and Corsica. This orogeny affected southwestern and central Europe and northwestern Africa. Activity occurred in the three main phases, at the Devonian-Carboniferous boundary and at the middle and upper parts of the Carboniferous. Most of the Mediterranean area at this time was occupied by the Variscan geosyncline, mainly in the general Mediterranean region.

Mesozoic - The Triassic and Jurassic represented a relatively quiet period between the close of the Variscan and the beginning of the Alpine orogenic events. Much of northern and central Europe and parts of southwestern Europe were emergent at this time, with the main geosynclinal area occupying the central and eastern Mediterranean region. The early phases of Alpine orogeny began in the central Alps, the Balkans, and the Hellenides (fig. 6). During the Late Triassic and Jurassic, with the opening of Tethys, the main geosynclinal area occupied most of the Mediterranean region.

Widespread Alpine folding began in southern Europe during the Cretaceous (fig. 6). Orogenic movements occurred at the close of the Early Cretaceous in the eastern Alps region and throughout the Alpine region at the close of the Late Cretaceous resulting in the deposition of widespread flysch in the associated troughs.

Cenozoic - After the latest phase of Cretaceous orogeny (Laramide), the main Alpine chains were in place. Activity continued into the early Paleogene, particularly in the Apennines, and a major orogenic phase occurred near the close of the Eocene. This event particularly affected the Swiss Alps, the eastern Alps, and the Pyrenees in Spain and France, and resulted in extensive deposition of thick molasse facies in the foredeep troughs. At the close of the Miocene, the final major phase of Alpine orogeny occurred.

Structural Evolution of the Mediterranean

The evolution of the western Tethys and the Mediterranean region took place in a sequence of several progressive events (Dercourt, 1986; Howell, 1989; Argyreadis and others, 1980; Laubscher and Bernoulli, 1978; Biju-Duval and others, 1979; Ager, 1980; Reconetal, 1986; Bernoulli and Lemoine, 1980; Argenio, 1980; Savosten and others, 1986; Rehault and others, 1985):

1. *Late Triassic-Early Jurassic* - An early extensional phase occurred in the Sicily-Apulia region where rifted basins formed, including the Nova-Streppenosa source rock rifts.

2. *Late Jurassic and Cretaceous* - Transform faulting occurred, related to the initial spreading and post-Pangea opening of the North Atlantic. Numerous pull-apart basins formed, allowing the North Atlantic seaway to connect with the Tethys ocean. A main period of opening in mid-Cretaceous time was accompanied by uplift and magmatism in the Saharan and Pelagian regions. This was the third crustal stretching phase. This event was accompanied by erosion with continental clastics shed to the north across the Saharan platform as part of the "Nubian" sandstone complex and related units.

3. *Late Cretaceous-Paleocene* - A closing stage occurred, related to opening of the South Atlantic and consequent counterclockwise rotation of Africa resulted in an increased convergence rate from west to east. Plate convergence and collision occurred along the Alpine folded belt, the main beginning of the Alpine orogeny, with eastward subduction of the European plate by the North African plate. Compression and shearing occurred along the northeast-southwest Syrian arc (fig. 1) in northern Egypt and the northern Middle East region. At this time, the early phase of Apennine orogeny occurred in Italy, and the paleotethys ocean closed with welding of the Cimmerian collage of continental blocks to the south margin of Eurasia between Indochina and Turkey.

4. *Eocene* - The Adriatic African promontory collided with and was underthrust by, the European plate. In middle Eocene time, India collided with Asia and effectively closed the neotethys sea. By late Eocene time, the main collision between Africa and Eurasia began. At this time, domal uplift occurred in the western Mediterranean region.

5. *Oligocene-early Miocene* - Crustal stretching and thinning associated with a rifting stage occurred (the west European rifting event). Subduction took place beneath the Hellenic Arc and a drifting stage proceeded in the western area. The initial rifting stage in formation of the western Mediterranean basins occurred. Corsica and Sardinia and the Balearic Islands rotated counterclockwise away from France and Spain, and collision occurred between Corsica and Apulia.

6. *Middle and upper Miocene* - The Calabrian and Hellenic arcs took their final form and active extension occurred in the Aegean Sea region forming the Neogene basins. The Provence, Tyrrhenian and other western basins opened and Morocco rotated

away from Spain to form the Algerian basin. These movements resulted in upbuilding in the Apennine and the North African ranges. In latest Miocene time (Messinian), regression and erosion of the Mediterranean margins occurred with evaporite deposition throughout most of the Mediterranean (Messinian evaporites), the Suez and Red Sea basins, following Mid-Miocene evaporite deposition in the Zagros, the foredeep of Iran.

7. *Pliocene* - This was a post-evaporitic stage, with overlap and transgression of the Mediterranean margins. Rifting and active subsidence occurred in the western Mediterranean and westward subduction of Apulia beneath the Calabrian Arc took place.

8. *Holocene* - The Mediterranean is currently undergoing compression between the European and African plates. Complete closure may occur in about 30-40 million years.

Summary of Stratigraphy and Sedimentary Facies

__North Africa__

Reviews on the stratigraphy and sedimentary facies of North Africa and adjacent areas include those of Conant and Goudarzi (1967); Klitzsch (1968); Bartov and others (1972); Bishop (1975); Bein and Gvirtzman (1977); Beydoun (1977); El Shazly (1977); Burollet and others (1978); Salaj (1978); Nathan (1978); Mart and Gai (1982); Sall and Bein (1982); Dixon and Robertson (1974); Peterson (1985, 1986); Canerot and others (1986); Hirsch and Picard (1988); Kuhnt and others (1990); and May (1991).

Paleozoic - Marine transgressions from the north and northwest have periodically covered the north African (Saharan) platform since Cambrian time. A relatively complete section of early and middle Paleozoic rocks, primarily marine and continental clastics, is more than 3,000 m (10,000 ft) thick in northern Libya, Tunisia, and north central and northeastern Algeria (figs. 11-19). A great thickness of lower Paleozoic argillaceous rocks is present in the High Atlas region of Morocco. Lower Paleozoic (Cambrian-Ordovician) rocks, primarily continental clastics derived from shield areas to the south, intertongue with marine sandstone, siltstone and shale to the north. Ordovician tillites are recognized in Algeria and other areas of northwestern Africa. Middle Paleozoic rocks (Silurian and Devonian) are marginal marine or continental sandstone, siltstone and shale which become more marine to the north and northwest. Ordovician sandstone is unconformably overlain by widespread Early Silurian black to dark gray organic-rich graptolitic shales which are a main source for hydrocarbons in Algeria, Tunisia and northwestern Libya (figs. 11, 12). These organic-rich beds were deposited during the early phase of Silurian transgression. An overlying regressive marine sandstone unit of Silurian age is present in most of northern Africa except where removed by Hercynian erosion. Devonian rocks are marginal marine or continental sandstone, siltstone and shale which become more marine to the north and northwest where carbonate beds intertongue with the clastic beds. Devonian reefs are reported in western Algeria and southwestern Morocco (Hazzard, 1961). Devonian rocks are absent because of Hercynian erosion in much of north central and northeastern Algeria, northern Libya and most of Egypt.

Upper Paleozoic (Carboniferous and Permian) rocks are shallow water marine and nonmarine transgressive sandstone, siltstone and shale, which may be unconformable on Devonian rocks in southern Libya and Algeria, but are probably conformable in northern Algeria. Shales in the lower part of this sequence are organic-rich in places. The Carboniferous marine transgression spread across North Africa from the west and northwest, with erosion occurring on several of the main uplifts at this time. Carbonate and some evaporites and redbeds are present in central and western Algeria and southwestern Libya. Carboniferous coal beds are present in western Morocco. Permian rocks are absent or very thin on almost all of the Sahara platform as a result of prolonged Hercynian emergence and erosion. However, a great thickness of fine clastic and carbonate facies, as much as 4,000 m (13,000 ft) thick, including reefal buildups, is present in southeastern Tunisia and northwestern Libya, including the offshore area of the southern part of the Pelagian platform (Bishop, 1975; Burollet and others, 1978). Thick clastic beds of Permian age are also reported in the Atlas region of northern Algeria and Morocco.

Mesozoic - After Hercynian emergence, Mesozoic transgression from the north (Tethys) accompanied widespread deposition of marginal marine and continental clastic beds in northern and central Algeria, which unconformably overlie rocks ranging in age from Carboniferous to Cambrian or Precambrian. These rocks include productive oil and gas reservoirs in Algeria and Tunisia (figs. 11, 12). Thin Triassic clastic rocks also are present in northern Egypt and Israel. In the western Sahara, the basal Triassic sandstone and redbed unit grades upward to marine shale, dolomite, anhydrite and salt, the upper part of which is of Lower Jurassic age. Salt beds are particularly thick in Triassic grabens in the Pelagian region. These beds are the main regional seal for important oil and gas fields in Algeria, northwestern Libya and southern Tunisia.

The Jurassic salt and anhydrite beds grade upward into Middle and Upper Jurassic marine fine clastic and limestone deposits in Morocco, northern Algeria and Tunisia and on the offshore Pelagian platform. The thick Middle and Upper Jurassic carbonate facies which represents the first widespread transgression of the Tethyan sea, is present along the entire north African platform margin, including the Moroccan and Algerian Atlas, Tunisia, northern Algeria and northern Egypt. The shelf margin carbonate facies grades southward into nearshore marine and continental clastic facies.

Periodic transgressions of the Tethyan sea continued across the north African platform during the Cretaceous, becoming increasingly more widespread with time. Lower Cretaceous beds are primarily continental sandstone to the south (part of the "Nubian" sandstone facies), grading northward to nearshore marine clastics containing marine limestone units. During Late Cretaceous time, the northern part of the Sahara platform continued to tilt northward into the Mediterranean Tethys region, accompanied by deposition of deep water clastics to the north. North-northwest to south-southeast rifting occurred at this time, forming the Sirte basin and probably affecting parts of northern Egypt. Latest Cretaceous rocks are dominated by widespread thick Tethyan shelf carbonate, including chalk, and offshore marine facies to the north, which are intertongued with nearshore marine and continental sandstone facies to the south (figs. 11-15).

Cenozoic - In the north central and northeastern parts of the Saharan platform, the Tethys marine transgression continued into the early Tertiary and extended as far south as southern Egypt and southern Libya. Paleocene and Eocene marine carbonate and shale are as much as 2,000-3,000 m (6,500-10,000 ft) thick in northeastern Tunisia, the Pelagian platform and northern Libya (figs. 12, 14). In these areas, this facies contains carbonate mound or bank buildups, including the lower Eocene nummulites reservoir facies. In northern Egypt, equivalent beds are thinner and more sandy. The western part of the platform was apparently emergent much of this time, where only a thin and discontinuous section of clastic beds is present. The Atlas Range area underwent a series of strong orogenic movements at this time (Stets and Wurster, 1982). Coarse clastic beds were deposited in some downwarped areas, and cherty limestone, marl, phosphatic beds and sandstones formed in the trough areas of the Atlas region. In middle and late Eocene time, folding, uplift, and erosion dominated in these areas, as well as farther west in the Rif region. Arcuate structures, open to the north, formed, and the Kabylia zone was overthrust to the south. Tectonic activity diminished in the Oligocene, but coarse orogenic clastics were deposited in lower areas. Thick shale deposits (Numidian flysch) formed north of the Tellian Atlas in northeastern Algeria, northern Tunisia, and northern Sicily. The Oligocene was a time of uplift in much of the eastern Sahara and Egypt. In the Sirte basin, however, Oligocene rocks are primarily marine shale.

The final southward transgression from the Mediterranean region took place during the early Miocene when marine carbonate and shale beds were deposited and prograded across eastern Tunisia, the Pelagian platform, Sirte basin, Cyrenaica platform, western Desert basin, and in the Suez Graben where reef beds of this age are significant oil reservoirs. During the middle and late Miocene, widespread regression of the Tethys sea occurred, related to Alpine orogeny in the Mediterranean region. Continental and nearshore marine deposits are prevalent in beds of this age and thick deposits of gypsum and salt were deposited in the Suez Graben, the Red Sea, and the central Mediterranean (fig. 4). The Sahara platform was a region of general uplift during the Pliocene; deposits of this age are relatively thin or absent over most of the platform. Continental clastic deposits are present in parts of Algeria and southern Tunisia, and marine Pliocene beds are present in Tunisia, in offshore areas of the Pelagian platform, and in northern Libya and northern Egypt. According to El Shazly (1977), at this time the proto-Nile River formed in the Nile graben, a fracture system more or less parallel to the Red Sea graben. Post-Miocene sediments several thousand meters thick in the Nile Delta north of Cairo consist of shallow marine sand and shale that become increasingly sandy and deltaic upward as the modern delta grew (fig. 15).

During Quaternary time, the Mediterranean shoreline in North Africa regressed slightly to the north, and a veneer of dune, small lake, and alluvial sand and fine clastic units was deposited on the Sahara platform. The Nile Delta accumulated as much as 800 m (2,500 ft) of sand and clay. Some oolitic carbonate beds were deposited along the Mediterranean coast, and several hundred meters of marine clastic deposits accumulated on the Pelagian platform.

Southern Europe

Reviews on the stratigraphy of southern Europe include those of Brinkmann (1960); Squyres (1975); Celet (1978); Rios (1978); Ager (1980); Boriani and others (1989); and Zappaterra (1990).

Cambrian rocks in southern Europe are primarily clastics composed of sandstones and shales with minor carbonates. Much of the section is difficult to recognize because of metamorphism. Ordovician rocks are continental and marine clastics to the north and become interbedded with shallow marine limestones in the Austrian Alps. Silurian rocks in most of southern Europe are chiefly limestone and shaly facies. Dark, graptolitic shales dominate in the lower part of the sequence, grading to widespread limestone in the Late Silurian. Organogenic carbonates, including widespread reef buildups, characterize the Devonian in most areas, with shale and graywacke facies present in some areas. Clastics in the form of conglomerates, graywackes, sandstones, and shale, derived from the Variscan mountain chains to the north, are dominant in the lower Carboniferous, interbedded with marine fossiliferous limestone in the eastern Alps. The upper Carboniferous is primarily conglomerate, sandstone, and shale in the lower part with interbedded fossiliferous limestone in the upper part. Coaly beds are common, particularly in the eastern Alpine region. Lower Permian sedimentary rocks are mainly clastics to the west, in part deposited in continental basins associated with the late phases of Variscan orogeny. Farther east, marine clastics and interbedded marine fossiliferous limestones become dominant. The clastic facies grades upward to widespread Upper Permian marine limestone and dolomite in the central Alpine region. In northern Italy, Permian rocks are characterized by conglomerate and redbeds, overlain by fine clastics, gypsum and limestone. Conglomerate and redbeds of probable Permian age are reported in parts of Greece. Beginning in the Triassic, the Mediterranean was in the Tethyan (equatorial) latitudes where optimum conditions for carbonate-evaporite associations prevailed. Widespread redbeds and evaporites characterize the lower part of the Triassic sequence, overlain by carbonates, including the massive reefal buildups, which are present in most of southern Europe bordering the Mediterranean. In the northeastern Alpine region, redbeds and evaporites, including salt, underlie reefal limestones. Thick Upper Triassic organic-rich, shaly beds are present locally in rift basins in parts of the area, particularly in Italy and Sicily. Jurassic sedimentary rocks are generally dominated by marine clastics to the north with crinoidal limestones and some coral reefs to the south. The Jurassic section in southern Europe adjacent to the Mediterranean is dominated by pelagic carbonate rocks. Locally, evaporites and redbeds are present. In general, most of the Cretaceous in southern Europe is characterized by widespread carbonate facies in the western Mediterranean area including rudist reef buildups. Coarse clastics and flysch facies with some coaly beds is present to the east, associated with mountain building, which began early in the Cretaceous in the northeastern Alpine region. Early Tertiary rocks are primarily flysch related to continuation of Alpine folding and thrusting, which began in the Cretaceous and lasted until the close of the Eocene. Carbonate facies are developed locally. Post-Eocene (Oligocene and Miocene) sedimentary facies are dominated by the development of the Alpine molasse complex of continental and marine conglomerate, sandstone, shale and marl. Pliocene and Quaternary sedimentary rocks are mainly nonmarine beds adjacent to Alpine mountain chains, except for trough areas such as the Po and Adriatic basins adjacent to the Mediterranean where continental sedimentary rocks are interbedded with marine clastics.

Alpine Cycles

Regional sedimentary sequences, now located in Italy, were deposited mostly on the African continental margin and the adjacent spreading Mediterranean (Pieri and Mattavelli, 1988). These authors describe several Alpine cycles that affected the structure and stratigraphy of Italy and the adjacent region:

- *Middle Permian to Late Triassic.* This was the beginning of the Alpine cycle, with deposition of continental clastics and local tectono-sedimentary conditions for emergent terranes, lagoons, terrigenous infill of subsiding basins, and volcanic episodes. Local conditions existed for euxinic deposition favorable for petroleum source rock facies. Segmentation and rifting of the carbonate shelf occurred in the Late Triassic.

- *Jurassic.* Regional oceanic spreading and extensional tectonics resulted in development of new basinal areas with the Jurassic opening of the Mediterranean Tethys ocean. The net result was a complex system of carbonate shelves and basins. By the end of the Jurassic, three dominant types of tectonic-sedimentary environments were present:

  a) Oceanic, with deposition of radiolarites and basinal carbonates above oceanic crust.

  b) Basinal, with foundering of the continental margin and deposition of pelagic sediments.

  c) Wide shelves, with deposition of shallow marine carbonates.

- *Cretaceous*. Compressive phases developed, with primarily clastic sedimentation in the oceanic realms and carbonate sedimentation in the continental margin areas. Organic-rich units and intervals of karst development occurred on the shallow marine shelves. Late in the Cretaceous, flysch derived from the Alpine orogenic belt became dominant.

- *Late Cretaceous to Eocene.* Subduction of oceanic crust was completed, and oceanic sequences were folded and thrust onto the European continental margin, forming the neo-Alpine chain, including the younger Apennine chains.

- *Oligocene-Miocene.* Deposition of Apennine flysch occurred, with turbidites sourced from the growing Alpine and early Apennine chains, and the Numidian flysch in Sicily and southern Italy sourced from the African craton.

- *Late Miocene.* Emergence of the shelf areas occurred, accompanied by deposition of thick evaporites in the deeper Mediterranean areas and gypsiferous limestone, gypsum, and clastics on the Italian peninsula and Sicily.

- *Post-evaporite Miocene and Pliocene.* Intense tectonic activity in the southern Alps and Apennine chains occurred, accompanied by deposition of predominantly marine sandstone and shale, as much as 7 km (22,000 ft) thick in the Po basin of northern Italy. The modern Apennine chain was in place by the end of the Miocene along with an extensive foredeep to the east in the Adriatic region.

PETROLEUM GEOLOGY AND RESOURCE ASSESSMENT

Introduction

The resource assessment of this province was conducted by a resource appraisal team of the U.S. Geological Survey (USGS) World Energy Resource Assessment program, following standard procedures developed since 1974 for analysis of petroleum resources, as described below. The technique, briefly, requires an in-depth geologic study of the particular province, with special attention to the factors controlling the genesis, occurrence, quality, and quantity of the petroleum resource. Critical elements of the investigation are standardized by the preparation of data forms for each province, which includes determination of specific hydrocarbon aspects as well as identification of basin analogs for comparison purposes. In addition, finding-rate histories and projections are constructed where possible. From these data and analyses, various analytical techniques are used as a means to calculate a set of resource numbers. Not considered in this assessment are resources of heavy-oil deposits, tar deposits, and oil shales, as well as gas in low-permeability reservoirs, coal, geopressured shales and brines, and in natural-gas hydrates. Likewise, specific economic considerations are not factored into the resource assessment itself.

The assessment process itself is subjective; the results of the geologic investigation and of the resource calculations are deliberated by the team of assessment specialists who make their personal estimates, conditional upon recoverable resources being present. Initial assessments are made for each province as follows:

(1) A low resource estimate approximately corresponding to a 95-percent probability of more than that amount; this estimate is the 95th fractile (F_{95}).

(2) A high resource estimate approximately corresponding to a 5-percent probability of more than that amount.

(3) A modal ("most likely") estimate of the quantity of resource associated with the greatest likelihood of occurrence and approximately corresponding to a statistically modal value.

The individual estimates are then posted and averaged, and the results are debated from the perspective of the personal experiences of the individual assessors; a second and third iteration of the procedure may follow, depending on consensus. If no commercial oil has been heretofore discovered in the province, then a marginal probability is subjectively assessed that reflects the probability that any commercial oil will ever be discovered.

Works on the petroleum potential of the Mediterranean basins include those of Johnson and others (1971); Byramjee and others (1975); Burollet (1980, 1984); Abdine (1981); Watson (1982); Spiro and others (1983); Schramm and Livraga (1984); Sestini and Flores (1984); Pieri and Mattavelli (1986); Bein and Sofer (1987); Bartling and Gips (1988); Chanliau and Bruneton (1988); Mattavelli and Novelli (1990); and Zappaterra (1990a, b).

The total area of the Mediterranean assessment province is approximately 2,500,000 km^2 (1,000,000 mi^2). Approximately one-half or 1,200,000 km^2 (465,000 mi^2) is occupied by water depths greater than 2,000 m (6,500 ft) (figs. 1,2). Approximately 20 percent of the total area (500,000 km^2 or 195,000 mi^2) is shelf area of less than 200 m (650 ft) water depths (Villa, 1988). The total shelf area of the Mediterranean thus equals more than the total area of either Texas or France. Except for the Adriatic Sea, the Pelagian shelf, and the Ebro delta area (fig. 33), the shelf areas have received only minimal exploratory drilling (table 1).

This report does not include the offshore Nile Delta or the offshore Pelagian platform areas, which were assessed earlier (Peterson, 1985, 1986). These assessment reports included the onshore basins of northern Africa and the offshore shelf areas out to 1,000 ft (300 m) water depth.

Some exploration of the marine Mediterranean has taken place during the past 30 years, particularly on the shelves in shallower water areas offshore Spain, Italy, Tunisia, Libya, Egypt, and Greece (table 1). Existing offshore oil and gas fields in the Mediterranean province are mainly in the Adriatic Sea, the Pelagian shelf offshore Tunisia, and offshore Libya (fig. 21). Several small gas fields have been found in the Nile Delta and two oil fields offshore Spain. Major oil and gas reserves are present onshore adjacent to the Mediterranean Sea in Algeria, Tunisia, Libya, Egypt, and Italy (fig. 21). Original oil and gas reserves (cumulative production plus identified reserves) of the North Africa countries total approximately 80 BBO (billion barrels oil) and 190 TCF (trillion cubic feet) gas (tables 2, 3) (Masters and others, 1991). USGS assessment of undiscovered hydrocarbon resources in these countries is approximately 11.5 BBO and 70 TCF gas, giving ultimate recoverable resources of approximately 99 BBO and 287

EXPLORATORY WELLS DRILLED IN MEDITERRANEAN DEEP WATER AREAS

In the 35 wells drilled in Mediterranean deep water areas, 7 are oil wells and 4 were reported as gas wells.

Country	Name	Year	Water Depth	Total Depth	Remarks
France	GLP-1	1982	1,700 m	3,607 m	Dry
	GLP-2	1983	1,250 m	5,354 m	Dry
Italy	Rovesti	1978	955 m	3,347 m	Dry
	Federica	1979	360 m	3,712 m	Dry
	Aquila	1981	827 m	4,246 m	Oil
	Falco	1981		2,839 m	Gas
		1981		2,767 m	Dry
	Fosca	1981		2,398 m	Dry
	Merlo	1982		2,307 m	Dry
	Grifone	1982	341 m	3,160 m	Dry
	Floriana	1982	219 m	2,625 m	Dry
Spain	Rapita	1975	614 m	9,461 m	Dry
	Montanazo D1	1977	470 m	9,190 m	Oil
	Montanazo D2	1978	746 m	2,741 m	Oil
	Montanazo C1	1978	673 m	2,891 m	Oil
	Montanazo D3	1981	756 m	2,864 m	Dry
Malta	Gozo 1	1982	415 m	3,287 m	susp.
Greece	W. Katakolon	1982		3,218 m	Oil and gas
	S. Katakolon	1982	220 m	2,963 m	Oil shows
Yugoslavia	Juzni Jadran 3		300 m	4,000 m	Dry
Algeria	Habibas	1977	935 m	4,500 m	Dry
Libya	E1 NC 41	1977	217 m	2,865 m	Oil
	A1 NC 35A	1977		4,905 m	Dry
	F1 NC 41	1978		4,080 m	Gas
	F2 NC 41	1980	274 m	2,789 m	Gas
	D1 NC 35A	1983		3,352 m	Gas
	E1 NC 35A	1983		3,597 m	Oil
	F1 NC 35A	1984			
Egypt	NDO 1	1975	408 m	2,845 m	Dry
	NDO B1	1975	413 m	3,810 m	Dry
	Nab 1	1978	528 m	2,863 m	Gas shows
	GEBEL el BAHRI	1981		1,204 m	Dry
	G.el BAHR 1A	1981		1,219 m	Dry

Table 1. Exploratory wells drilled in Mediterranean deep water areas (greater than 200 m) as of 1984. From Burollet (1986)

Table 2.

NORTH AFRICA - HYDROCARBON RESOURCE ASSESSMENT 1/1/90

AREA	ORIGINAL RESERVES		UNDISCOVERED RESOURCES		ULTIMATE RESOURCES	
	Oil	Gas	Oil (Mode)	Gas (Mode)	Oil	Gas
Egypt	10 BB	13 TCF	2 BB	21 TCF	15.5 BB	43 TCF
Libya	47 BB	35 TCF	6 BB	18 TCF	55 BB	62 TCF
Algeria	19 BB	134 TCF	1.5 BB	19 TCF	22 BB	160 TCF
Tunisia	2 BB	5 TCF	2 BB	12 TCF	6 BB	22 TCF
TOTAL, NORTH AFRICA	78 BB	187 TCF	11.5 BB	70 TCF	99 BB	287 TCF

Table 2.--U.S. Geological Survey estimates of original reserves, undiscovered resources, and ultimate resources of conventional crude oil and natural gas, north African countries (from Masters and others, 1991). Original reserves shown are the sum of cumulative production and identified reserves as of 1/1/90.

Table 3.

MIDDLE EAST - HYDROCARBON RESOURCE ASSESSMENT 1/1/90

AREA	ORIGINAL RESERVES		UNDISCOVERED RESOURCES		ULTIMATE RESOURCES	
	Oil	Gas	Oil (Mode)	Gas (Mode)	Oil	Gas
Saudi Arabia	318 BB	198 TCF	50 BB	300 TCF	368 BB	498 TCF
Bahrain	1 BB	8.1 TCF	?	?	1+ BB	9+ TCF
Neutral Zone	19 BB	8 TCF	2 BB	2 TCF	21 BB	10 TCF
Kuwait	110 BB	54 TCF	2 BB	5 TCF	112 BB	59 TCF
Iraq	127 BB	113 TCF	35 BB	100 TCF	162 BB	213 TCF
Syria	3.3 BB	7 TCF	?	?	3.3+ BB	7+ TCF
Iran	111 BB	618 TCF	19 BB	450 TCF	130 BB	1,068 TCF
Qatar	8.5 BB	303 TCF	?	?	8.5+ BB	303+ TCF
United Arab Emirates	77 BB	192 TCF	5 BB	50 TCF	82 BB	242 TCF
Oman	10 BB	10.5 TCF	1 BB	8 TCF	11 BB	19 TCF
TOTAL, MIDDLE EAST	784 BB	1,512 TCF	114+ BB	915+ TCF	899+ BB	2,428+ TCF

Table 3.--U.S. Geological Survey estimates of original reserves, undiscovered resources, and ultimate resources of conventional crude oil and natural gas, Middle East countries (from Masters and others, 1991).

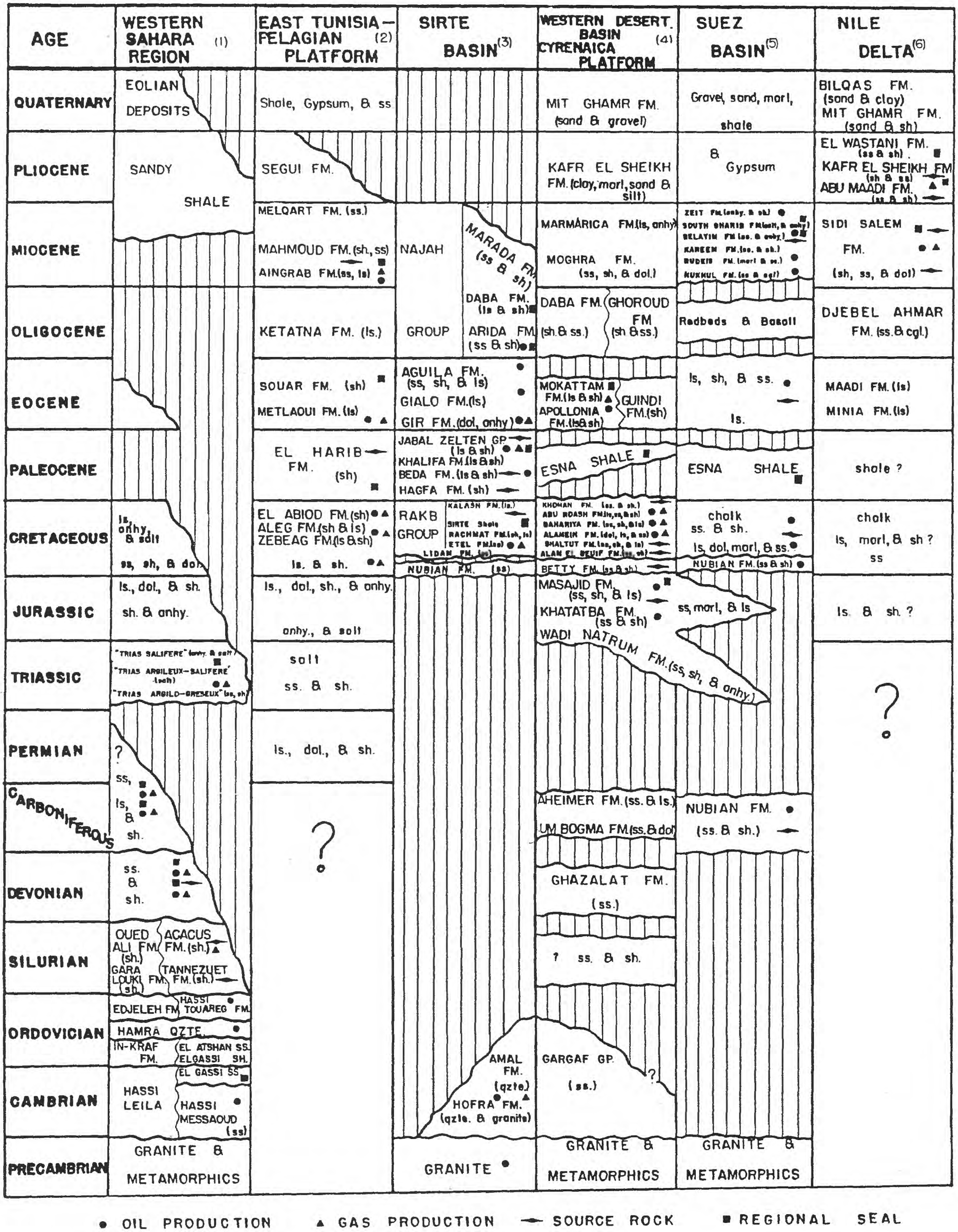


Figure 20. Generalized composite subsurface correlation chart, north-central and northeastern Africa

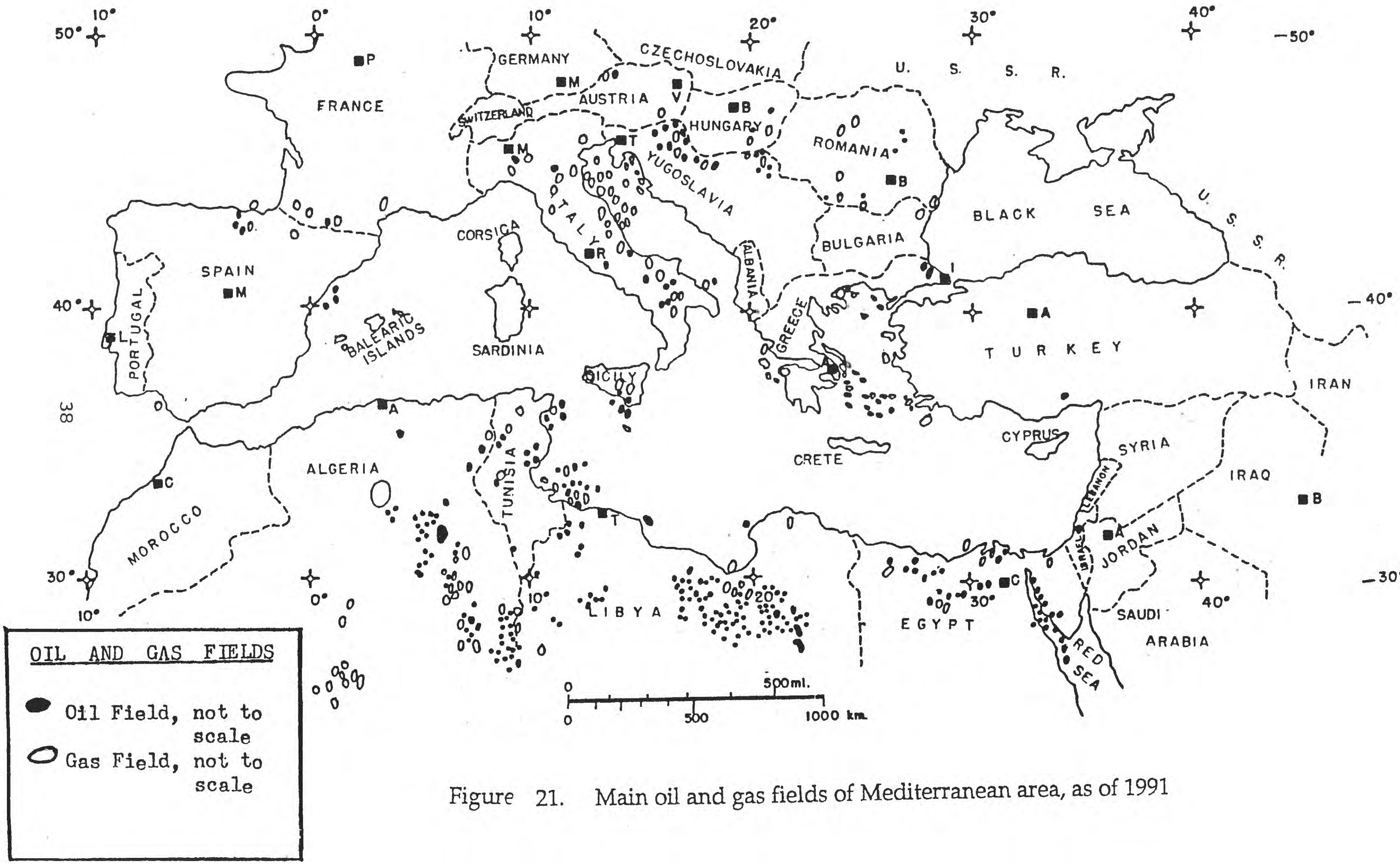


Figure 21. Main oil and gas fields of Mediterranean area, as of 1991

TCF gas. Deeper water areas of the Mediterranean have not yet received much attention, except for geophysical work. Considerable data have been accumulated in DSDP site drilling. During the 1980's, exploratory interest decreased significantly, in part related to a surplus of oil supply and decrease in price. In recent years, significant discoveries have been reported offshore Libya, the Bonni Field, offshore western Libya (fig. 21), reported to have 5 BBO in place, is the largest found in the offshore Mediterranean thus far. Another discovery offshore northeastern Libya, the Benghazi field, is reported to be a 765 MMB oil field.

The Mediterranean is bordered by continental margins of Jurassic and younger age. The floor is of Middle Jurassic and younger oceanic crust or of attenuated continental crust stretched in Middle Jurassic and later time, controlled by relative motions of Africa and Europe during the evolution of the Tethys realm and the opening of the Atlantic Ocean. A large offshore area is probably underlain by segments of the original Paleozoic, Mesozoic, and early Tertiary North African platform (figs. 16-19). Identified or potential source rocks for hydrocarbons are widespread in the Mediterranean region, ranging in age from Silurian through Cenozoic (fig. 22). Likewise, potential reservoirs and traps are probably present in many parts of the region.

The main problems of off-shelf exploration in the Mediterranean involve: 1) costly operations in deep water; 2) questionable quality and expense of seismic surveys in pre-evaporite beds; 3) the problem of source rock immaturity in younger beds and overmaturity in the older section; 4) the questionable distribution of suitable reservoir facies; and 5) the extremely complex structural configurations in pre-Neogene beds with resultant destruction of earlier-formed seals and traps.

For the purposes of assessment of oil and gas potential, the Mediterranean province is divided into three regions of approximately similar size: Western (Area A), Central (Area B), and Eastern (Area C) (figs. 1, 2). The Western Mediterranean region is approximately 800,000 km^2 (320,000 mi^2) and includes the Valencia-North Balearic - Provencal - Ligurian basins (figs. 11, 23), the Balearic Islands, Corsica and Sardinia, and the Algero-South Balearic basin. The Central Mediterranean is approximately 1,000,000 km^2 (385,000 mi^2) and includes the Tyrrhenian basin, Italy, Sicily, the Adriatic Sea basin, and the Ionian basin - Sirte shelf (figs. 12-14). The eastern Mediterranean is approximately 700,000 km^2 (270,000 mi^2) and includes Greece, Crete, Cyprus, Hellenic trench and Hellenic Arc, Mediterranean Ridge, Herodotus basin, Nile Cone, Cyprus basin, Cyprus Arc, and Levantine basin (fig. 15).

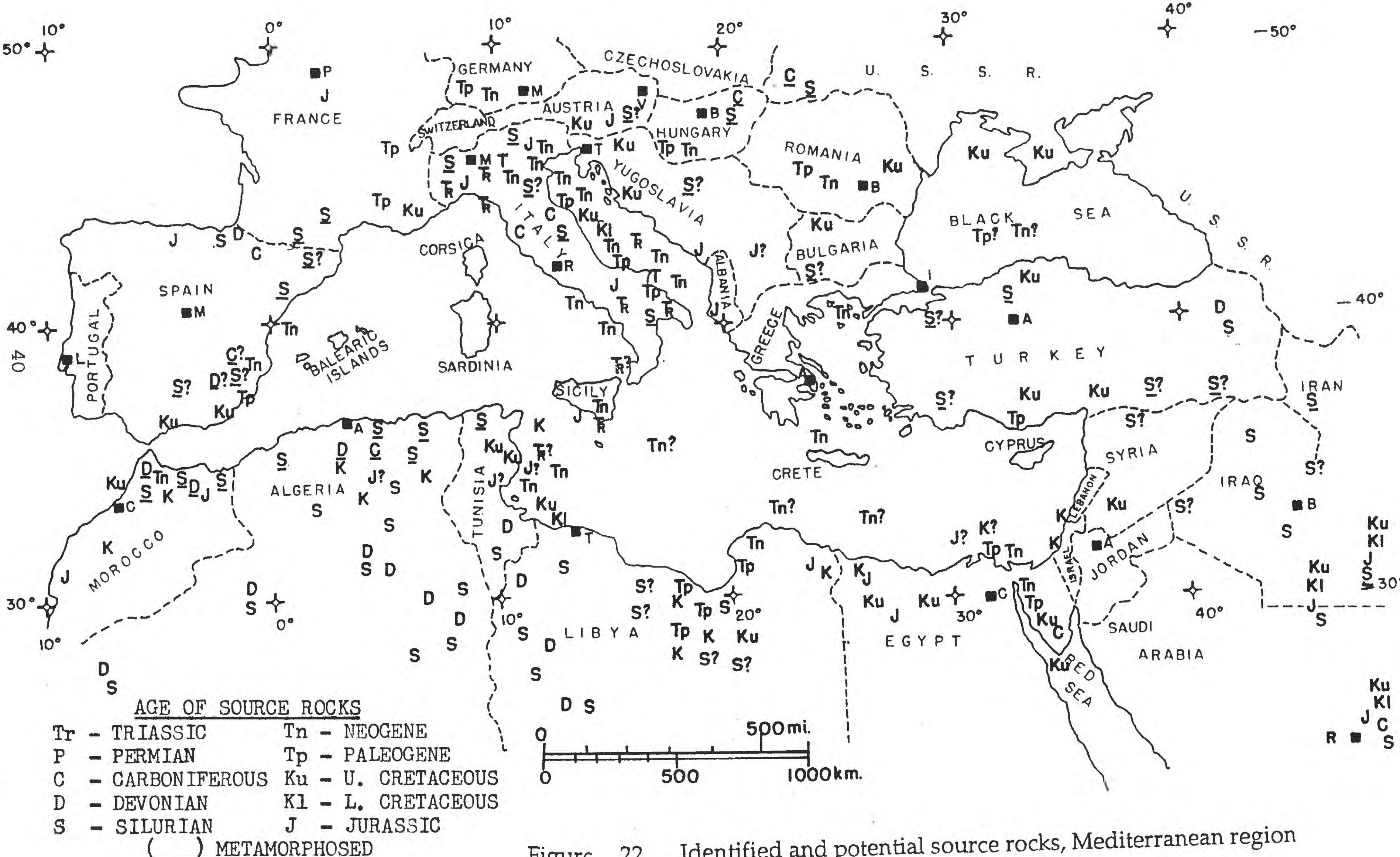
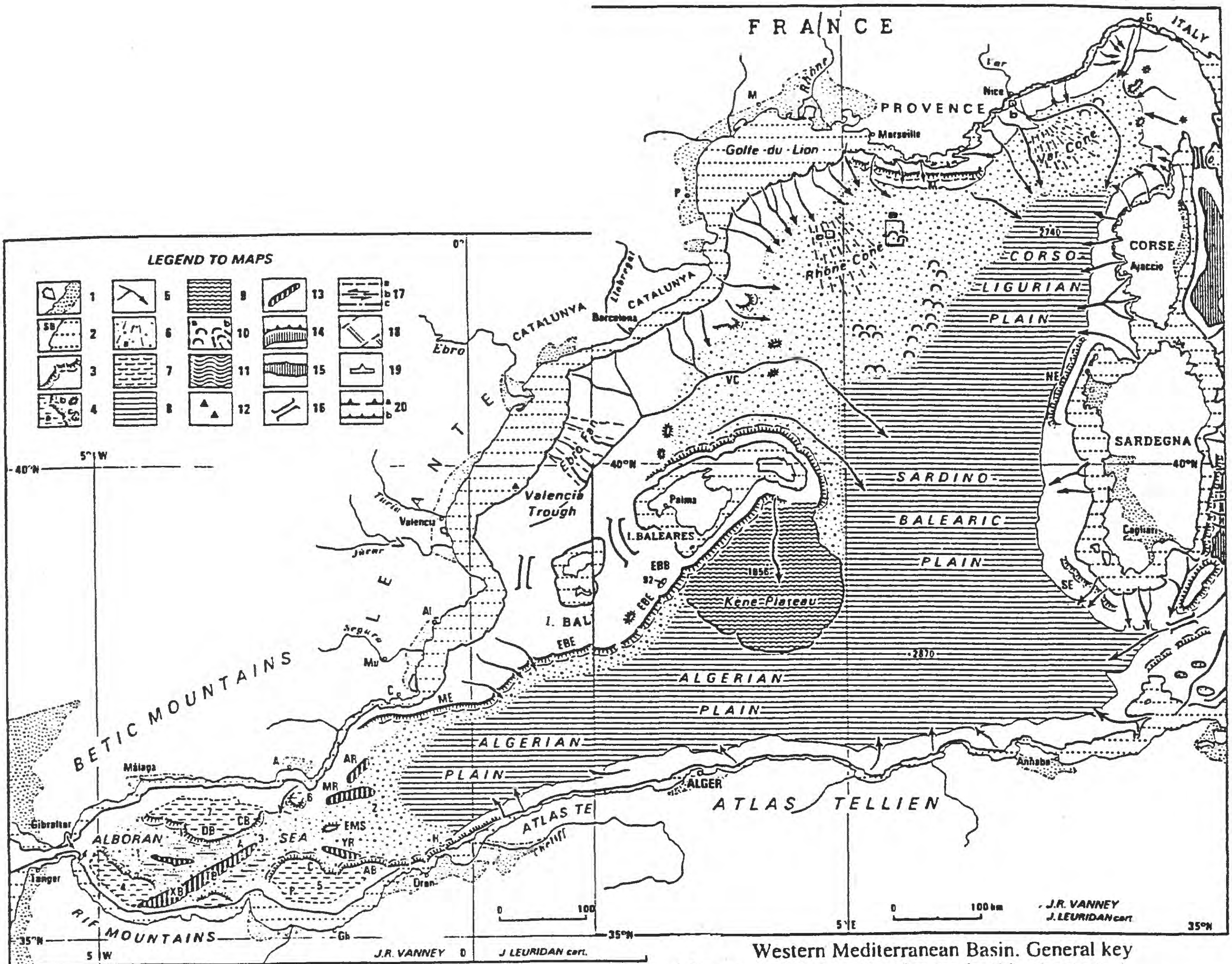


Figure 22. Identified and potential source rocks, Mediterranean region



Western Mediterranean Basin. General key (also applicable to other figures in this chapter): 1, coastal and lacustrine plain (arrow: retreating coastline); 2, continental-insular shelf (SB: shelfbreak); 3, escarpment; 4, marginal plateau (a) and seamount (b); 5, submarine canyon and sea valley; 6, continental rise and deep-sea fan (a); 7, erosional moat; 8, abyssal (bathyal) plain; 9, Kene Plateau; 10, halokinetic features: domes (a) and low diapirs (b); 11, Levant Platform; 12, volcanic features; 13, submarine ridge; 14, subduction trench; 15, faulted trough and ridge-basin complex; 16, submarine passage; 17, fracture, fault (a), shear zone (b), buried structure (c); 18, spreading axis; 19, monocline; 20, frontal boundary of compression features (a) and olistostrome (b). For Alboran Sea: 1, Western Alboran Basin; 2, Eastern Alboran Basin; 3, Alboran Ridge; 4, Ceuta Plateau; 5, Moulouya Plateau; 6, Avenzoar Plateau; 7, Andalucia Plateau. Abbreviations: A, Alboran Island; AB, Alidade Bk; AR, Abubacer Ridge; C, Cabliers Bk; CB, Chella Bk; CaB, Cabliers Bk; DB, Djibouti Bk; EBB, Emile-Baudot Bk; EBE, Emile-Baudot Escarpment; EMS, El Mansour Smt; H, Habibas Escarpment; M, Maures Escarpment; ME, Mazarron Escarpment; MR, Maimonide Ridge; NE, Nurra Escarpment; P, Les Provençaux Bk; SE, Sulcia Escarpment; TB, Tofiño Bk; VC, Valencia Cone; XB, Xauen Bk; YR, Yusuf Ridge. Towns: A, Almeria; Al, Alicante; C, Cartagena; G, Genova; Gh, Ghazaouet; M, Montpellier; Mu, Murcia; P, Perpignan. Detailed Sea-Beam maps of (a) Rhône salt dome (in Fig. 1.8), (b) prodelta of Var River (Fig. 1.9), and (c) channels of the Rhône deep-sea fan (Fig. 1.10).

Figure 23. Sea bottom features of the western Mediterranean basin. From Vanney and Gennesseaux (1985)

Western Mediterranean

The western Mediterranean region is surrounded in large part by the Alpine System (figs. 2, 6). Much of the region is part of a back-arc (Calabrian-Atlas arc) province related to convergence of the African and European plates since Cretaceous time. Continental crust is severely stretched and attenuated. Pre-Tertiary beds are absent or very deep and would be expected to be severely broken up in isolated blocks as remnants of stretching. Oceanic crust occupies much of the region (fig. 23, table 4). A general chronology of tectonic events affecting the offshore region of the western Mediterranean includes: 1) plate convergence during the Cretaceous, followed by collision between the European and African plates during Paleogene time; 2) southward underthrusting of the Africa and Apulian plate by the European plate during the Eocene, followed by deposition of flysch in the oceanic basins of the time; 3) rifting and volcanic activity between Oligocene and middle Miocene time, particularly in the North Balearic-Provencal basin area. After the main Alpine event, a northeast-southwest graben system developed, accompanied by marine transgression of the Mediterranean margins; 4) post-spreading subsidence and infilling of the northern part of the region with as much as 6-7 km (20-23,000 ft) of late Paleogene and Neogene generally fine-grained clastic and marly sediments; 5) a major phase of regression and erosion of the margins in late Miocene (Messinian) time with deposition of thick evaporites, including major amounts of salt, in the deeper basin areas (fig. 4); 6) post-evaporite overlap and transgression of the margins during Pliocene time; and 7) present-day compression between the European plate and the African plate, which is moving northwest (fig. 9).

Alboran - South Balearic - Algerian basin *(figs. 24, 25)*

The sedimentary cover in this basin is generally thin, consisting primarily of fine-grained Neogene clastics, but including turbidites, underlain by thick Messinian evaporites and an unknown thickness of pre-evaporite clastics overlying oceanic basement. Salt structures are present. There may be as much as 20 km (33,000 ft) of continental crust in the Alboran basin, adjacent to northwestern Africa and southeastern Spain. The main structural trends are northeast to east-northeast (fig. 25). The shelf area along the African coast is very narrow (figs. 1, 2).

<u>USGS Team Hydrocarbon Assessment Summary:</u>

Water Depth - mostly greater than 2,000 m (6,500 ft).

Reservoirs - Late Tertiary sandstones, turbidites; early Tertiary and Mesozoic carbonate and sandstone units, probably fractured

Source rocks - Early Tertiary and Mesozoic shale and carbonates; late Tertiary shale, possibly some biogenic source

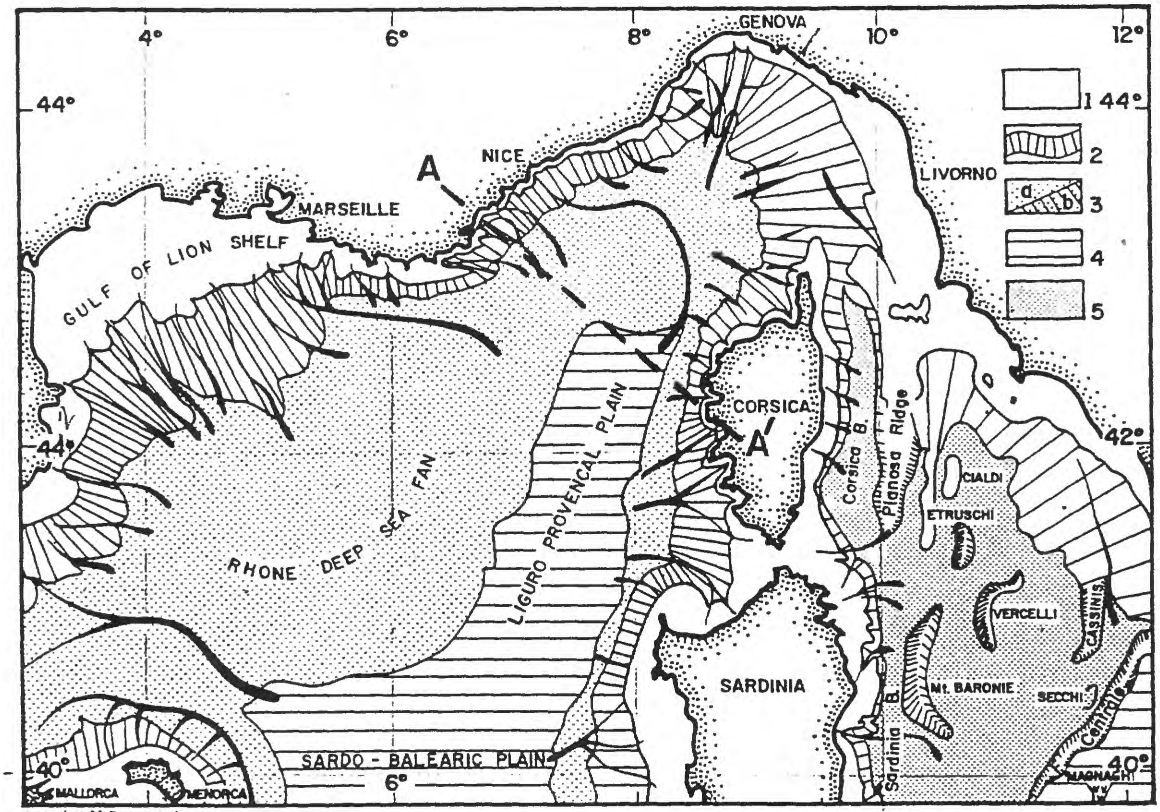
Seals - Tertiary shale, Messinian evaporites

Traps - Isolated sandstones and turbidites, Neogene; fault block traps in older beds

Summary of the geological evolution of the Western Mediterranean Basin.

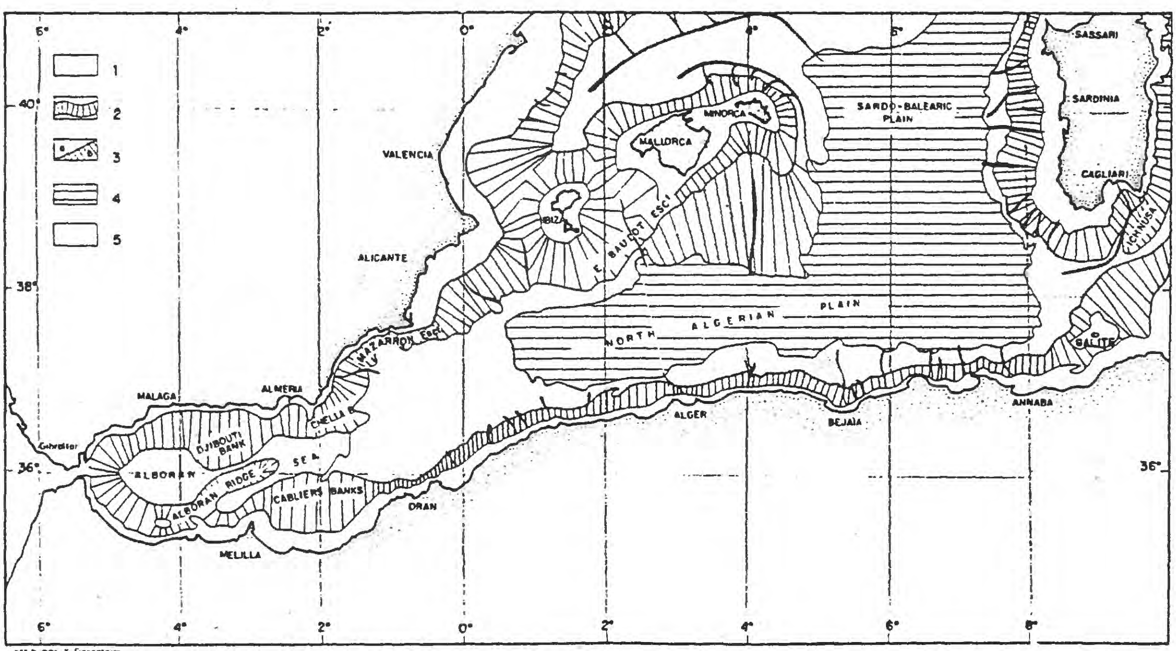
Geological changes with time	Valencia Gulf	Balearic Island DSDP Site 372	Gulf of Lion: Autan	Gulf of Lion: Mistral	Gulf of Lion: Tramontane	Rhône Valley	Ligurian Sea Provence Stoechades Canyon	Corsica Sardinia	Algeria Khabylie	Alboran Basin Spain
Domal Uplift Upper Eocene Oligocene	Erosion of the Mesozoic series in the central part		Erosion of the Mesozoic layers?	Erosion of the Mesozoic layers?	Erosion of the Mesozoic layers?	?	Maures–Esterel Uplift	Upper Eocene Uplift	Uplift and erosion	?
Rifting Stage Oligocene 28 m.y. Aquitanian 22 m.y.	Questionable Oligocene red beds impregnated with asphalt. Evaporite layers (Valles Penedes and Ebro continental shelf)	Questionable Oligocene red beds (Menorca Island). Marine Oligocene and Aquitanian sediments (Mallorca Island)	Oligocene siltstone shales with interbedded anhydrite layers. Aquitanian siltstones and sandstones. Gray marls	Aquitanian: polygenic breccia, dolomitic rocks. Anhydrite shales, bituminous marls, limestones with algae, corals, and benthonic foraminifera	Aquitanian dolomitic breccia. Anhydrite beds. Shales, siltstone	Oligocene evaporite beds (anhydrite, halite red beds). Strong erosion and graben formation. Aquitanian: gray marls or varicolored. Lignites	Horst and graben formation. Evaporite beds. Andesitic volcanism. Upper Oligocene marine platform sediments and detrital blocks, gravels, and sandstones (Stoechades Canyon). Aquitanian, transgression (Carry-Le-Rouet)	Oligocene faulting Detritical continental series (Cicceri Formation) Marine Aquitanian sediments filling the grabens. Andesitic volcanism	Conglomerates, micaceous sandstones, limestones. End of Numidian sandstone deposits. Subsidence of the Khabylie Massifs	Detrital series, thin marls (Chattian). Molasse, detrital deposits (Aquitanian). End of Numidian sandstone deposits
Drifting Stage Lower Burdigalian 21–17 m.y.	Amposta chalk: corals, algae and benthonic forams. Alcanar group: breccias or conglomerates, dark shales; shallow or restricted marine environment	DSDP 372 nannofossil mudstones to marlstones with a very high sedimentation rate (10 cm/1000 year) detritical fraction dominant. Bottom of the hole: silt, sandstones, and fragments of rock	Siltstones and marls. High sedimentation rate	Siltstones and marls. High sedimentation rate	Siltstones and marls. High sedimentation rate	Thick detrital layers filling Oligocene grabens	Marine Burdigalian sediments with interbedded cinerites. Alkaline volcanism in Ligurian Basin	Paleomagnetic evidence for rotation. Intense volcanic activity	Silexite (from Morocco to Italy) 19 m.y. Large subsidence in the internal massifs. Numidian overthrusting	Numidian overthrusting
Post-Drifting Subsidence Upper Burdigalian to Tortonian 17–7 m.y.	Alcanar group: clays, sands, and limestones. Castellon shales (Serravallian–Tortonian) pelagic sediments	DSDP 372 nannofossil marls and marlstones. Lack of turbidite-type sediments. Low sedimentation rate. Pelagic sediments (Mallorca Island). Large Burdigalian. transgression on land	Siltstones and marlstones. Low sedimentation rate. Pelagic influence	Siltstones and marlstones. Low sedimentation rate. Pelagic influence	Siltstones and marlstones. Low sedimentation rate. Pelagic influence	Large transgression into the Rhône Valley	Large transgression on land and pelagic deposits in the deep basin	Langhian transgression. Pteropod marls and pelagic sediments	Middle Burdigalian end of compressional movements. "Structural relaxation." Volcanism. Transgression	Trangression

Table 4. Summary of geological evolution of the western Mediterranean basin



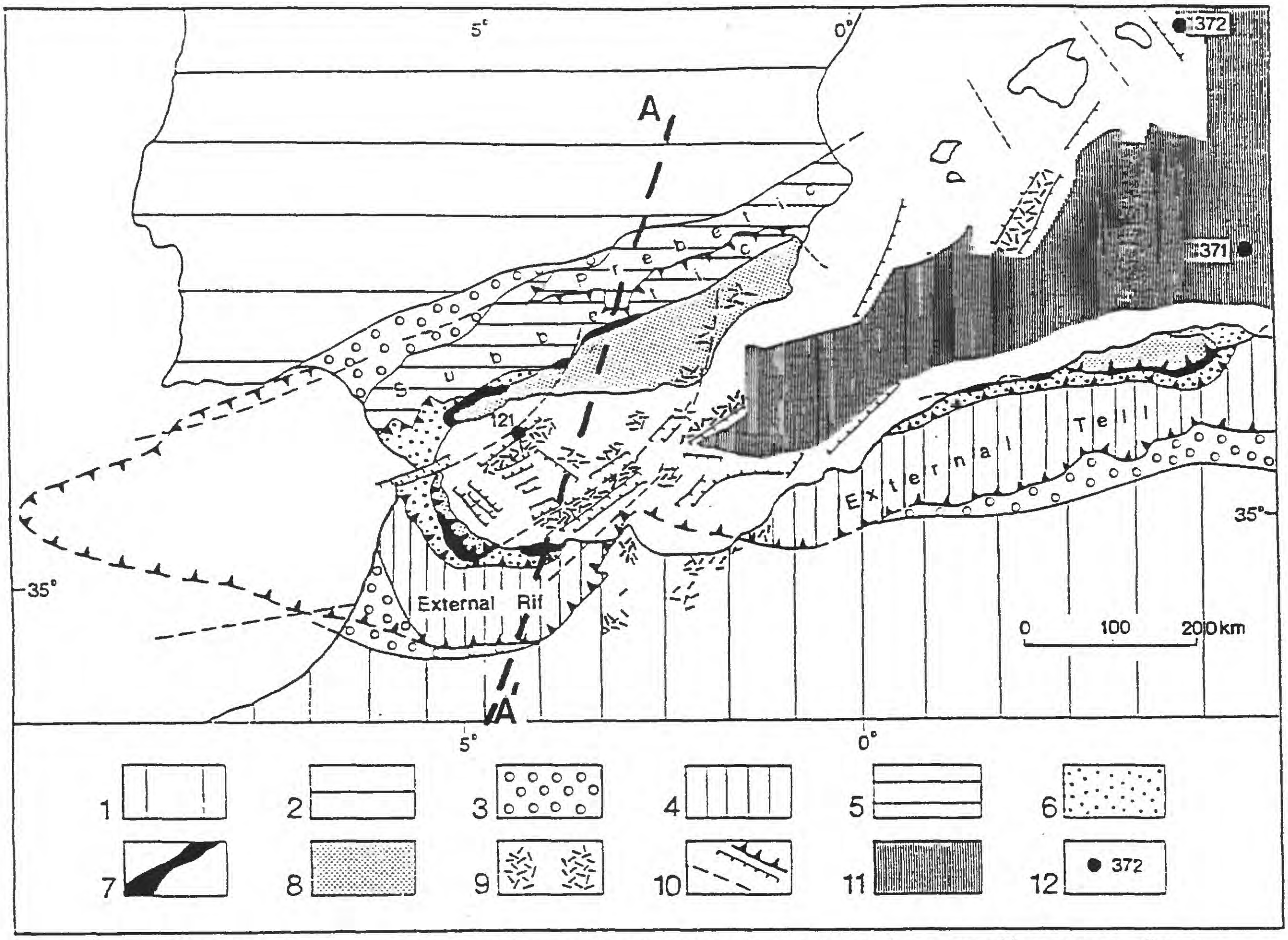
Dessin: Y. Descatoire.

A. Simplified chart of the northwestern Mediterranean, including the Liguro-Provençal Basin. 1, continental shelf; 2, slope; 3, rise and coalescent deep-sea fans; 4, bathyal plain; 5, north Tyrrhenian sedimentary basins.

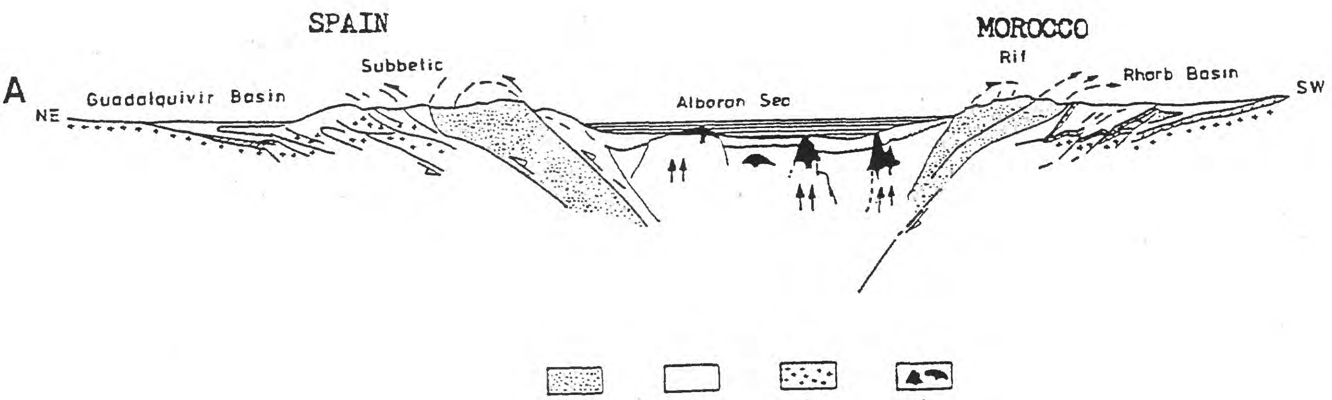


B. Simplified chart of the southwestern Mediterranean, including the Sardo-Balearic and North Algerian basins and Alboran Sea. 1, continental shelf; 2, slope; 3, rise and coalescent deep-sea fans; 4, bathyal plain; 5, Alboran sedimentary basins.

Figure 24. Subdivisions of the western Mediterranean basin region. From Rehault, and others, (1985). A - North Balearic-Provencal-Tyrrhenian-Corsica-Sardinia; B - South Balearic-Algerian basins

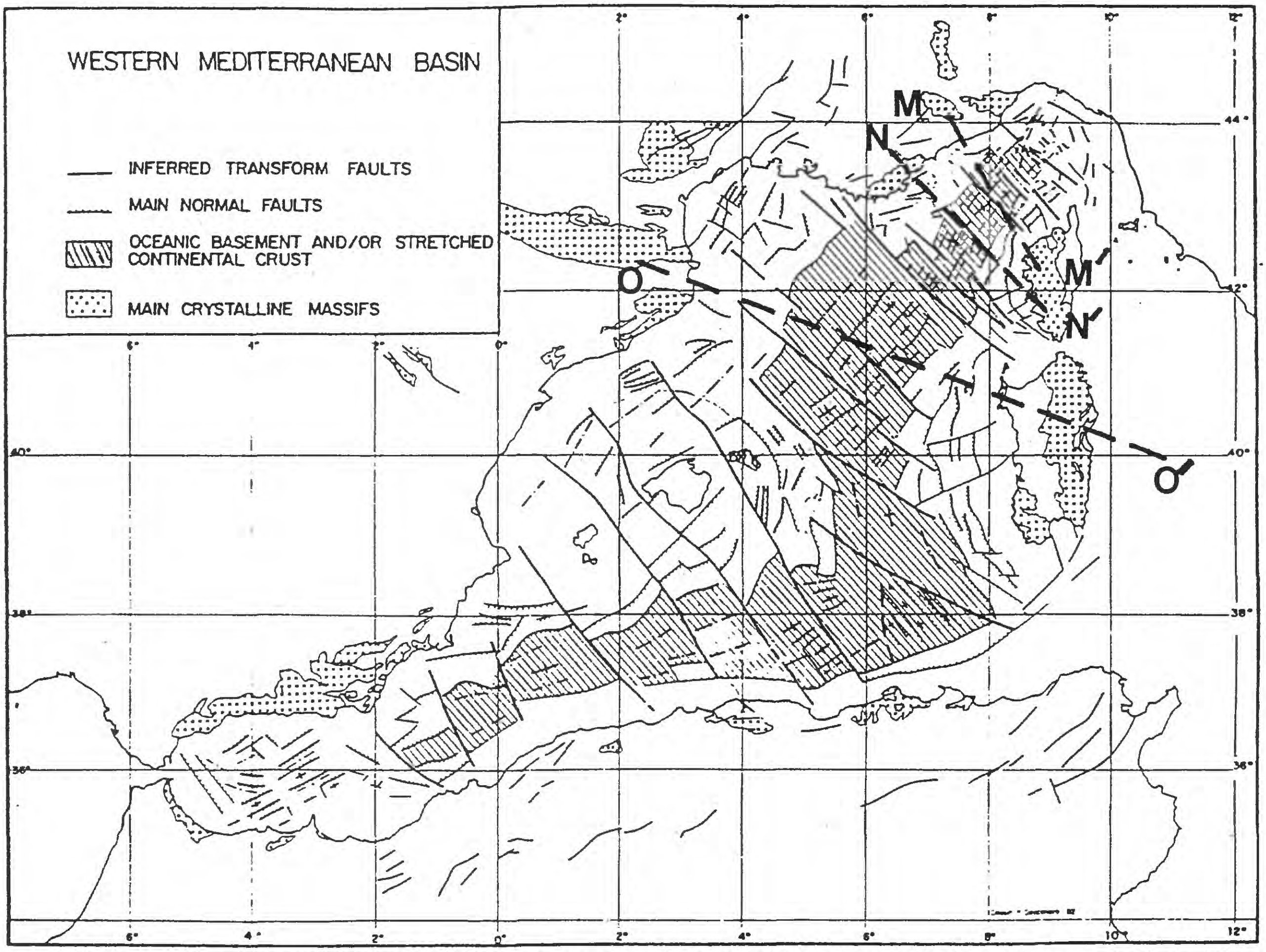


A. Geotectonic sketch of the Alboran-South Balearic basin and surrounding areas. Keys: 1 = African foreland. 2 = European foreland. 3 = Molasse foredeep. 4 = Deformed margin of Africa. 5 = Deformed margin of Europe. 6 = Numidian flysch nappes. 7 = Chain Calcaire. 8 = Internal zones of the Betics, Rif, and Tell. 9 = Neogene, mostly calc-alkaline volcanics. 10 = Transcurrent fault, normal fault major thrust. 11 = Balearic abyssal plain. 12 = DSDP holes.

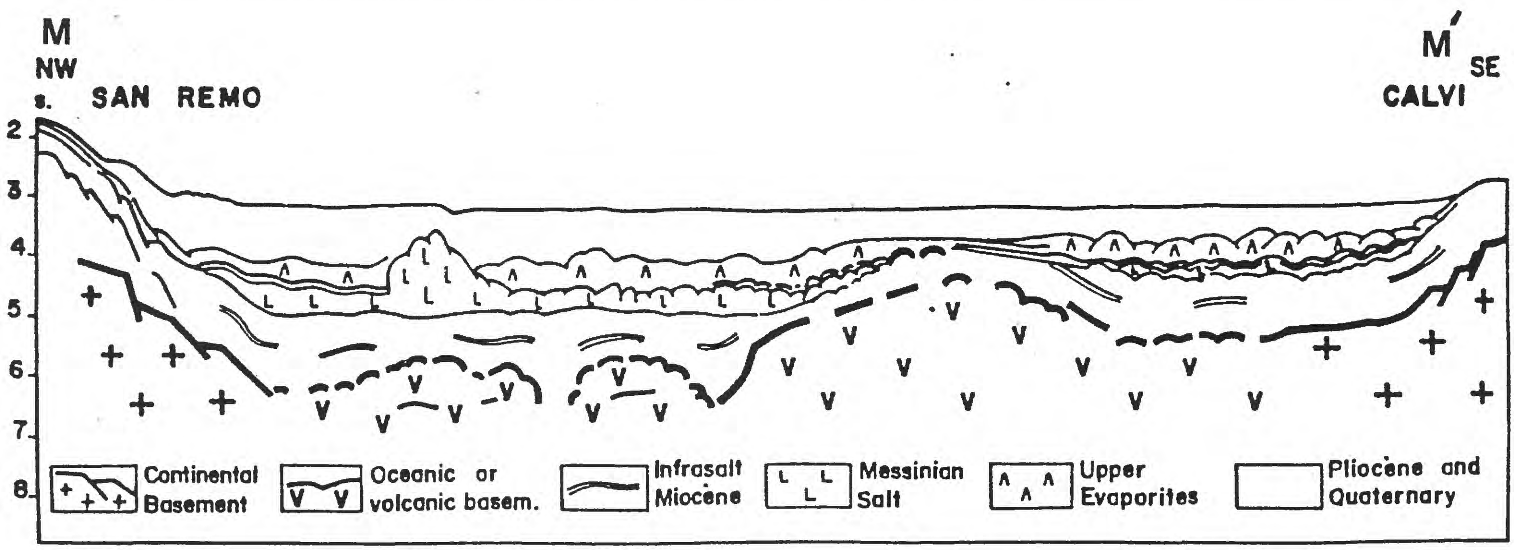


B. Geological section through the Alboran sea area after Biju-Duval et al., (1978). Keys: 1 = Orogenic belt; 2 = Stable margins, foredeep and external zones of orogenic belts; 3 = Basement; 4 = Submarine volcanoes.

Figure 25. A - Tectonic features of Alboran-South Balearic basin; B - Cross-section across Alboran basin. From Hovart and Berckhemer (1982). Line of cross-section shown on A



A. Scheme of Western Mediterranean structural features based on seismic and magnetic data. The major margin normal faults and oceanic transform faults are depicted.



B. Schematic Ligurian Basin section between San Remo and Calvi, from MS 47 OGS Profile (Finetti and Morelli, 1974). Messinian erosion affected the central basin volcanic body. Asymmetry of the northern Ligurian Basin is depicted by thicker sedimentary layers along the European margin than the Corsican margin.

Figure 26. A - Western Mediterranean structural features; B - Schematic cross-section, Ligurian basin. From Rehault and others (1985). Line of cross-section shown on A

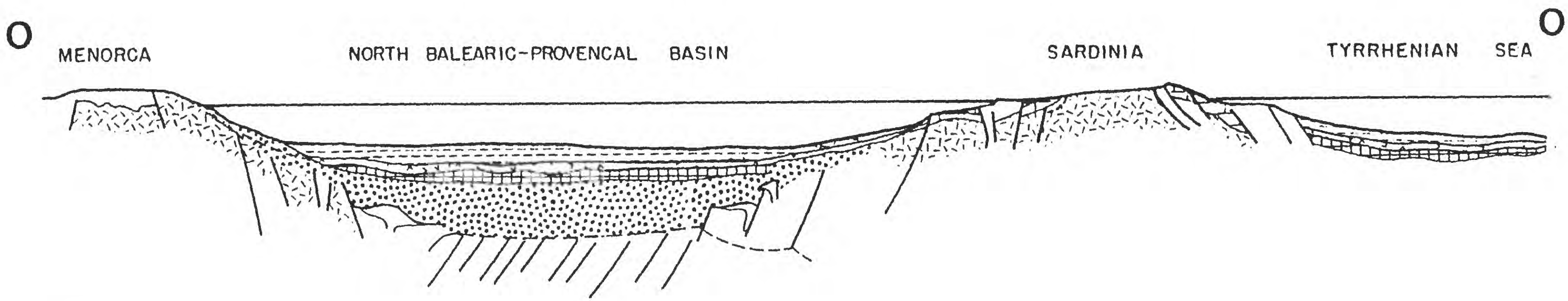


Figure 27. West-East stratigraphic-structural cross-section, Menorca Island to Sardinia and western Tyrrhenian basin. Modified after Biju-Duval and others (1979). Line of cross-section shown on figure 26A

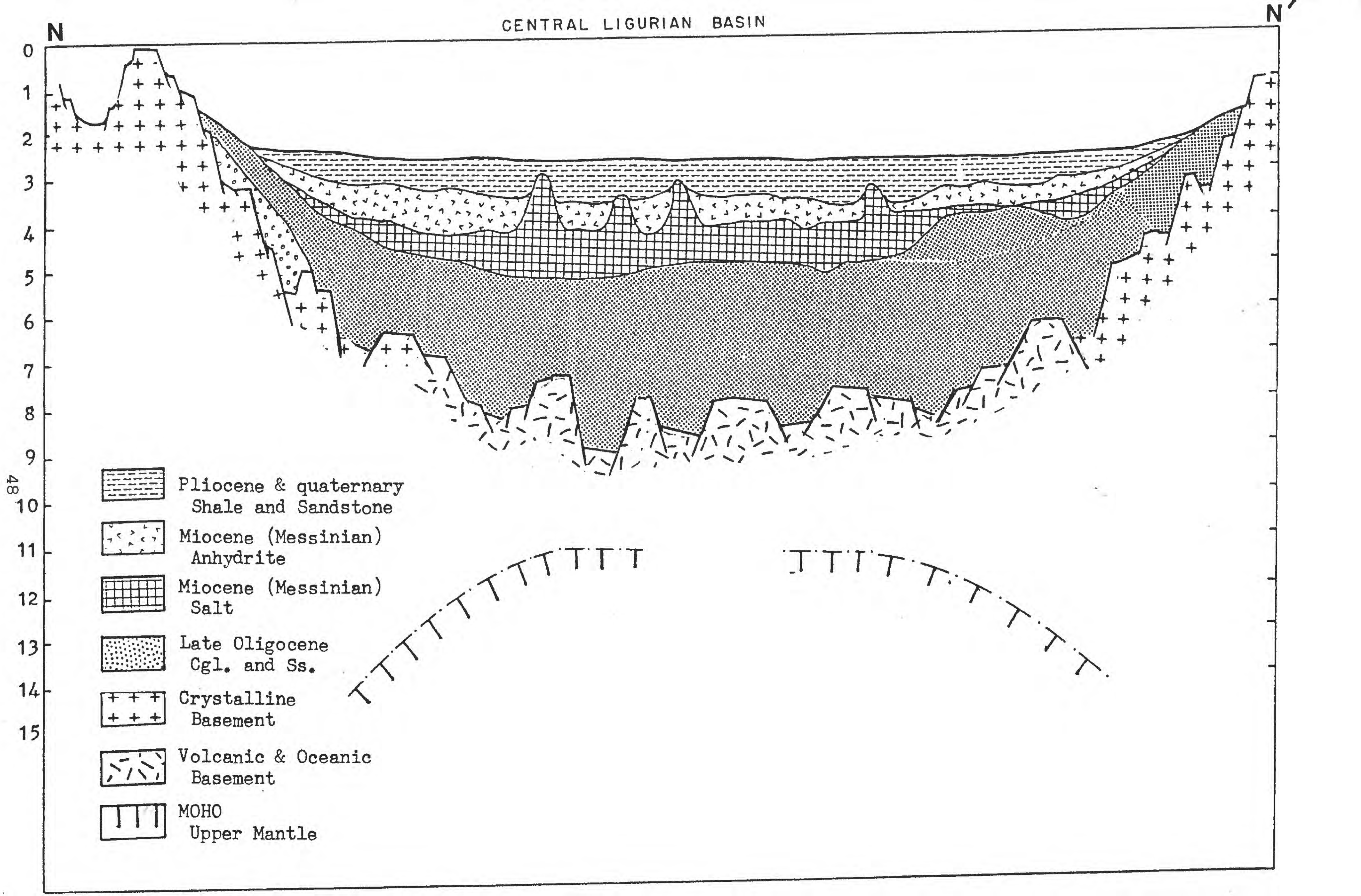
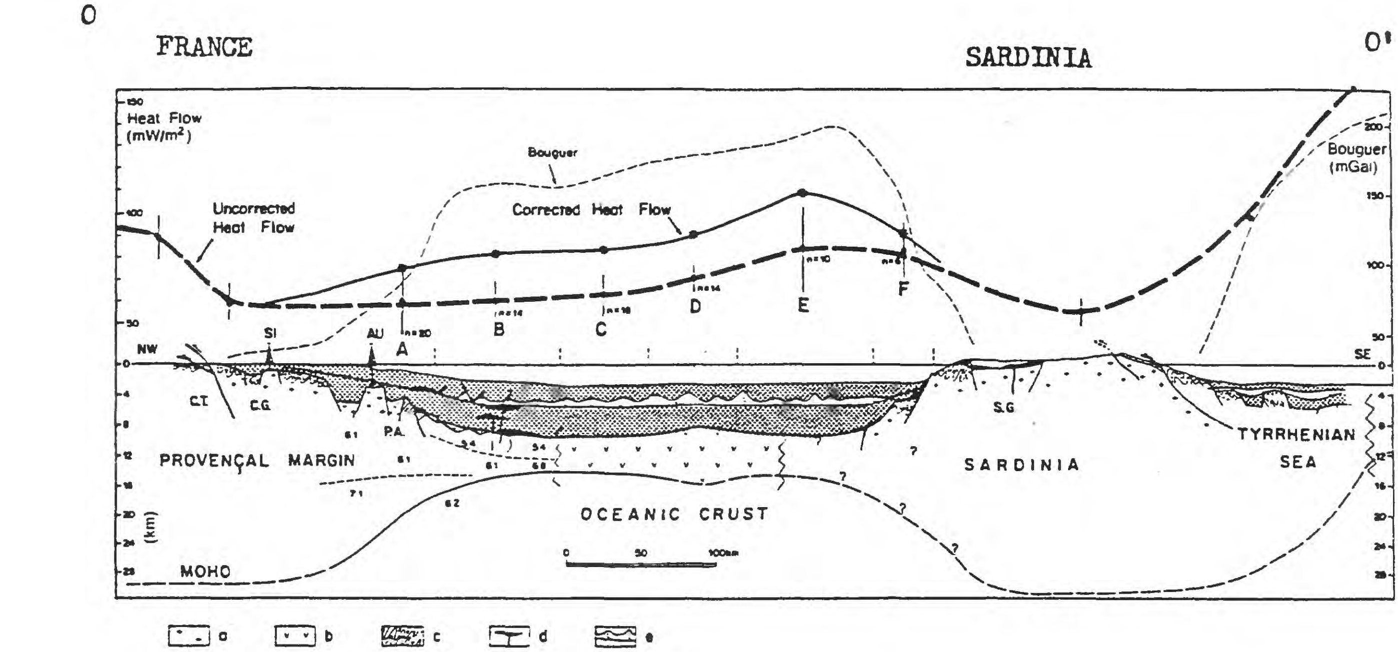
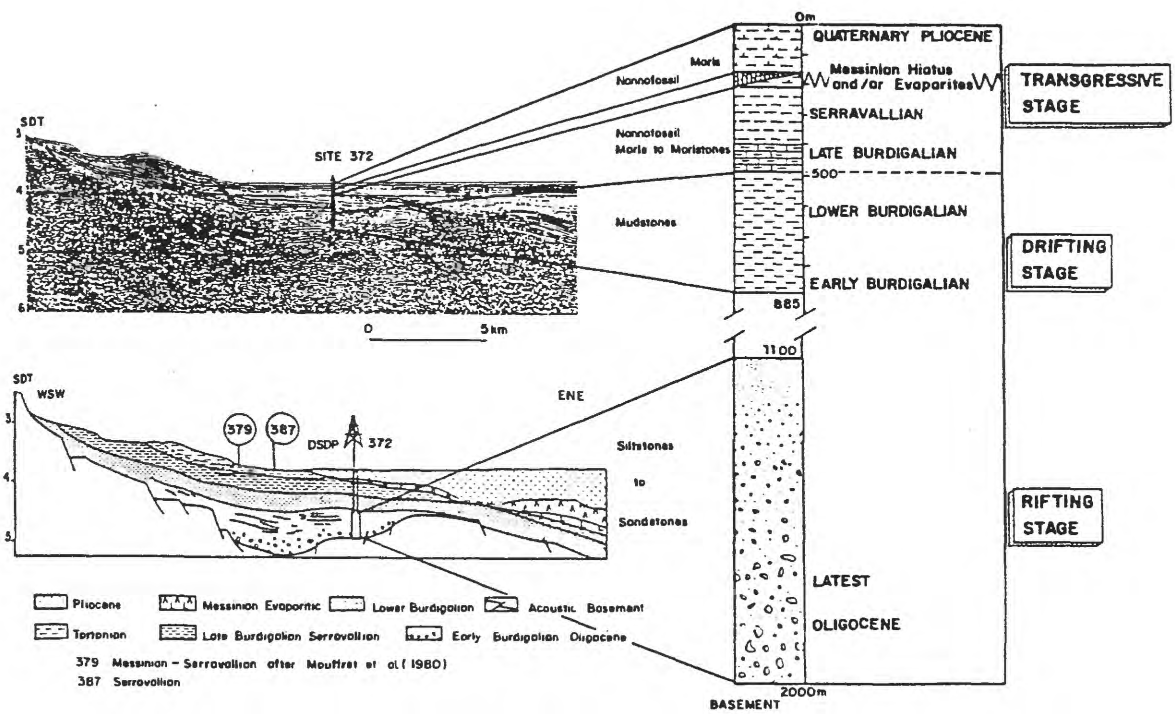


Figure 28. WNW - ESE schematic lithologic-structural cross-section across Ligurian basin. Modified after Rehault and others (1985). Line of cross-section shown on figure 26A

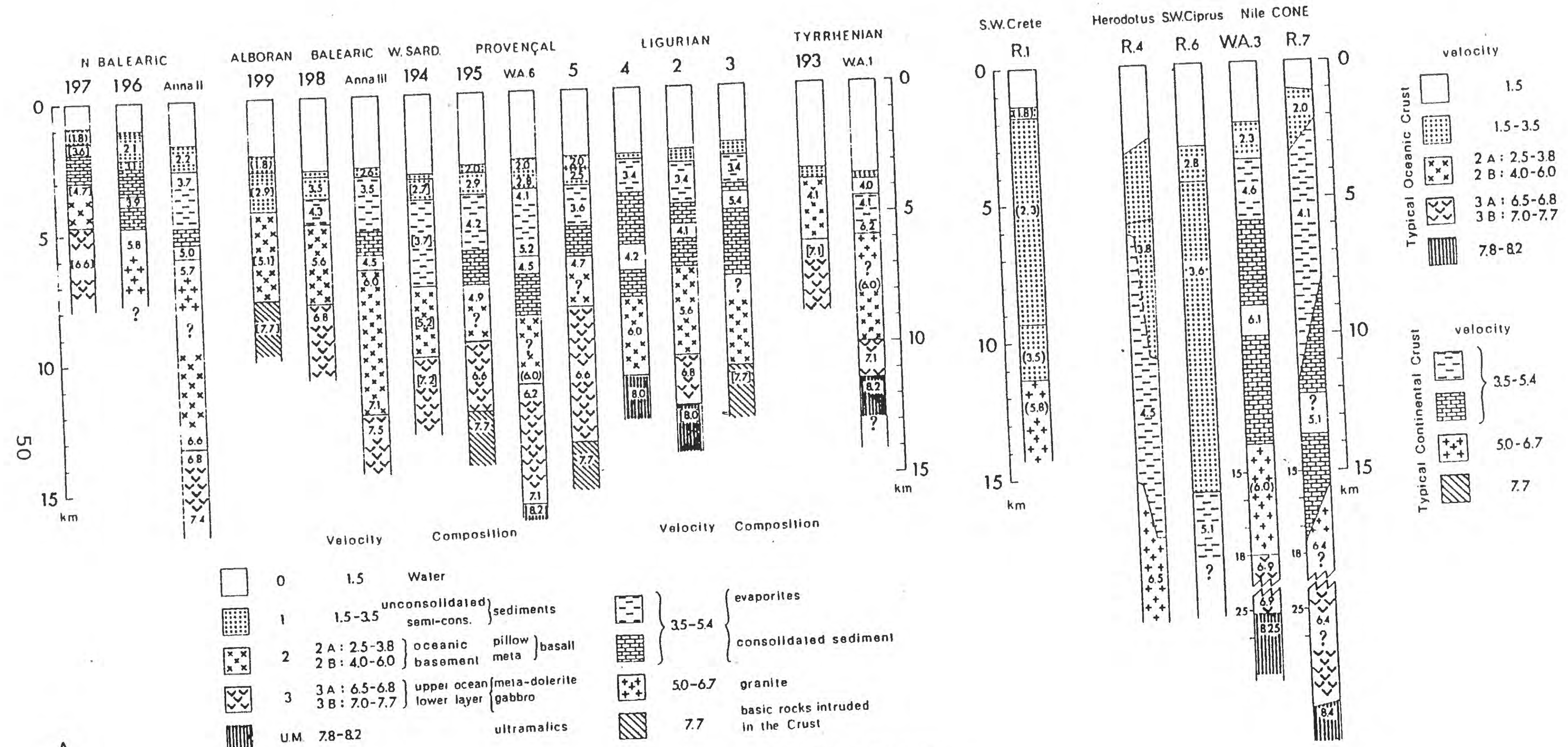


—Geophysical transect across line AA'A" (shown in Figure 1). The Gulf of Lions and the Sardinian margin are asymmetric conjugated margins. The asymmetry is also reflected by the Bouguer profile (Morelli et al., 1977) and the heat-flow profile (corrected for sedimentation) (Burrus and Foucher, 1986). The predicted history of surface heat flow at locations A, B, C, and D is shown in Figure 9; n refers to the numbers of heat-flow measurements used to compute the mean heat flow at locations A–F. Values of *P*-wave velocities derived from refraction seismic (Le Douaran et al., 1984) are given across the margin of the Gulf of Lions. Lithological labels are as follows: a = continental crust, b = oceanic crust, c = Hercynian metamorphic substratum, d = volcanic intrusions, e = Messinian salt. SI = Sirocco well, AU = Autan well (projected), S.G. = Sardinian Graben, P.A. = possible Pyrenean axial zone, C.G. = Camarque-Vistrenque Graben, C.T. = Pyrenean structures on shore. Numbers indicate locations where tectonic subsidence was studied.



Margin structures, sedimentary layers, and DSDP Site 372 stratigraphy, on the eastern Menorca margin (after Mauffret et al., 1978, *in* Hsü et al., 1978). Drifting and transgressive series lie on rifted facies (probably conglomerate and sandy sediments, as inferred from seismic data).

Figure 29. A - Northwest-southeast geophysical transect across Provencal basin. From Burrus and Audebert (1990); line of cross-section shown on figure 26A; B - Structure and stratigraphy at DSDP site 372, eastern Menorca margin. From Rehault and others (1985)



DSS results for the Western (A) and for the Eastern (B) Mediterranean. Location of sites shown in Figure 4.1. V = velocity in km/sec.

Figure 30. Sedimentary columns, DSS sites. From Morelli (1985). Locations are shown on figure 31

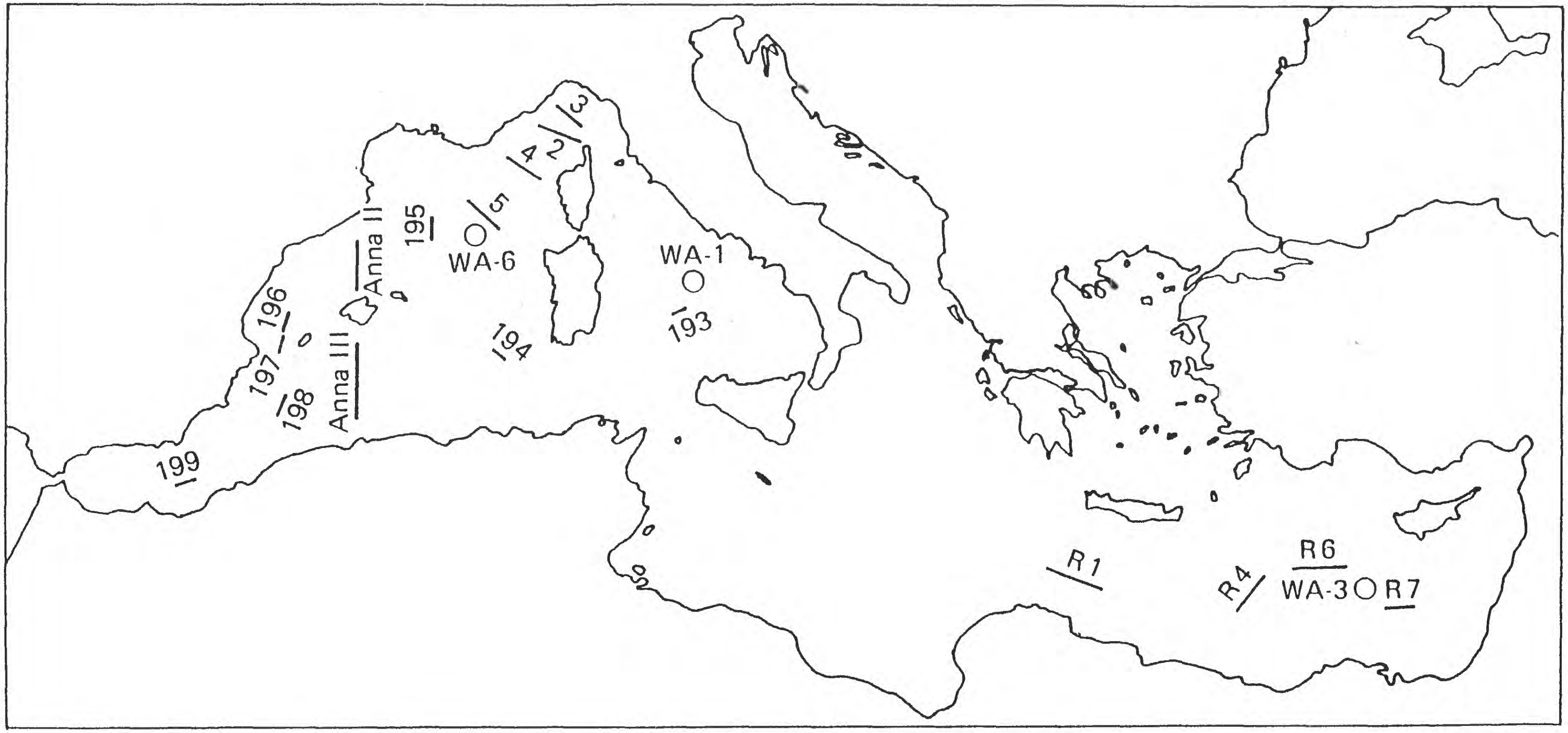
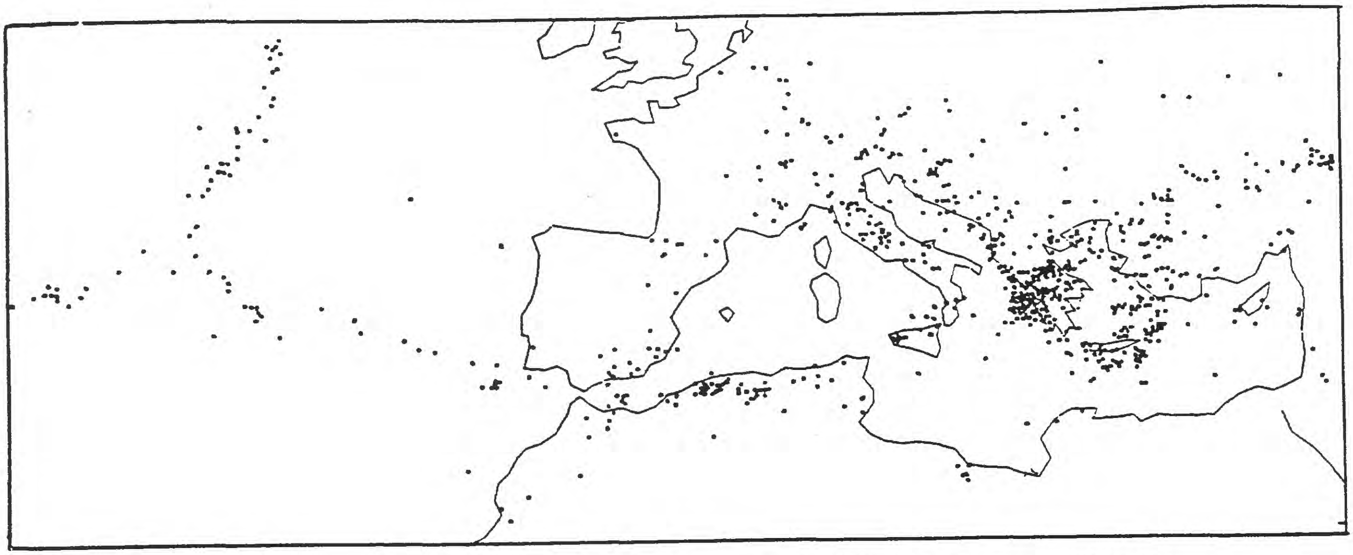
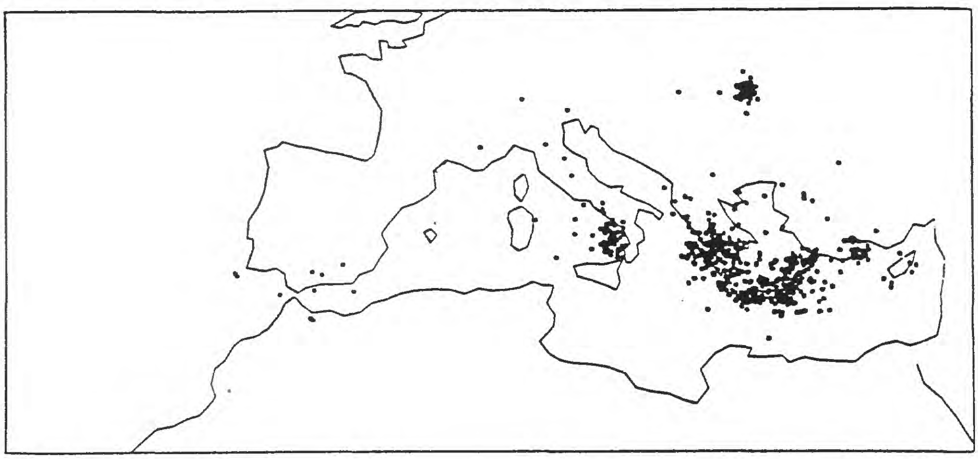


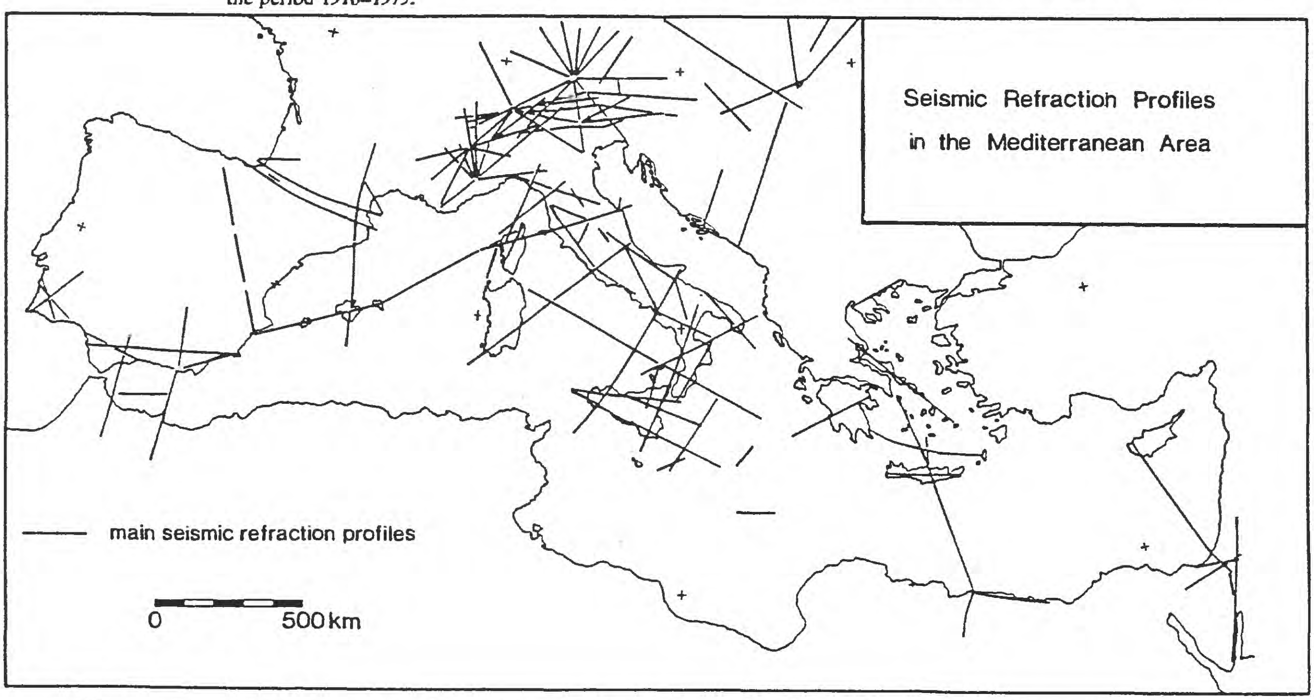
Figure 31. Location map, DSS sites shown on figure 30. From Morelli (1985)



A. Location of surface earthquakes in the Mediterranean region, h ≤ 60 km, M ≥ 5 for the period 1910–1970.



B. Location of intermediate and deep earthquakes in the Mediterranean region, h ≥ 60 km, M ≥ 4, for the period 1910–1979.



C. Position map of the most important seismic-refraction lines in the Mediterranean area.

Figure 32. A, B - Earthquake frequencies, Mediterranean region. From Udias (1985).

C - Seismic reflection lines, Mediterranean area. From Giese and others (1982)

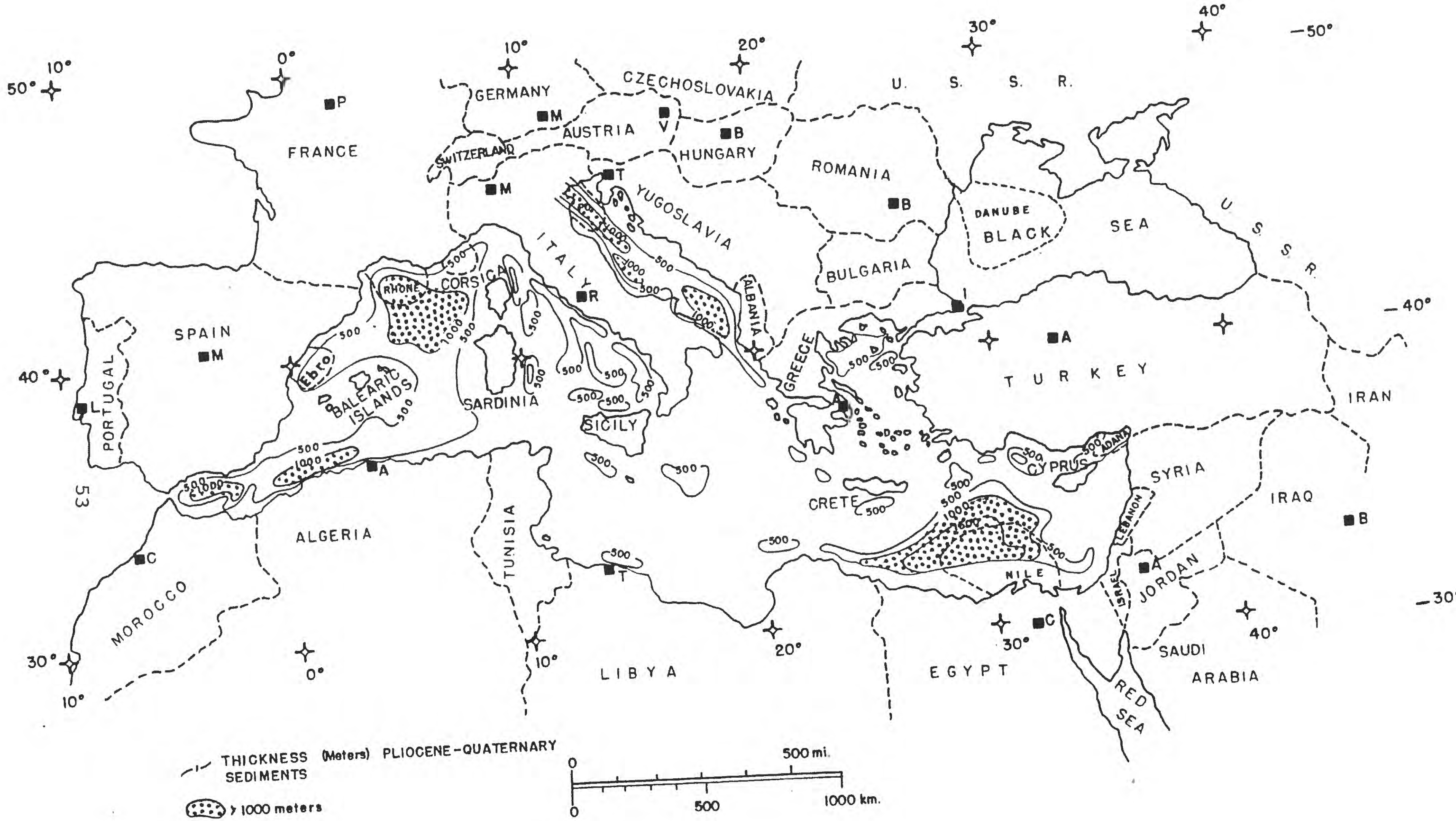


Figure 33. Thickness in meters, Pliocene-Quaternary sediments, offshore Mediterranean.

Thermal - Greater than normal, very high in places

Potential - Low to marginal

Problems - Water depth; need for detailed seismic and other geophysical work

Resources - No oil or gas fields present; no drilling except for DSS and DSDP sites.

Estimated Undiscovered Resources					
Low Amount (95% probability)		Most Likely Amount (Modal estimate)		High Amount (5% probability)	
Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF
5	1.0	20	5	40	15

Ligurian-Provencal Region

The sedimentary cover in this area is as much as 7 km (23,000 ft) thick (figs 26-32), consisting of: 1) a lower detrital and marly section of lower and middle Miocene age, probably underlain in areas by coarse clastic Oligocene beds overlying oceanic basement; 2) a middle evaporite layer (Messinian); and 3) an upper, mainly marly section of Pliocene-Quaternary age, with relatively thick deltaic facies and associated deep water turbidites off the mouth of the Rhone and Ebro rivers (fig. 33). Numerous salt domes are present (fig. 4). The basin was formed by the rotation of Corsica and Sardinia away from France during the early Miocene (Rehault and others, 1985). At the same time, the Gulf of Valencia basin formed during the rotation of the Balearic Islands chain away from Spain. Structural lineaments trend northeast, approximately parallel to the Oligocene-Miocene rifts. Pliocene-Quaternary beds are approximately one km (3,250 ft) thick (fig. 33). The Gulf of Valencia basin is a V-shaped trough, part of the continental rise of Oligocene rift origin. The northern margin comprises a 60 km (37 mi) wide shelf built up by Pliocene-Quaternary sedimentation. The southern margin is a deep escarpment along the Belearic Islands (figs. 23, 24).

USGS Team Hydrocarbon Assessment Summary

Water depth - Mostly greater than 2,000 m (6,500 ft), but substantial area of less than 1,000 m (3,250 ft) on the northern and northwestern shelf

Reservoirs - Pre-evaporite sandstones and turbidites - Miocene and Oligocene; Cretaceous carbonates, probably fractured, in discontinuous blocks; some deltaic sandstones. Possible Pliocene-Pleistocene sandstones and turbidites, and deltaic sandstone

Source Rocks - Miocene and Oligocene shales, possibly Miocene shales for biogenic gas; biogenic shales in post Messinian section; early Tertiary or Mesozoic shales are probably highly mature or overmature, if present

Seals - Messinian evaporites; Tertiary shales in pre-salt and post-evaporite beds.

Traps - Isolated Tertiary sandstones; salt structures; Paleogene and older fault blocks

Thermal -Greater than normal, very high in places

Potential - Low to marginal

Problems - Same as So. Balearic, except the presence of several large deltas enhance possibilities, especially for biogenic gas

Resources - No oil or gas fields present

Estimated Undiscovered Resources					
Low Amount (95% probability)		Most Likely Amount (Modal estimate)		High Amount (5% probability)	
Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF
50	1.0	500	5	1,500	20

Corsica and Sardinia (figs. 26, 29)

These blocks are remnants of continental crust, originally a part of Europe, which rotated away from France in early Miocene time (Rehault and others, 1985). Isolated patches of marine Triassic and Cretaceous marine carbonates, overthrusting metamorphosed Lower Cambrian to Lower Carboniferous basement, are present (Pieri and Mattavelli, 1986). A north-south Oligocene-Miocene extensional basin filled with clastics and associated volcanics is present in southwestern Sardinia.

USGS Team Hydrocarbon Assessment Summary:

Reservoirs - Tertiary sandstones, Mesozoic carbonates and sandstones, fractured reservoirs

Source Rocks - Late Tertiary shales; Late Triassic-Early Jurassic shale?; Paleozoic shales; these are probably overmature

Seals - Tertiary shales; possibly early Mesozoic evaporites

Traps - Isolated Tertiary sandstones; deeper fault block traps; small folds

Thermal - Probably higher than normal

Potential - Marginal to low because of structural history

Problems - Uncertainty of traps; loss of earlier hydrocarbons because of complex later structural history; older source rock beds may be overmature.

Resources - No oil or gas fields present

Estimated Undiscovered Resources					
Low Amount (95% probability)		Most Likely Amount (Modal estimate)		High Amount (5% probability)	
Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF
5	0.1	50	0.5	150	1.5

Central Mediterranean

The central Mediterranean assessment area includes the Tyrrhenian Sea basin, Italy and Sicily, the Adriatic Sea basin, and the Ionian basin--Libyan shelf (figs. 1, 13, 14, 27). This area includes most of Apulia (fig. 3), which was part of Africa until the Cretaceous (Dercourt and others, 1986).

Tyrrhenian Sea basin (Figs. 30, 31, 34).

This basin formed during rifting accompanying rotation of the Calabrian block away from the Corsica-Sardinia block, beginning in upper Miocene time, accompanied by rapid foundering of oceanic crust (Livermore & Smith, 1985). At the same time, rotation of the Tellian (north Algerian) Massif may have resulted in the north Algerian basin. The Miocene stratigraphic sequence in this basin is of similar thickness to that of the Ligurian basin (fig. 30). North-south fault trends are predominant with a north-trending horst and graben complex in the northern part. The center is a relatively flat plain with large seamounts and ridges, some of volcanic origin and some composed of tilted blocks of continental crust (Morelli, 1985). The sedimentary cover is thin, underlain by oceanic crust (figs. 12, 27).

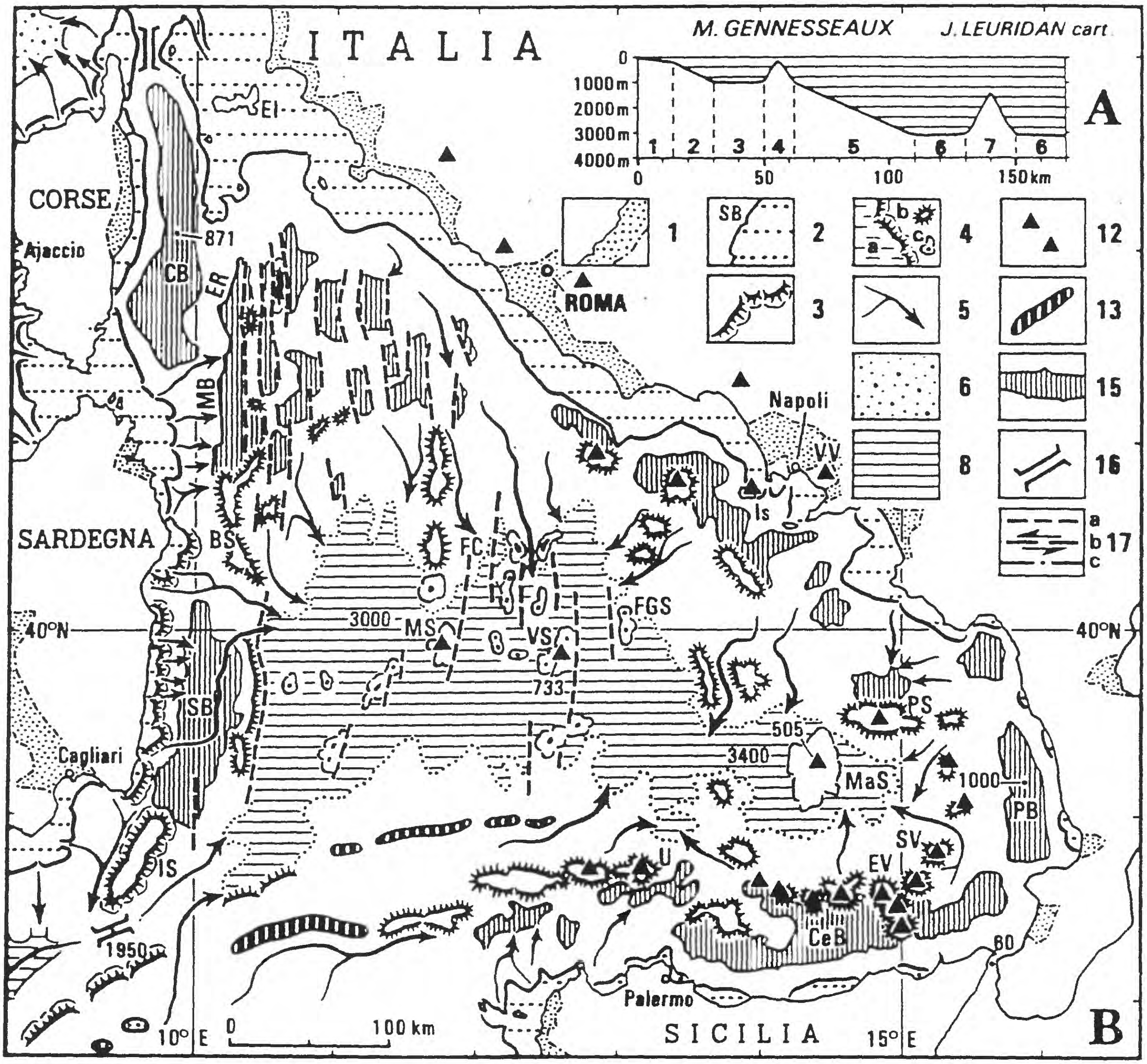
USGS Team Hydrocarbon Assessment Summary:

Water depth - mostly greater than 2,000 m (6,500 ft)

Reservoirs - Isolated sandstones and possibly turbidites in younger Tertiary

Source rocks - Probably doubtful, except for isolated biogenic shales in some depocenters

Seals - Messinian evaporites and Cenozoic shales



Tyrrhenian Sea and surrounding areas. Legend for cross-section, in A: 1, continental shelf; 2, upper slope; 3, intraslope basin; 4, midslope smt; 5, lower slope; 6, central plain; 7, central smt. Legend for the chart, B: 1, coastal and lacustrine plain; 2, continental/insular shelf (SB: shelfbreak); 3, escarpment; 4, marginal plateau (a), intraslope smt (b), and central smt (c); 5, submarine canyon; 8, abyssal plain; 12, volcanic features; 13, submarine ridge; 15, faulted trough and ridge basin complex; 16, submarine passage; 17, fracture. Abbreviations: BS, Baronie Smt; CB, Corsica Basin; CeB, Cefalu Basin; El, Elba island; ER, Elba Ridge; EV, Aeolian volcanic isles; FC, Faglia Centrale (Central Fault); FGS, Flavio Gioia Smt; IS, Ichnusa Smt; MB, Montecristo Basin; MS, Magnaghi Smt; MaS, Marsili Smt; PB, Paola Basin; PS, Palinuro Smt; SB, Sardinia Basin; SV, Stromboli Volcano; U, Ustica; VV, Vesuvius Volcano; VS, Vavilov Smt (see Fig. 1.12).

Figure 34. Topographic and structural features of Tyrrhenian Sea. From Vanney and Gennesseaux (1985)

Traps - Mainly draping over volcanic plugs and extensional fault blocks

Thermal - High heat flow, in back arc area

Potential - very low

Problems - Thin sedimentary cover, deep water, high heat flow; poor seismic quality

Resources - No oil or gas fields present

Estimated Undiscovered Resources					
Low Amount (95% probability)		Most Likely Amount (Modal estimate)		High Amount (5% probability)	
Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF
Negligible	Negligible.	Negligible.	Negligible.	20	3

Italy - Sicily - Adriatic Sea (figs. 35-44)

Early exploration efforts in Italy and Sicily concentrated on the Apennine Mountains belt, where indications of oil and gas were present. The poor success in this complexly folded and thrusted region was followed by post-World War II reflection seismic exploration in the Alpine and Apeninne foreland region (Pieri and Mattavelli, 1986). Caviaga oil field in northwestern Italy was discovered in 1944. Since that time, approximately 2,000 onshore and offshore exploratory wells have been drilled, resulting in the discovery of more than 200 fields (fig. 21). Original reserves, as of 1990, were 1.2 BBO and 27 TCF gas. Identified or potential source rocks for oil and gas, ranging in age from Triassic to Pliocene, are present in the basins of Italy, Sicily, and the Adriatic (tables 5, 6). Reservoirs for oil are primarily Mesozoic and early Tertiary platform carbonates, which are widespread throughout the Italy-Sicily-Adriatic region (Zappaterra, 1990; Pieri and Mattavelli, 1986) (figs. 38-44). Reservoirs for gas, and for oil migrated vertically from underlying Mesozoic source rocks, are Tertiary and Quaternary foredeep sandstones and siltstones deposited during development of the Alpine mountain chains. Gas in the Neogene reservoirs is primarily biogenic. Traps are in thrusted and block faulted uplifts beneath the Cenozoic cover, or in isolated Cenozoic foreland sandstones and siltstones.

The present-day position and geology of the Italy-Sicily and the Adriatic Sea are the result of several factors associated with a complicated geologic history related to: 1) the evolution of the Tethys realm, 2) the breakup of Pangea, and the associated opening of the Atlantic ocean after Permian time, and 3) the convergent and divergent movements between Europe and North Africa (figs. 3, 9, 10). The resultant movements of the Calabrian Arc and the Apulian (Adria) African microplate (fig. 3) are major factors.

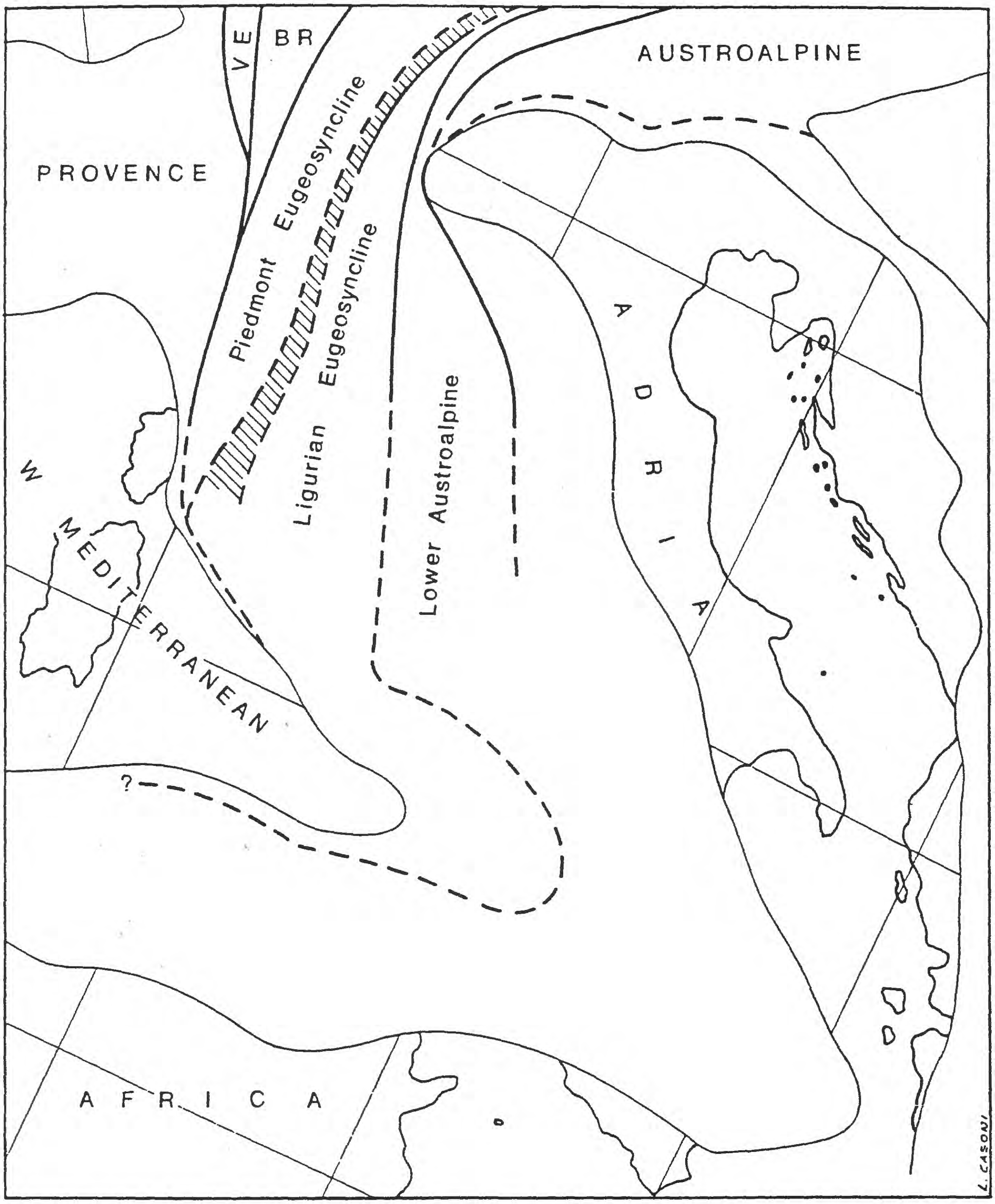
Table 5 Hydrocarbon source rock data, Italy-Sicily

Formation	Age	Area	Average TOC (%)	Kerogen Type: Amorphous and Marine	Kerogen Type: Herbaceous	Kerogen Type: Woody	Correlatable To
Turbidites	Quaternary-Pliocene-late Miocene	Po plain subsurface	0.7	13	44	43	Po plain dry gas fields
Tripoli	Late Miocene	Sicily surface	1.0	mostly marine			?
Flysch	Late-Middle Miocene	Po plain subsurface	0.44	19	47	34	Northwest Apennine oil and wet gas fields
Scaglia (Bonarelli horizon)	Late Cretaceous	Marches surface	5.12	90	2	8	?
Fucoidi Shale	Early Cretaceous	Marches surface	0.6	32	35	33	?
Riva di Solto Shale	Rhaetian	Lombardy Alps surface	0.8	21	34	45	Malossa and Seregna wet gas fields
Streppenosa Shale	Early Jurassic	Southeast Sicily subsurface	0.8	62	4	34	Southeast Sicily oil fields
Noto Formation	Rhaetian	Southeast Sicily subsurface	4.0	78	4	18	Southeast Sicily oil fields
Mufara Shale*	Middle-Late Triassic	North Sicily surface	0.2	12	23	65	?
Filettino Dolomite	Late Triassic	Latium surface	1.15	45	32	23	?
Resiutta Shale	Late Triassic	Southeast Alps surface	8.0	79	10	11	?
Meride Limestone	Middle-Late Triassic	West Po plain subsurface	0.9	55	28	17	Gaggiano 1 well oil shows

*Analyses on a limited number of samples.

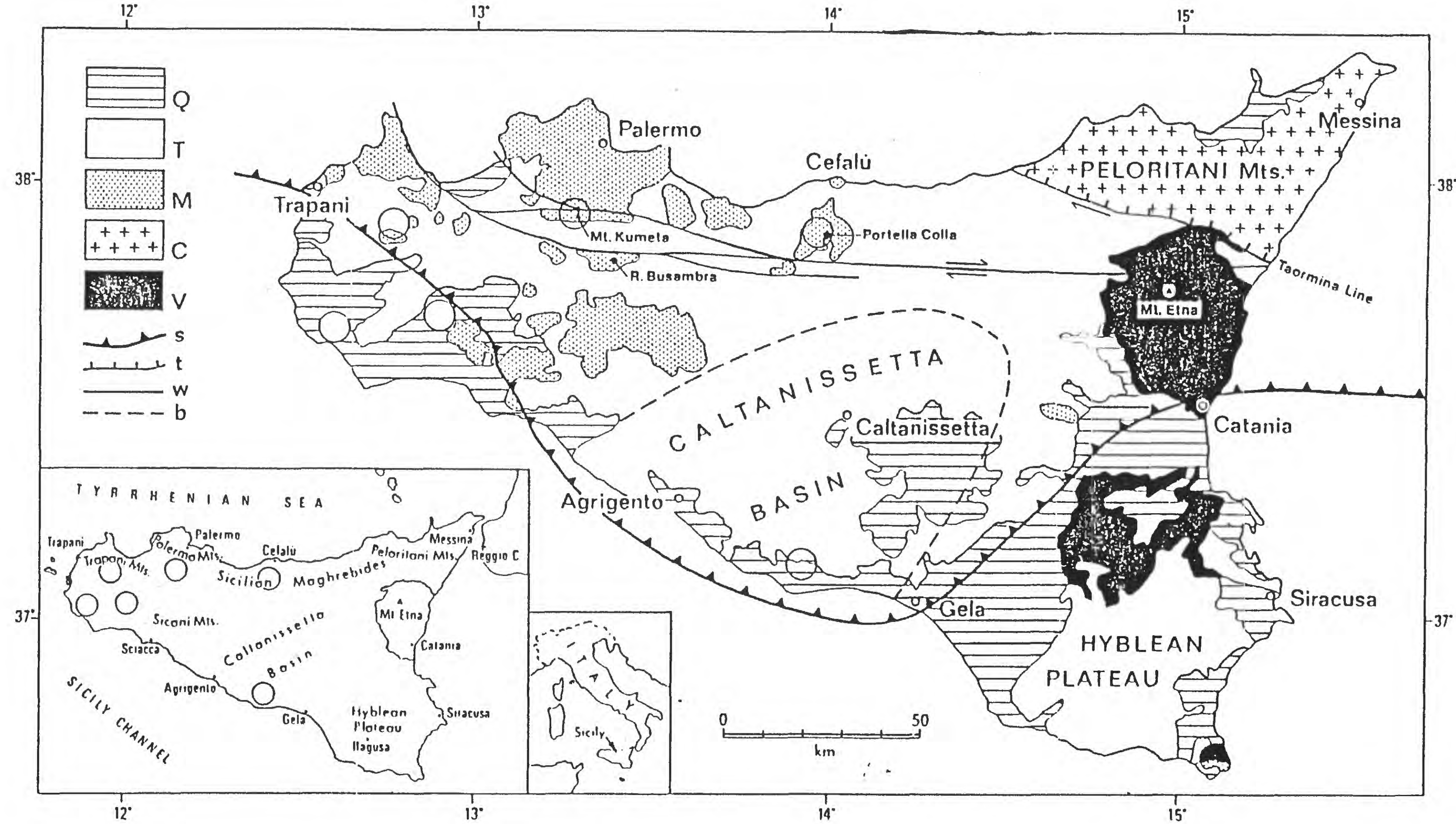
Table 6. Average TOC (Total organic carbon) (%) of Streppenosa and Noto Formations

Well	Streppenosa Formation (Hettangian-Late Rhaetian) Thickness (m)	Average TOC (%)	No. of Samples	Noto Formation (Rhaetian) Thickness (m)	Average TOC (%)	No. of Samples
Gela 1	80	1.62	13	228	3.02	19
Gela 23	228	2.15	23	212	3.81	29
Gela 28	187	0.82	9	163	1.96	5
Gela 31	349	0.77	16	185	6.03	8
Gela 32	52			203	4.59	141
Troitta 1	35	1.43	5	265	5.81	7
Vittoria 1	170	0.79	4	230	3.12	9
S. Croce Camerian 2	325	0.72	17	190	1.82	10
Licodia 1	40	3.76	2	157	7.21	2
Ragusa 22	219	0.46	9	110	2.49	10
Modica 1	295	0.41	10	136	2.5	8
Scicli 1	>1,854	0.84	13	—	—	—
Pachino 4	>2,923	0.82	69	—	—	—
Noto 2	70	0.44	5	236	2.2	10



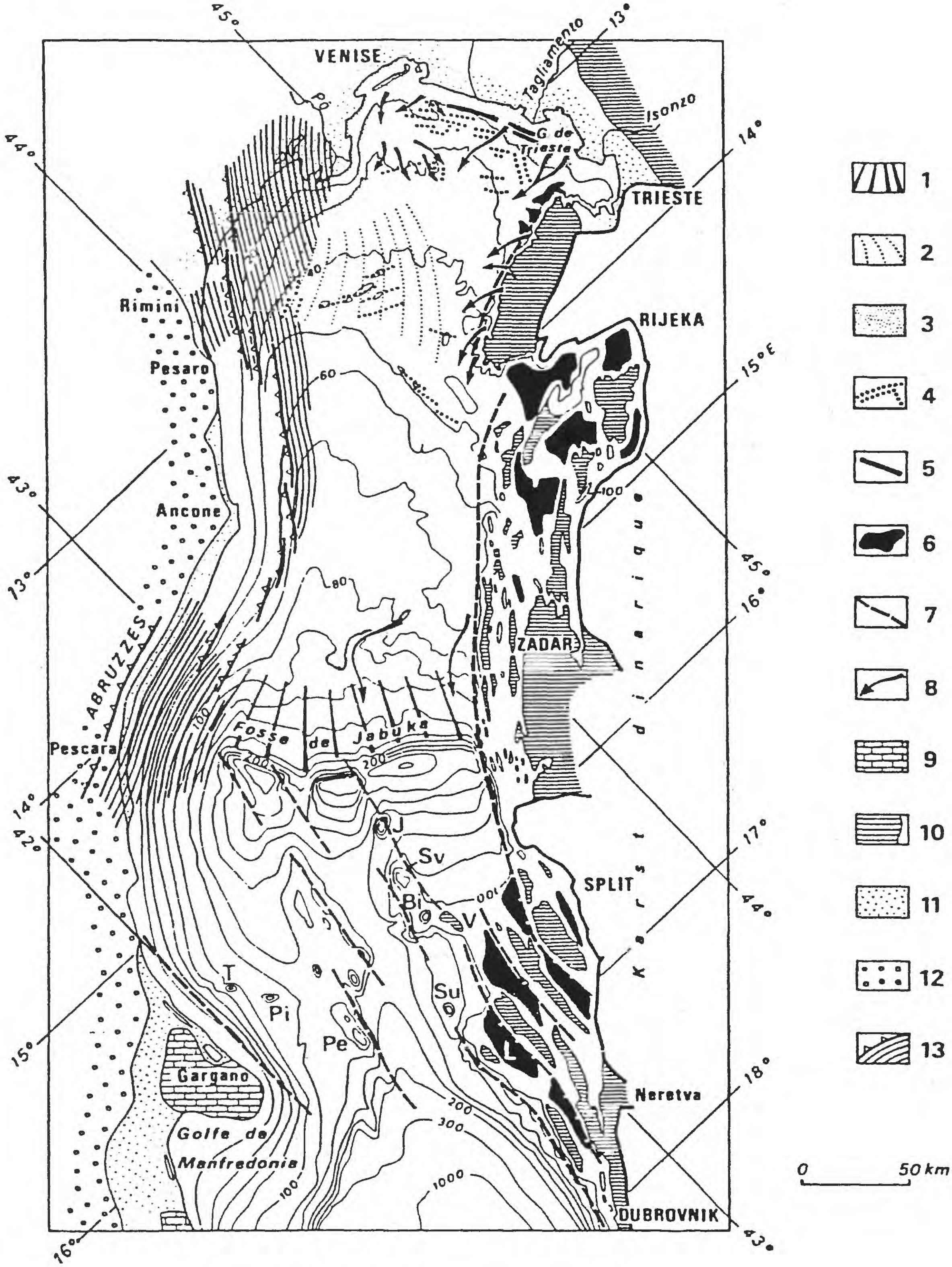
Tentative reconstruction of the Central Mediterranean area in the Late Jurassic. This simplified scheme shows the Western Mediterranean and Adria ancient microplates separated by geosynclinal troughs. This interpretation is no more hypothetical than many existing models. BR, Briançonnais zone; VE, Valais trough.

Figure 35. Paleogeographic reconstruction, central Mediterranean area in Late Jurassic time. From Selli (1985)



Simplified map showing some of the elements of the geology of Sicily discussed in the text (compiled from various sources). Q, Quaternary (including upper Pliocene); T, Tertiary (excluding upper Pliocene); M, Mesozoic massifs (mainly of carbonate rocks); C, crystalline units; V, volcanics; s, southern front of the nappes; t, "Taormina line"; w, east-west transcurrent faults; b, boundaries of Caltanissetta subsident basin. The small circles (inset) mark the more important stops on the NATO-ARI field trip.

Figure 36. General geology of Sicily. From Ruggieri (1985)



Geomorphic sketch of the Adriatic Sea (after J.R. Vanney, 1977). 1, ancient delta; 2, recent delta; 3, present deltaic progradation; 4, submerged dune ridges or barrier-beaches; 5, beach-rock; 6, tectonic-karstic depressions; 7, escarpment controlled by structure; 8, paleo-valley; 9, plateau with table-like structure; 10, coastal wave-out platform; 11, plain of marine deposits; 12, hills shaped in Neogene formations; 13, upturned and overthrusted sections in thick (3–4 km) Pliocene series. Abbreviations (islands): Bi, Bisevo; J, Jabuka; L, Lastovo; Pe, Pelagruža, Pi, Pianosa; Su, Sučac; Sv, Svetać; T, Tremiti; V, Vis.

Figure 37. Sea bottom topography of the Adriatic Sea. Water depth contours in meters. From Vanney and Gennesseaux (1985)

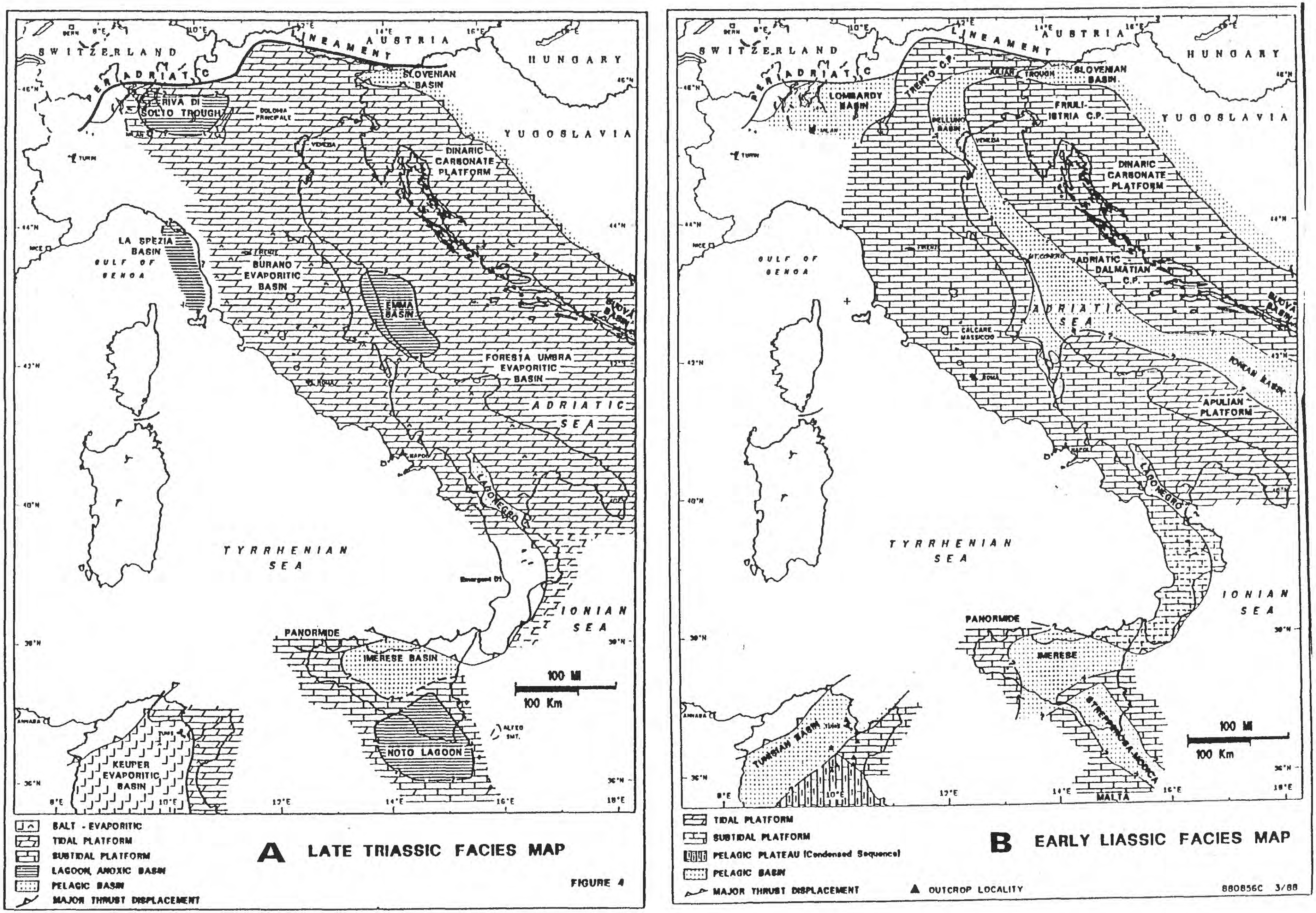


Figure 38. A - Late Triassic facies map, Italy. From Zappaterra (1990)

B - Early Liassic facies map, Italy. From Zappaterra (1990)

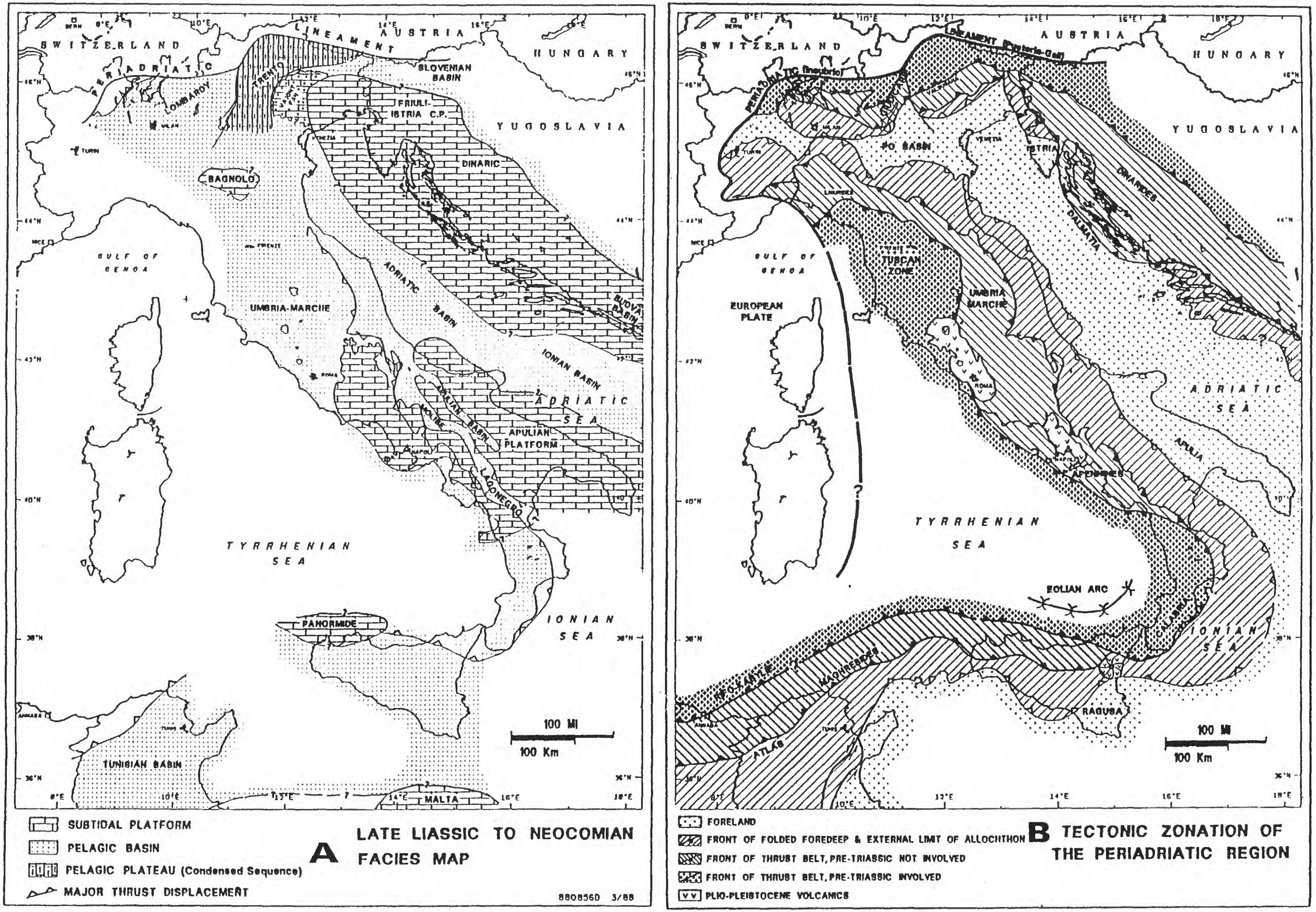
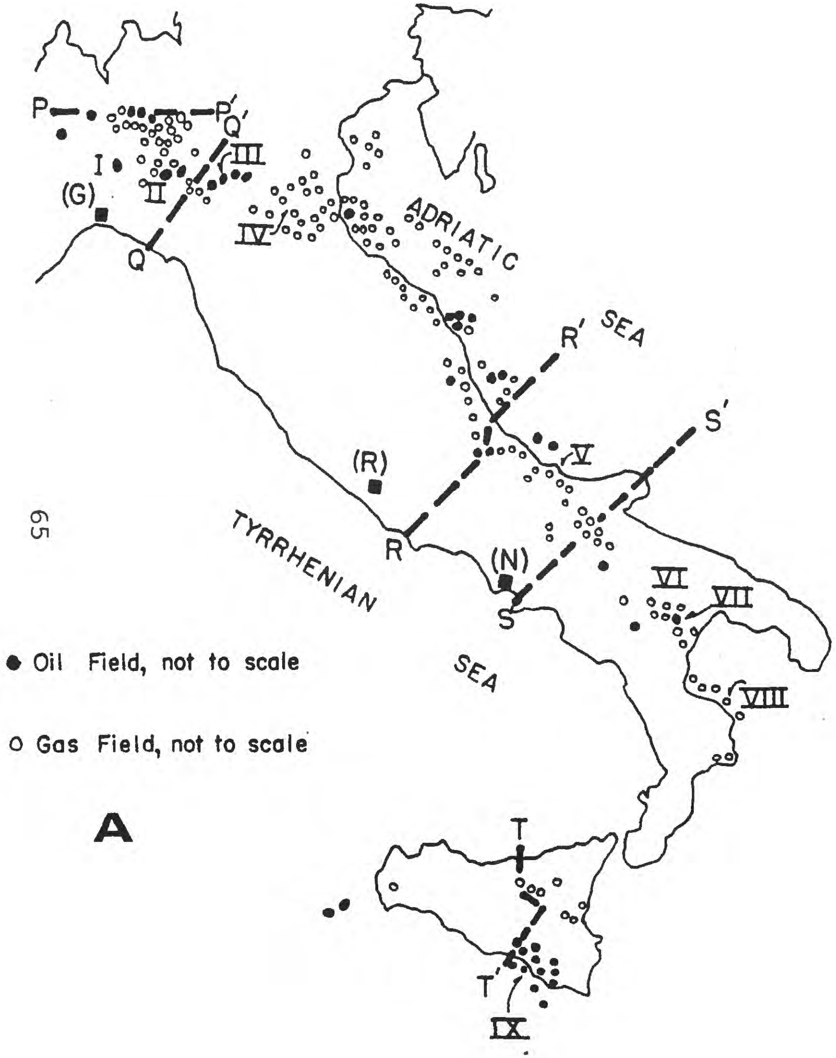
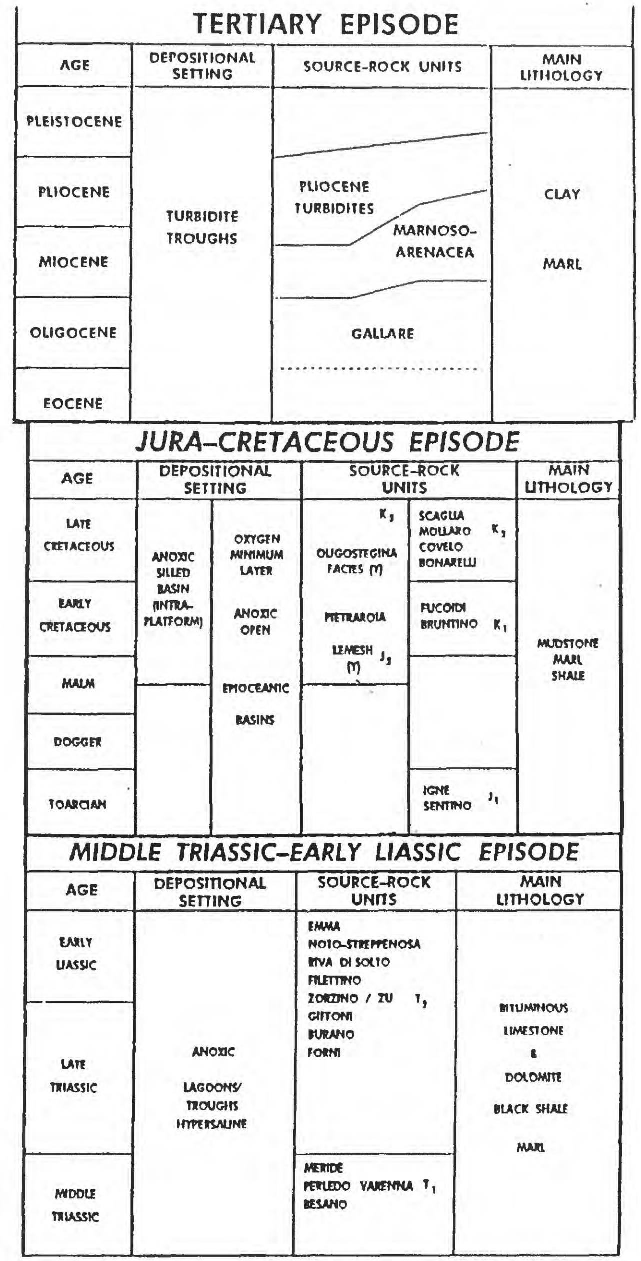


Figure 39. A - Late Liassic to Neocomian facies map, Italy. From Zappaterra (1990)

B - Tectonic zonation

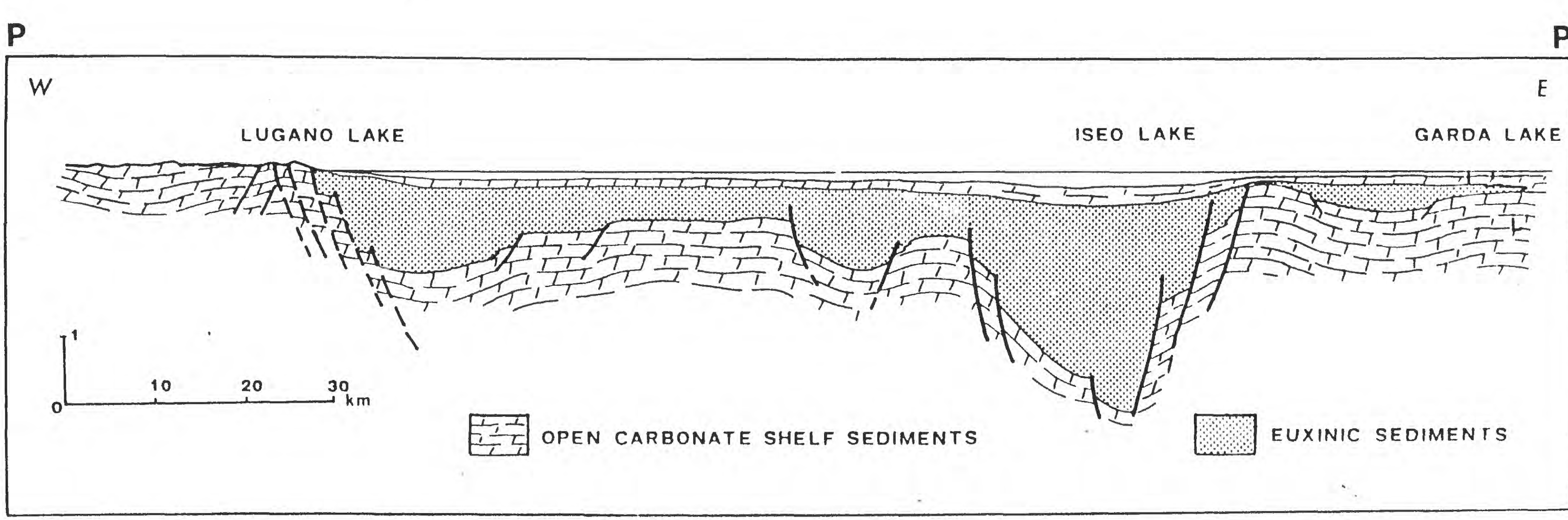




B

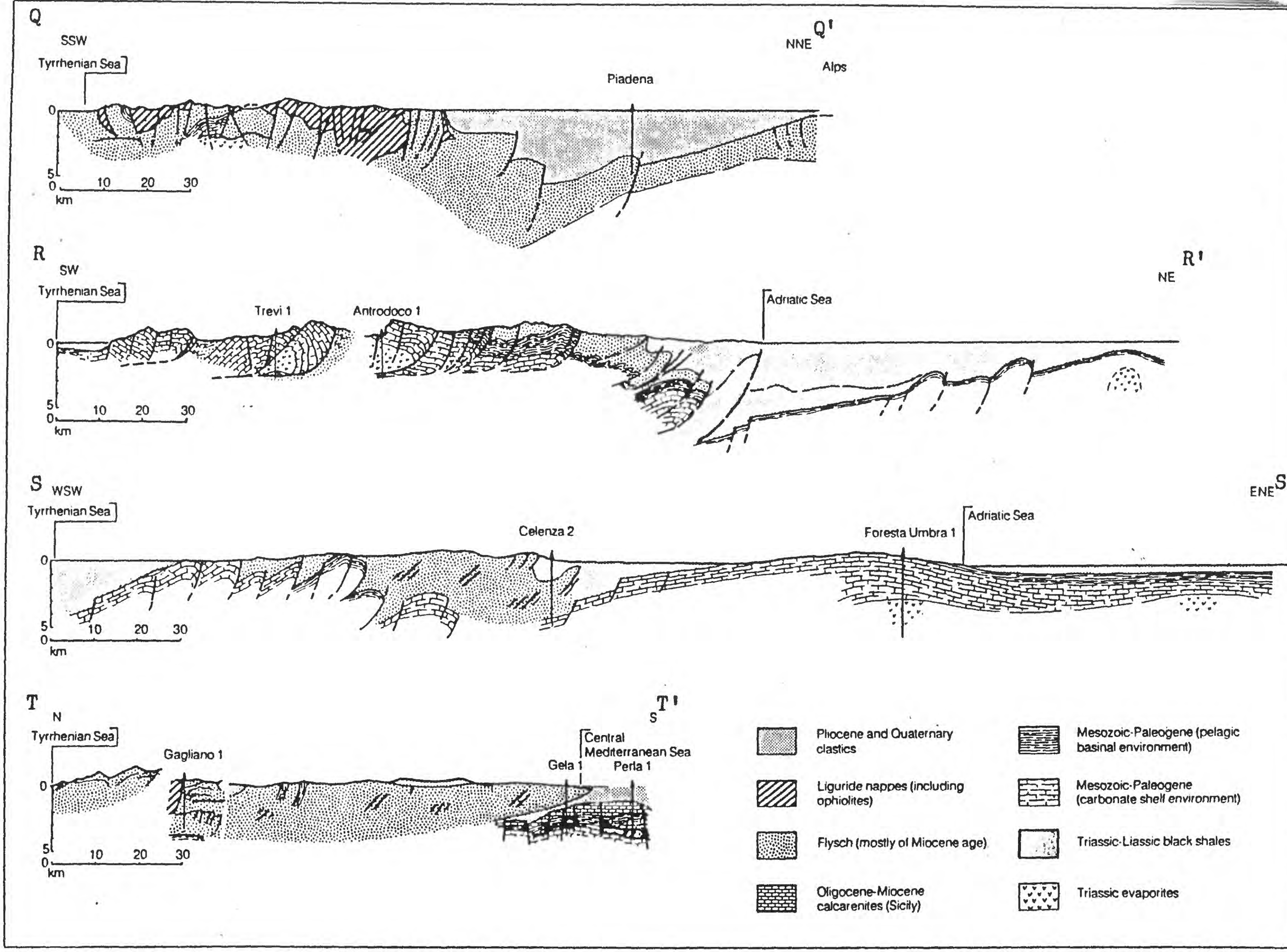
Figure 40. A - Oil and gas fields of Italy. Not to scale

B - Stratigraphic chart, Italy, showing general lithology, depositional setting, and source rock units. From Zappaterra (1990)



Paleostructural cross section through southern Alps of Lombardy (near end of Triassic)

Figure 41. A - West-East paleostructural cross-section, northwestern Italy, illustrating Upper Triassic organic-rich mud and related shelf carbonate deposition in early Mesozoic fault-bounded trough. Location of cross- section shown on figure 40



—Structural cross sections of foredeep and associated Apennines (including Sicily).

Figure 42. Structural-stratigraphic cross-sections of oil and gas occurrences in Apennine belt of Italy and Sicily. From Pieri and Mattavelli (1986). Location of cross-sections shown on figure 40

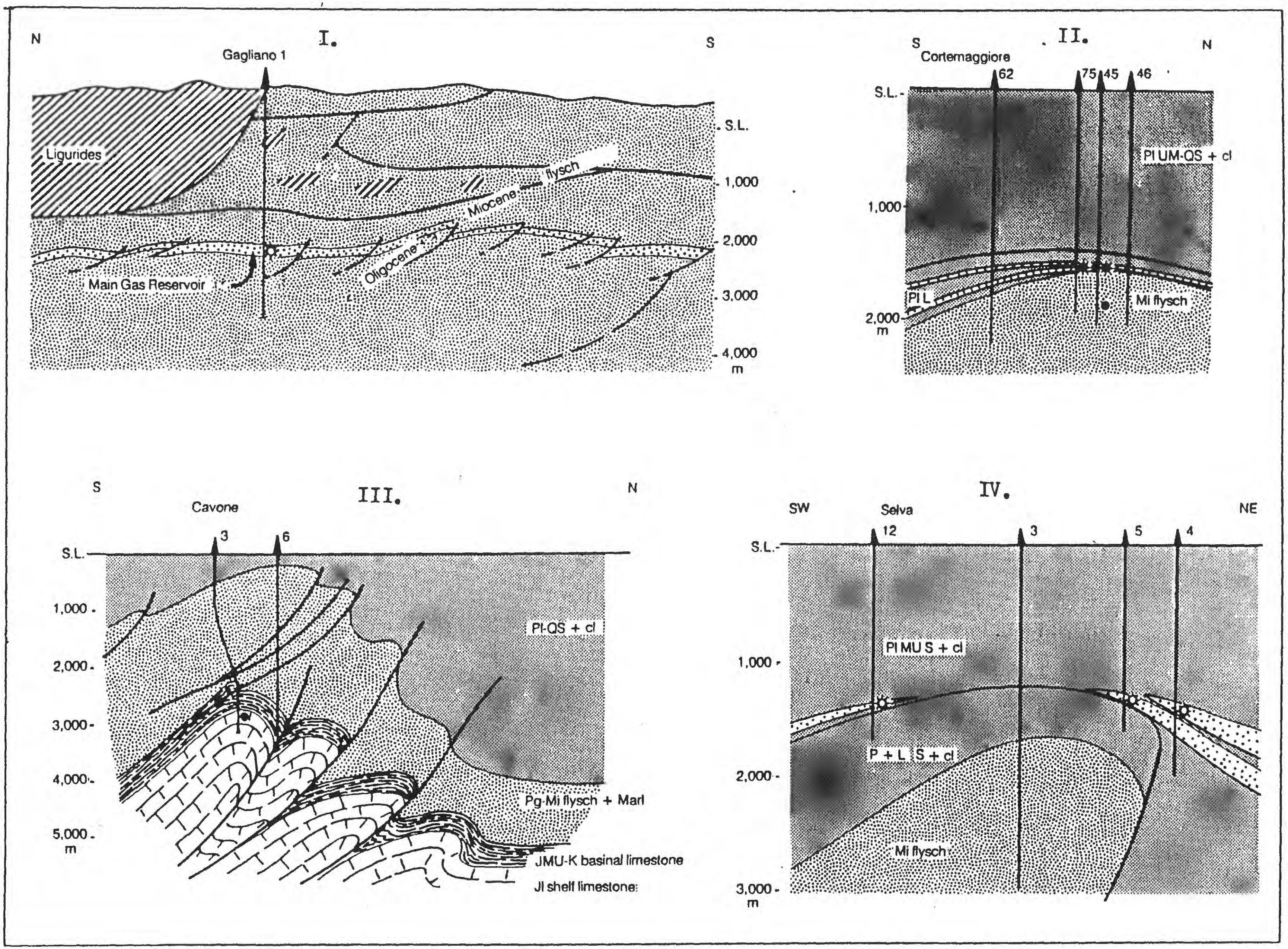
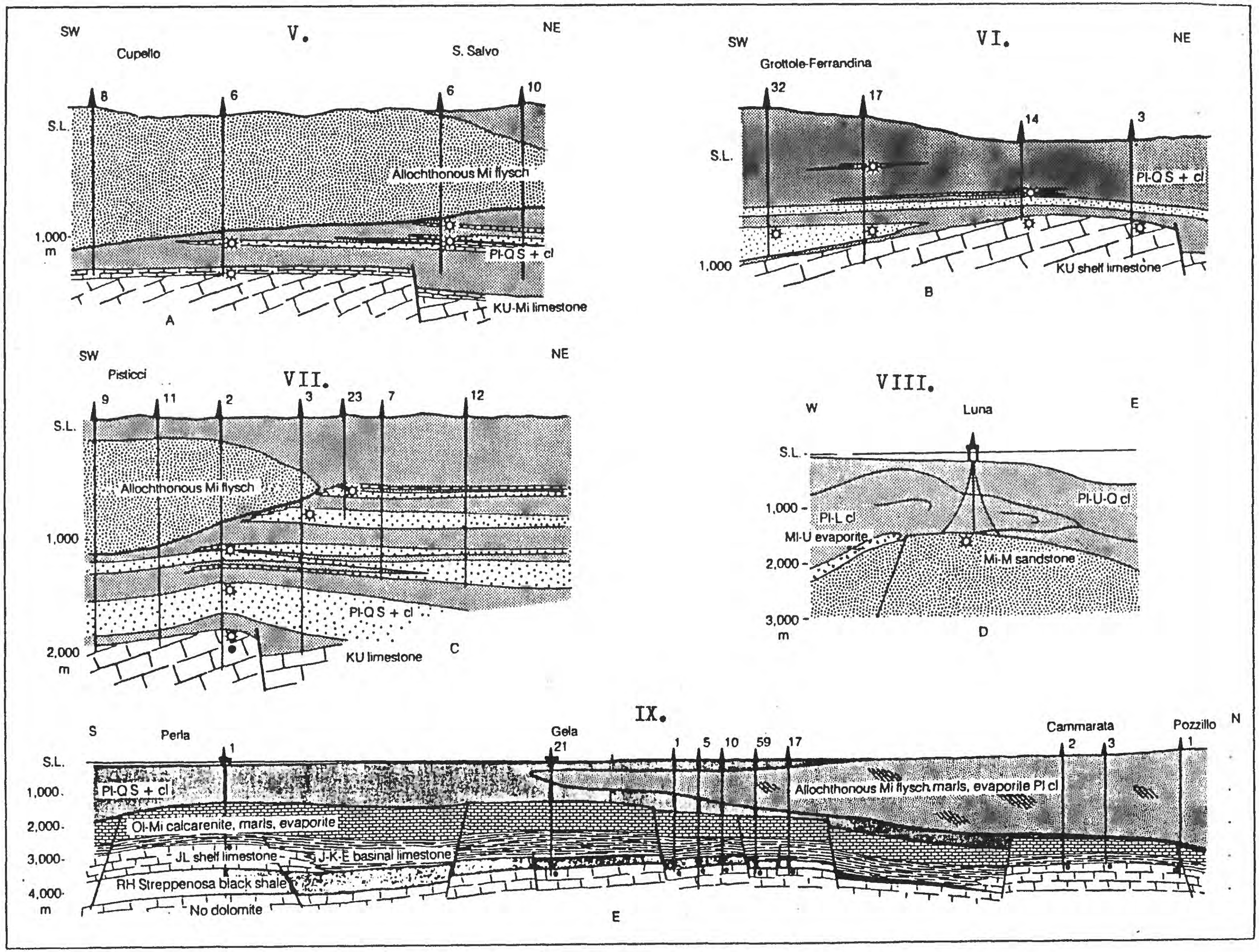


Figure 43. Examples of structure and stratigraphy in selected Italian oil and gas fields. From Pieri and Mattavelli (1986). Locations of fields shown on figure 37. Legend shown on figure 42



–Oil and gas fields: (A) Cupello–S. Salvo, (B) Grottole-Ferrandina, (C) Pisticci, (D) Luna, and (E) Gela-Cammarata-Perla.

Figure 44. Examples of structure and stratigraphy in selected Italian oil and gas fields. From Pieri and Mattavelli (1986). Locations of fields shown on figure 37. Legend shown on figure 42

Major events affecting both the stratigraphic facies and the final structure of the region include: 1) separation of the European and African plates with early movements of Apulia (Adria) during the Jurassic and the creation of new oceanic crust in the Tethyan realm; 2) convergence of the African and European plates, which began in the Cretaceous and initiated the Alpine orogeny, with development of the early phases of the Alps and the Apennines; 3) subduction of the fragmented African (Apulian) plate beneath the European plate, which has been active since the Eocene; 4) detachment and counterclockwise movement of the Sardinia-Corsica massif away from the Iberian (Spain-France) peninsula and collision between this massif and the Apulia-African plate, and further subduction of Apulia beneath the Italian peninsula. Some authors (e.g., Selli, 1985), however, consider that the Sardinia-Corsica Islands were Africa fragments rotated and separated from the African plate; 5) By the end of the Miocene, the roots of the Apennine system were essentially in place, but at least four succeeding compressive phases, progressively moved the Apennine chain toward the northeast, further deepening the Adriatic foredeep and resulting in intricately faulted and folded nappe layers, overlain by a younger clastic sedimentary complex, itself deformed by the succeeding orogenic phase (Patacca and Scandone, 1989). Total shortening in the Apennine system has been calculated as a few tens of kms. in the northwest, about 100 km (60 mi) in the central area, and at least 300 km (180 mi) in the southern (Calabrian) area (Patacca and Scandone, 1989).

The Apennine mountain chain is underlain by a system of older nappes and folds with a northeast vergence and overlain by progressively younger systems. In the northern Apennines, flysch and other shaly units dominate, resulting in a very complex structural system of nappes, folds and faults merging with and overlain by thick late Tertiary clastics in the Alpine foredeep (figs. 39-44). In the northern and central Apennines, Triassic evaporites are the main deeper decollement surface. Other ductile decollement units are present in the Oligocene-Miocene flysch. The foredeep and foreland form a northwest-southeast belt that includes the northeastern margin of the Italian peninsula and the southwestern flank of the Adriatic Sea. To the east of the Apennine chain, the nappe systems are overlain by younger sediments, themselves subsequently deformed by the succeeding orogenic phase. In the southern Apennines, complexly folded and faulted Mesozoic shelf carbonate and clastic sequences are thrust over basinal Mesozoic sequences and Miocene flysch. The orogenic units are overlain by thick Miocene flysch deposited in tectonic troughs formed in advance of older compressive movements. Patacca and Scandone (1989) suggest that the driving mechanism may have been the sinking and dipping of the foreland lithosphere (Apulia) beneath the mountain chain, mostly resulting from the higher density of the subducted slab.

Much of the structure of Sicily is somewhat similar to that of the southern Apennines. Metamorphic and igneous rocks make up the deeper core of the Island with patches of Mesozoic and Tertiary sedimentary cover crossed by the Calabrian Arc (fig. 7). The southern Apennine chain extends across the toe of Italy and continues across northeastern Sicily. The Calabrian Arc crosses northeastern Sicily. Thick Jurassic-Cretaceous carbonates are exposed in the Palermo Mountains and adjacent areas of northwestern Sicily and locally in eastern Sicily. The main Tertiary basins, some with thick clastic deposits, are north of the Calabrian Arc trend. Significant reserves of gas and condensate have been discovered behind the Arc in Miocene Numidian flysch sandstone reservoirs in east-central and western Sicily. In recent years, large reserves of heavy oil have been found in front of the Arc in Mesozoic carbonate reservoirs of southern Italy and southern Sicily.

USGS Team Hydrocarbon Assessment Summary:

Reservoirs - Pliocene-Pleistocene sandstones and turbidites; lower Miocene carbonates; oolitic and reefal Mesozoic carbonates

Source rocks - Triassic-Jurassic shale (Nova-Streppenosa) in local graben areas; Aptian-Albian shale; Pliocene-Pleistocene humic shales (biogenic gas)

Seals - Mainly Tertiary and Quaternary shales; Cretaceous shales

Traps - Sandstone stratigraphic traps and foreland folds; deltaic sandstones and traps in pre-Tertiary nappes and faulted folds (figs. 41-44)

Thermal - generally low, but may be higher locally

Potential - good potential for oil and thermogenic gas in deeper structures beneath flysch deposits and for biogenic gas in foreland clastics and deltaic complexes

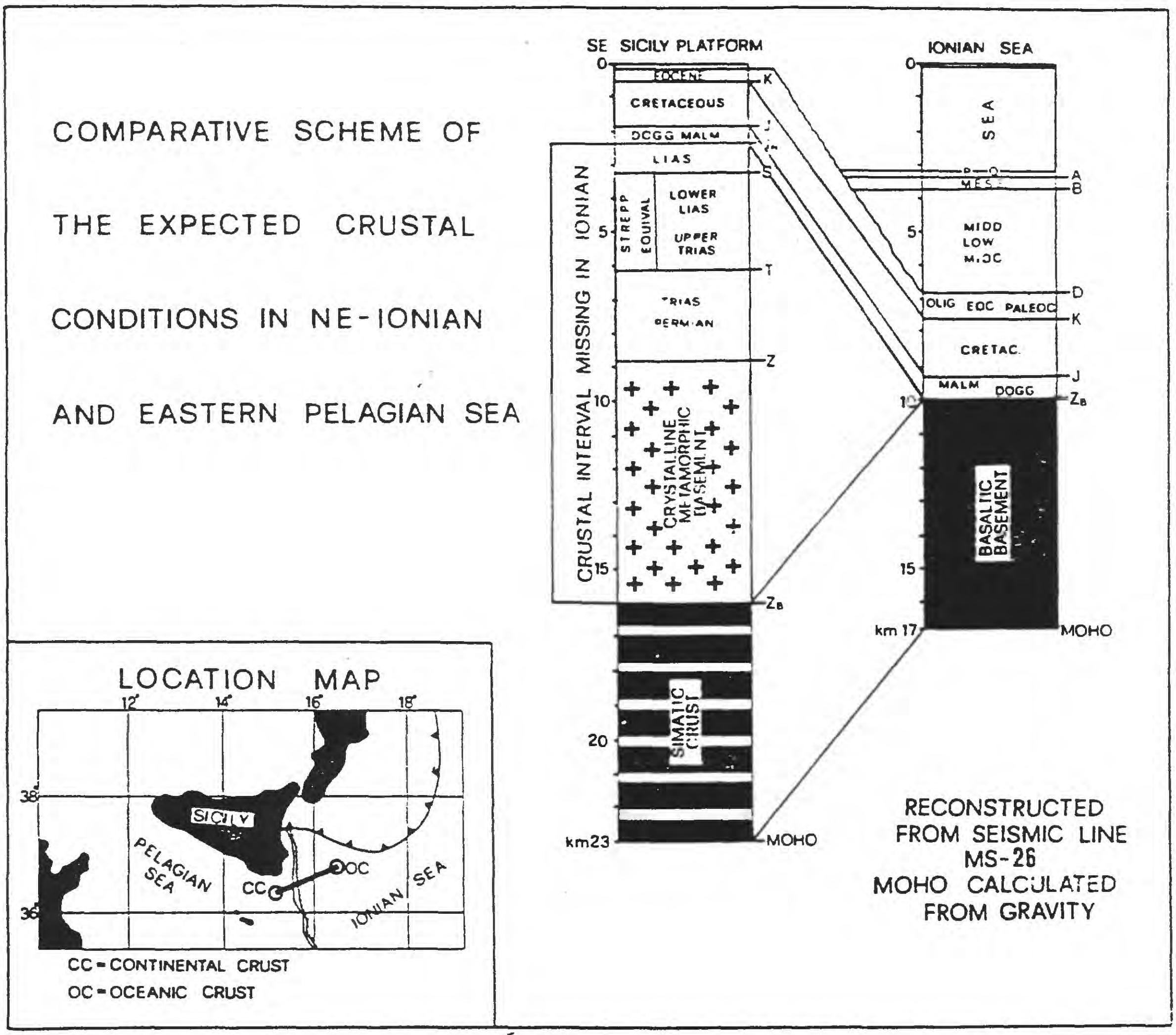
Problems - complex deep structure and discontinuous nature of reservoirs in late Tertiary and Quaternary clastics

Resources - approximately 200 oil and gas fields present with original resources greater than 1.2 BBO and 27 TCF gas

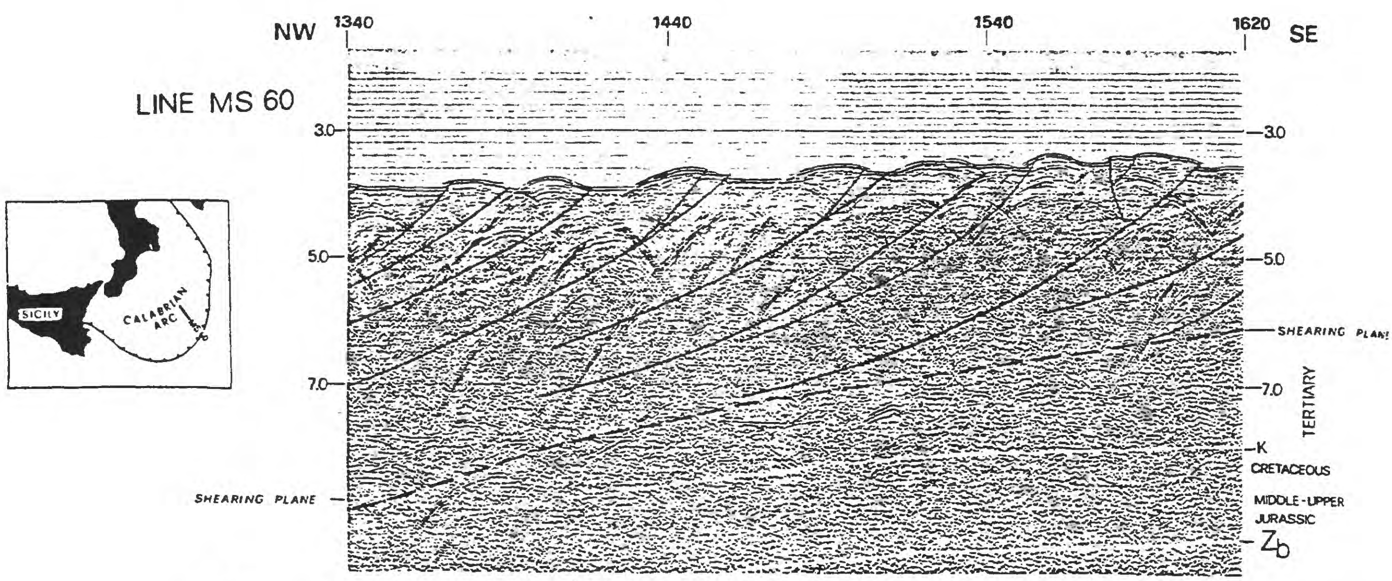
Estimated Undiscovered Resources					
Low Amount (95% probability)		Most Likely Amount (Modal estimate)		High Amount (5% probability)	
Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF
800	10	1,500	30	4,000	75

Ionian Sea basin - Sirte Rise (figs. 45-48)

The Ionian Sea basin occupies the central part of the Mediterranean Sea south and southeast of Italy and north of Libya (figs. 1, 2). Water depths are greater than 2,000 m (6,250 ft) over much of the area. The region is generally underlain by Mesozoic and early Tertiary platform deposits, primarily carbonates, a part of the downfaulted and foundered North African platform. Old oceanic crust, probably of Mesozoic age, Scheme comparing crustal attributes in the Pelagian Sea (Ragusa–Malta Plateau area) with those in the Ionian Basin. (After Finetti, 1982, with permission of O.G.S., Trieste.)



A



B Interpreted Seismic Reflection Line across the Calabrian Arc (Line MS-60; S.P. 1340–1620), showing forearc scraped blocks on a shearing plane that progressively deepens landward, from about 6 to 8 sec. (After Finetti, 1982, with permission of O.G.S., Trieste.)

Figure 45. A - Crustal and stratigraphic interpretations, offshore southeastern Sicily and Ionian Sea in front of Calabrian Arc; B - Seismic cross-section across Calabrian Arc. From Finetti (1985)

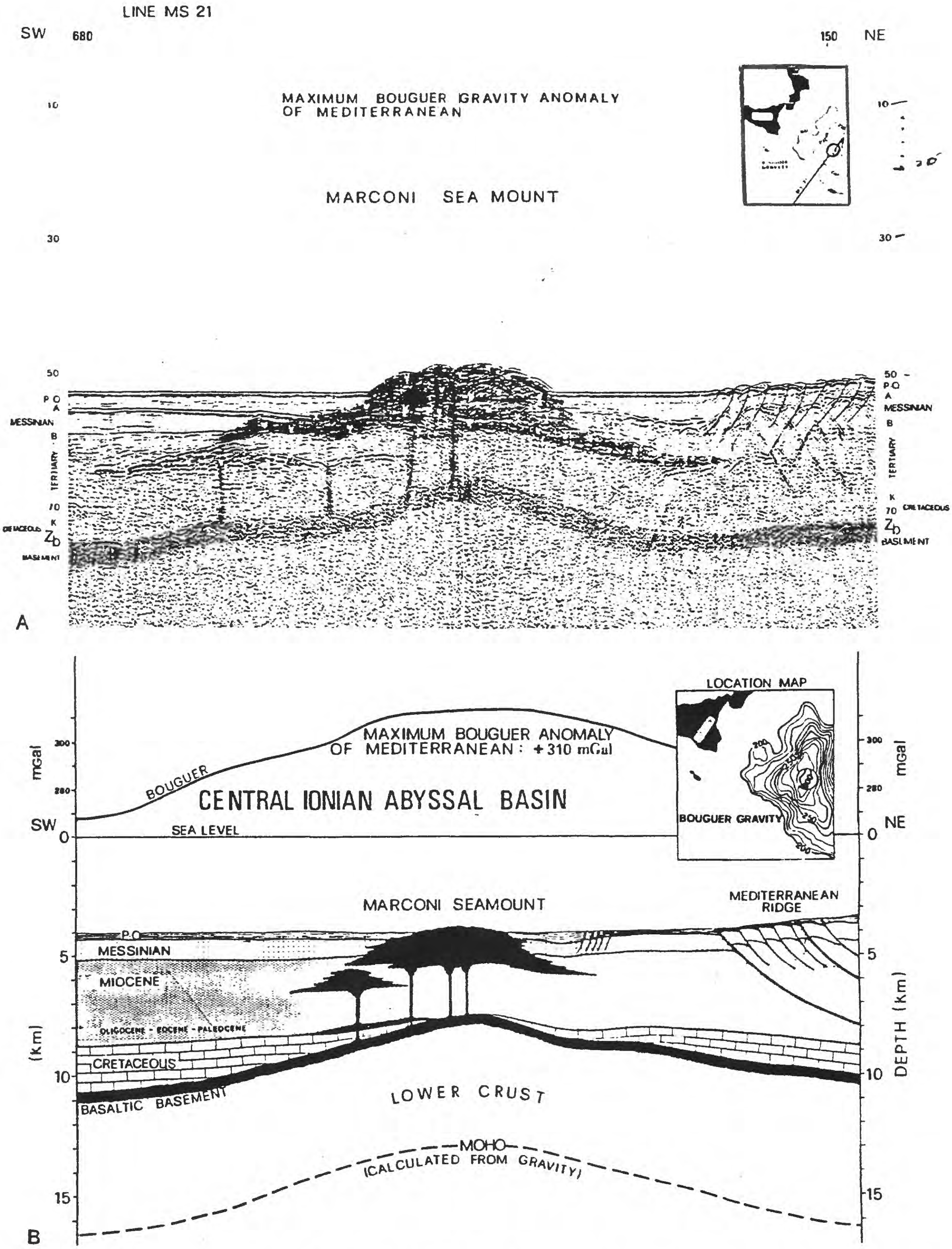
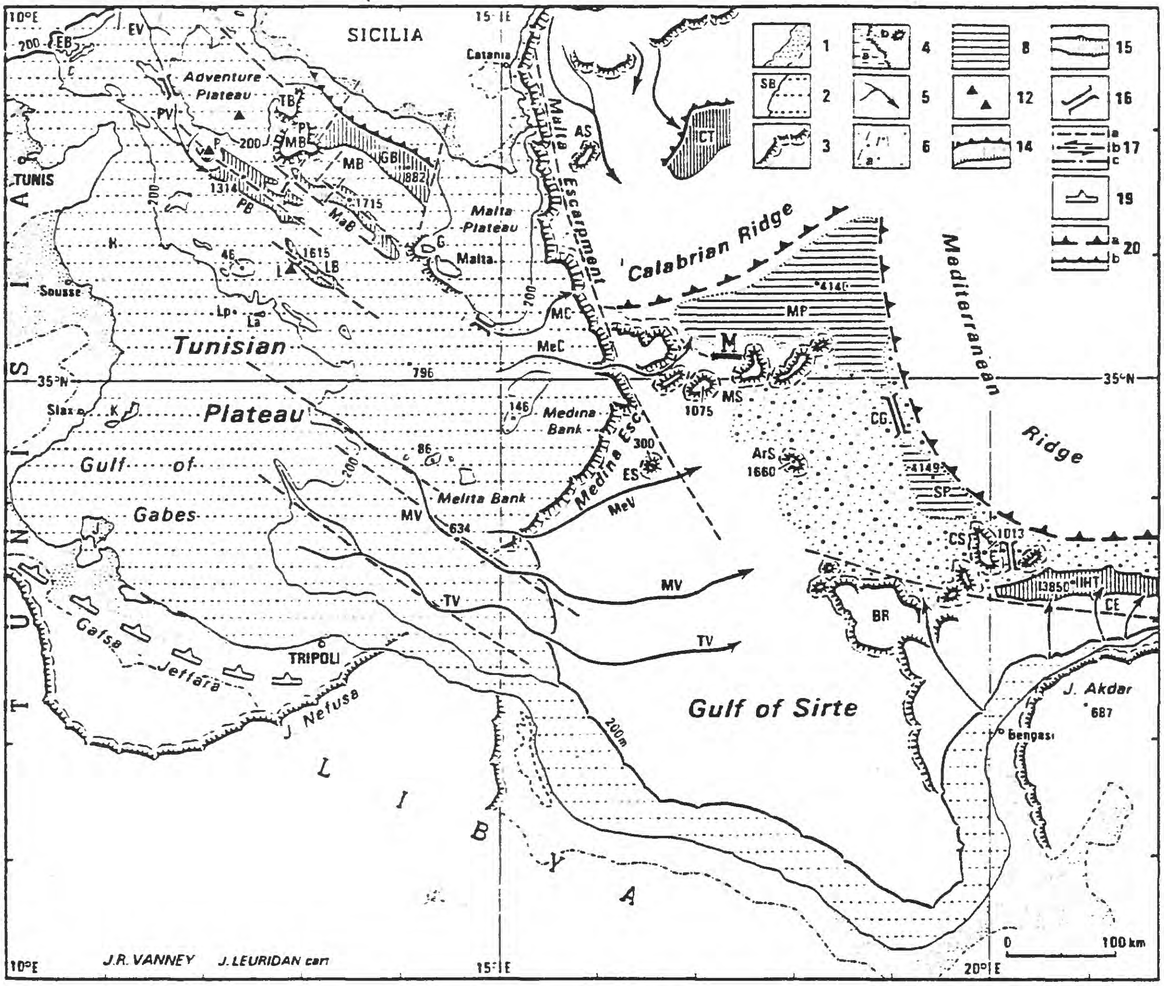


Fig. 10.11. A, interpreted Seismic Reflection Line in the Ionian abyssal basin (Line MS-21; S.P. 680–150), located on the maximum Bouguer anomaly area (+310 mGal) in the Central Ionian Basin. Note the prominent magmatic extrusions forming a seamount herein named the Marconi Seamount. The sedimentary sequence is considerably thinned, and the basement uplifted. B, interpretation of area shown in A depicting the prominent volcanic activity associated with NQ and probably older phases. (After Finetti, 1982, with permission of O.G.S., Trieste.)

Figure 46. Seismic interpretation, Marconi Seamount area, central Ionian basin. From Finetti (1985). Location of Marconi Seamount shown on figures 47 and 48



.. South-central Mediterranean Sea (Pelagian Sea and Gulf of Sirte). 1. coastal and lacustrine plain; 2, continental shelf; 3. escarpment; 4. marginal plateau (a) and seamount (b); 5. submarine canyon and sea valley; 6, continental rise and deep-sea fan; 8, basin plain; 12, volcanic features; 14, subduction; 15, faulted trough; 16, submarine passage; 17, fracture; 19, monocline; 20, frontal boundary features (a) and olistostromes (b). Additional legend shown in Figure 1.7. Abbreviations: AS, Alfeo Smt; ArS, Archimedes Smt; BR, Benghazi Ridge; CE, Cyrenaica Escarpment; CG, Callymachos–Ionian Gap; CS, Cyrene Smt; CT, Calabrian Trench; EB, Esquerquis Bk; ES, Epicharmos Smt; EV, Egadi Valley; G. Gozo Isl.; GB, Gela Basin; H. Gulf of Hammamet; HT, Herodotus Trench; J, Jerba Isl., K, Kerkennah Isl.; L, Linosa Isl., LB, Linosa Basin; La, Lampedusa Isl.; Lp, Lampione Isl.; MaB, Malta Basin; MB, Madrepore Bk; MC, Malta Channel; MeC, Medina Channel; MeV, Melita Valley; MP, Messina Plain; MS, Medina Smt; MV, Misratha Valley; P, Pantelleria Isl.; PB, Pantelleria Basin; PV, Pantelleria Valley; PMB, Pinne Marine Bk; SP, Sirte Plain; TB, Terrible Bk; TV, Tripolitanian Valley.

Figure 47. Sea bottom features, Ionian Sea area. Modified after Vanney and Gennesseaux (1985). Approximate location of Marconi Seamount of figure 46, shown by letter M

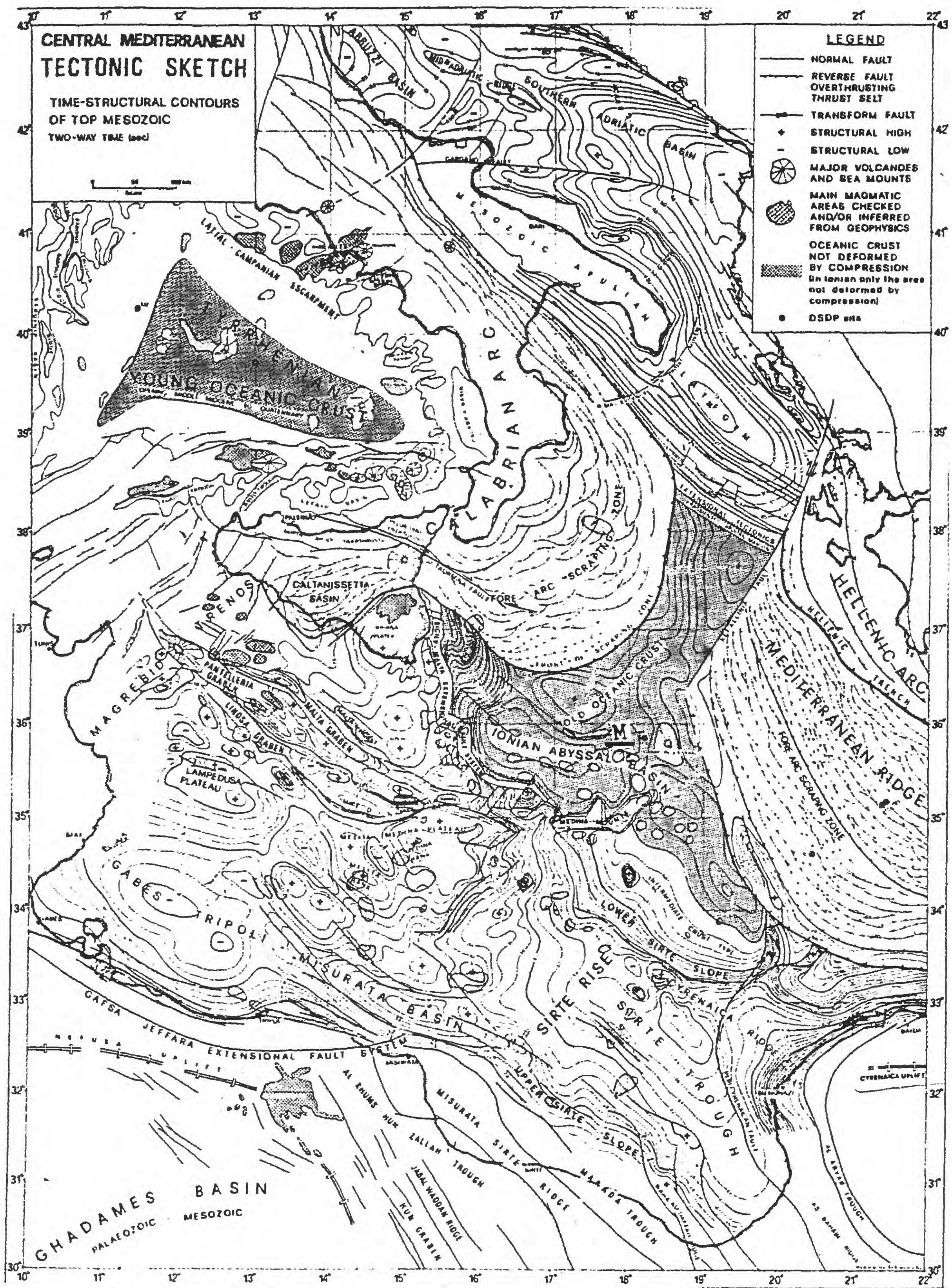


Fig. 10.12. Time-structural map of the top of the Mesozoic, from multichannel seismic exploration data. (After Finetti, 1982, with permission of O.G.S., Trieste.)

Figure 48. Structure, top of Mesozoic, Ionian Sea. Modified after Finetti (1985).

Approximate location of Marconi Seamount of figure 46, shown by letter M underlies young Cenozoic sediments in the Ionian abyssal plain, where water depths are as much as 4,100 m (17,000 ft). Four main phases of extensional faulting are recognized in the general Ionian Sea area (Finetti, 1985): 1) Middle and Upper Triassic, which opened the west-east Gabes trough along the south border of the Pelagian shelf adjacent to northwestern Libya, and the west-east Streppenosa trough adjacent to southern Sicily (fig. 1, 2, 36); 2) Middle Jurassic, which resulted in opening of the Ionian Sea basin. At this time, the Apulian plate continued movement to the northeast; 3) Middle and Upper Cretaceous, accompanied by subsidence; and 4) Middle Miocene to Quaternary, accompanied by extensional faulting and volcanic activity. This later extensional phase, still active today, has deformed the entire sedimentary sequence into a tectonically complex system of faulted troughs, uplifted blocks, volcanic uplifts, and basalt-cored seamounts (figs. 46-48), as well as probably salt movement induced features adjacent to the North African shelf. Deformation apparently was less intense in the southern area where the Pelagian platform, Sirte Rise, and Sirte trough are dominant features (Finetti, 1985).

The pre-Neogene sedimentary cover in the Ionian Sea basin and adjacent area is as old as early to middle Mesozoic and ranges in thickness from as much as 8-10 km (25-30,000 ft) to less than 5 km (16,000 ft) (Morelli, 1985; Finetti, 1985), with minimal cover by young sediments in the more recently faulted areas, particularly the central abyssal plain (figs. 12-14). The Sirte Rise lies between the Cyrenaica escarpment on the east and the Pelagian platform on the west (figs. 47, 48). The rise is essentially a northward-dipping monocline representing a collapsed block of the African plate, detached from the onshore Sirte basin and cut by numerous extensional faults and step-like tilted blocks (Finetti, 1985). The sedimentary cover is as much as 10 km (33,000 ft) or more thick, consisting of north African Upper Cretaceous platform carbonates and clastics resting on Cambro-Ordovician or younger Paleozoic beds and overlain by a thick Cenozoic cover (Finetti, 1985; Vanney & Gennesseaux, 1985; Biju-Duval and others, 1979). Geophysical results indicate northward thickening of the pre-Upper Cretaceous Mesozoic section beneath the Upper Cretaceous beds. This older section is correlated with a similar sedimentary sequence on the Pelagian platform to the west and the Cyrenaica platform to the east.

<u>USGS Team Hydrocarbon Assessment Summary:</u>

Reservoirs - Mesozoic and early Tertiary platform carbonates and sandstones; Neogene sandstones and possibly turbidites; possibly Paleozoic sandstones and carbonates on some fault blocks

Source rocks - Paleogene and Cretaceous shales and argillaceous limestones; possibly Neogene humic shales; possibly Silurian, Devonian, and Carboniferous shales, although these are likely overmature in most of the area

Seals - Mesozoic and Paleogene shales and possibly some evaporites; Neogene shales and evaporites

Traps - Fault blocks in pre-Neogene section; isolated carbonate build-ups in Mesozoic and Paleogene; isolated sandstones and turbidites in Neogene and possibly Paleogene beds in front of buried Calabrian Arc; salt structures and possibly volcanic uplifts

Thermal conditions - Unknown

Potential - Good to fair potential offshore of Libyan-Pelagian shelf, poor to fair potential for gas in the deeper basin

Problems - Water depths; complex structure and need for high-resolution seismic work; vulcanism in central and northern area

Resources - No oil or gas fields present

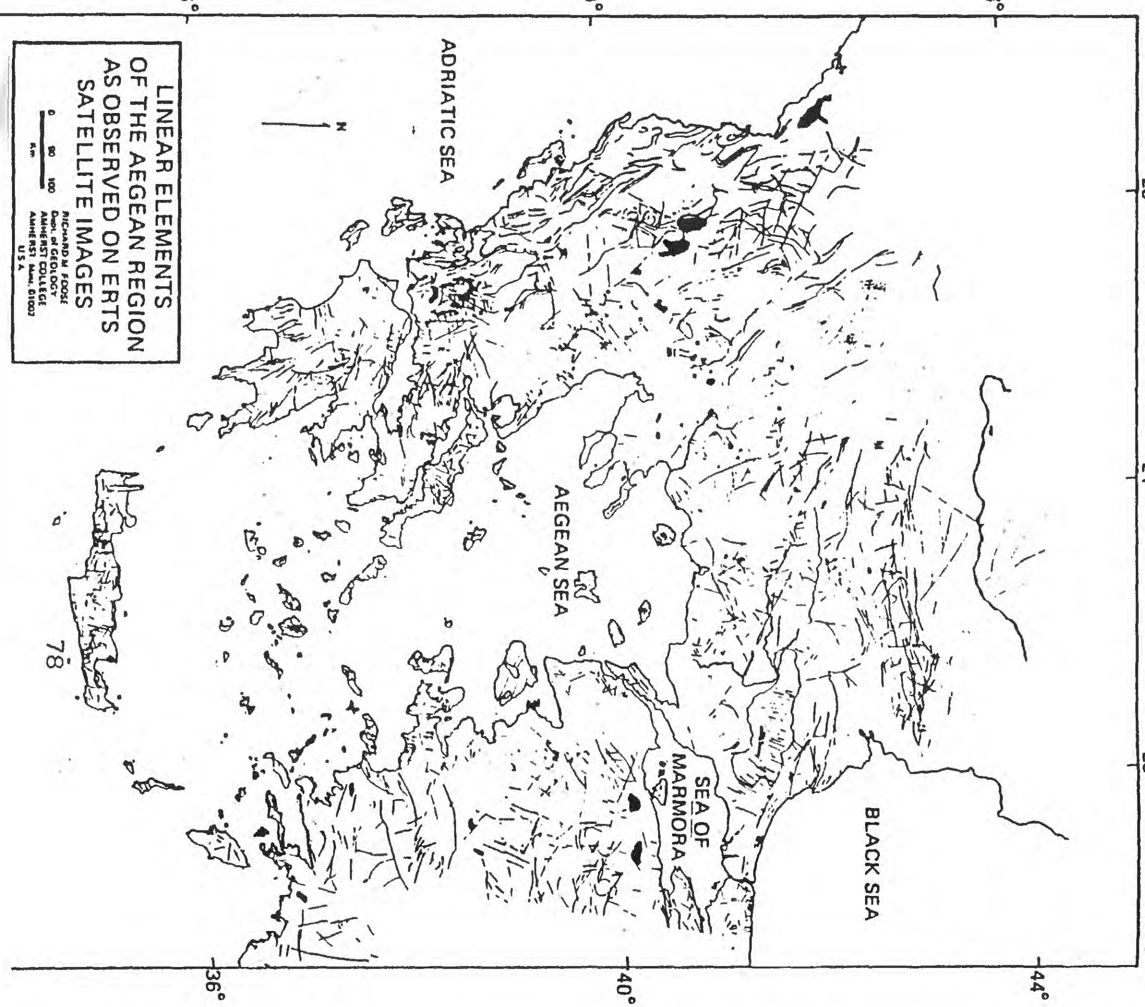
Estimated Undiscovered Resources					
Low Amount (95% probability)		Most Likely Amount (Modal estimate)		High Amount (5% probability)	
Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF
25	15	200	50	1,000	150

Eastern Mediterranean

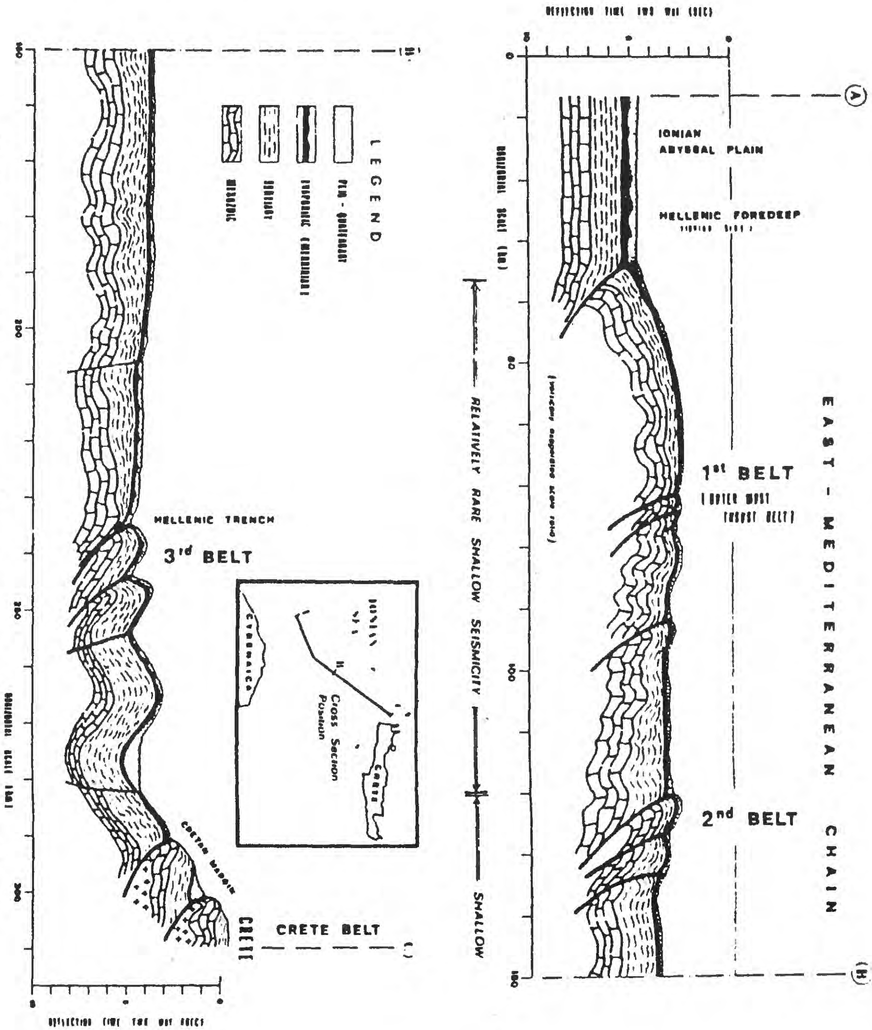
The Eastern Mediterranean assessment province includes: 1) the Mediterranean Ridge-Hellenic Trench - Herodotus basin area; 2) the Nile Cone-Levant platform area; 3) the Hellenic Arc-Aegean basin area; and 4) the Cyprus basin-Cyprus Arc area (figs. 1, 15, 49-53)

Mediterranean Ridge-Hellenic Trench-Herodotus basin

The Mediterranean Ridge is an arcuate seafloor feature approximately 100 kms (60 mi) wide and approximately 2,000 km (1,200 mi) long, parallel to the Hellenic Arc (figs. 1, 2). It has been described as the "external envelope" of the Hellenic Arc, separated from the main arc by the downwarped Hellenic trench (Morelli, 1985). The submarine swell or ridge consists of a series of structurally-deformed "bundles" of controversial origin. Several interpretations have been offered, including compression of an outer arc system, autochthonous sliding, or decollement (Vanney and Genesseaux, 1985). Geophysical studies indicate that the Ridge may follow the zone of present-day subduction of the African plate beneath the European plate related to continuing late Cenozoic movement of Africa toward Europe. Seismic results indicate the presence of a thick sedimentary sequence (10-11 km or 33-35,000 ft) in the ridge area (figs. 13, 15, 50) (Morelli, 1985).

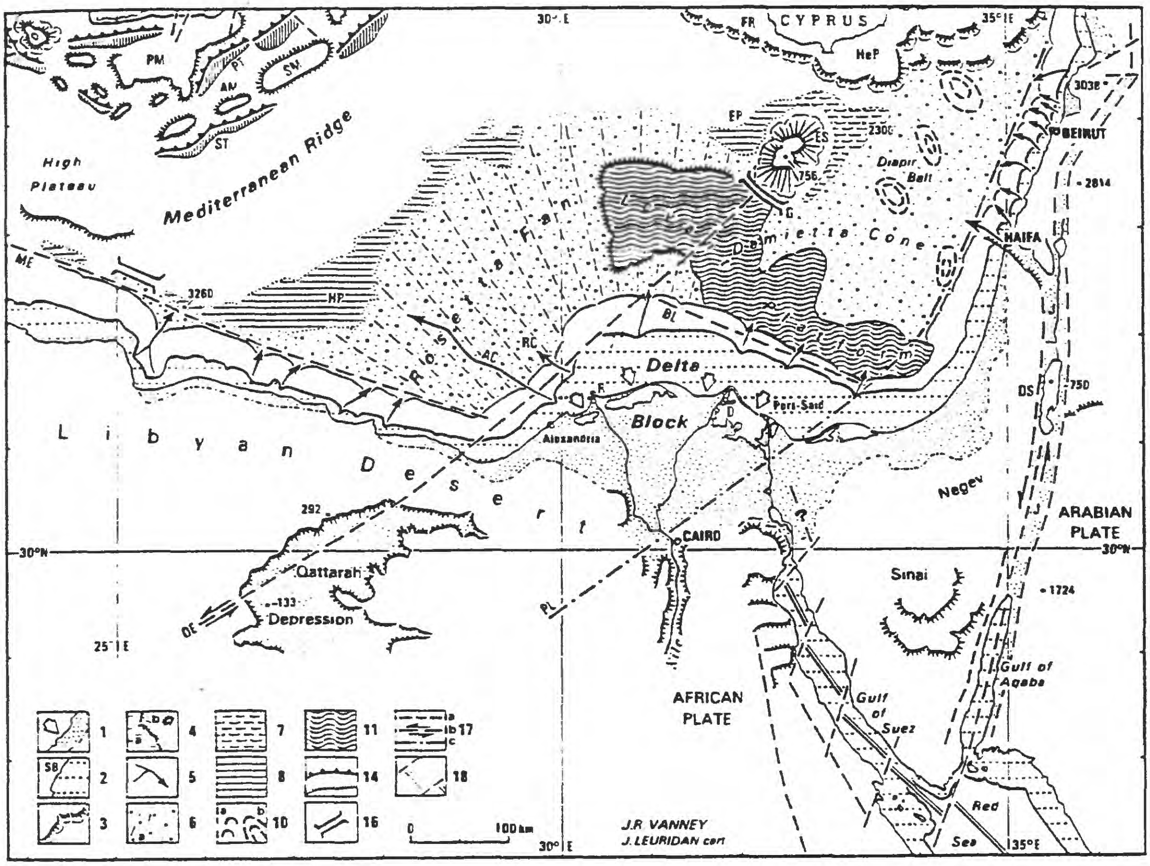


A. Lineament map of the Aegean Basin. From Foose, 1977

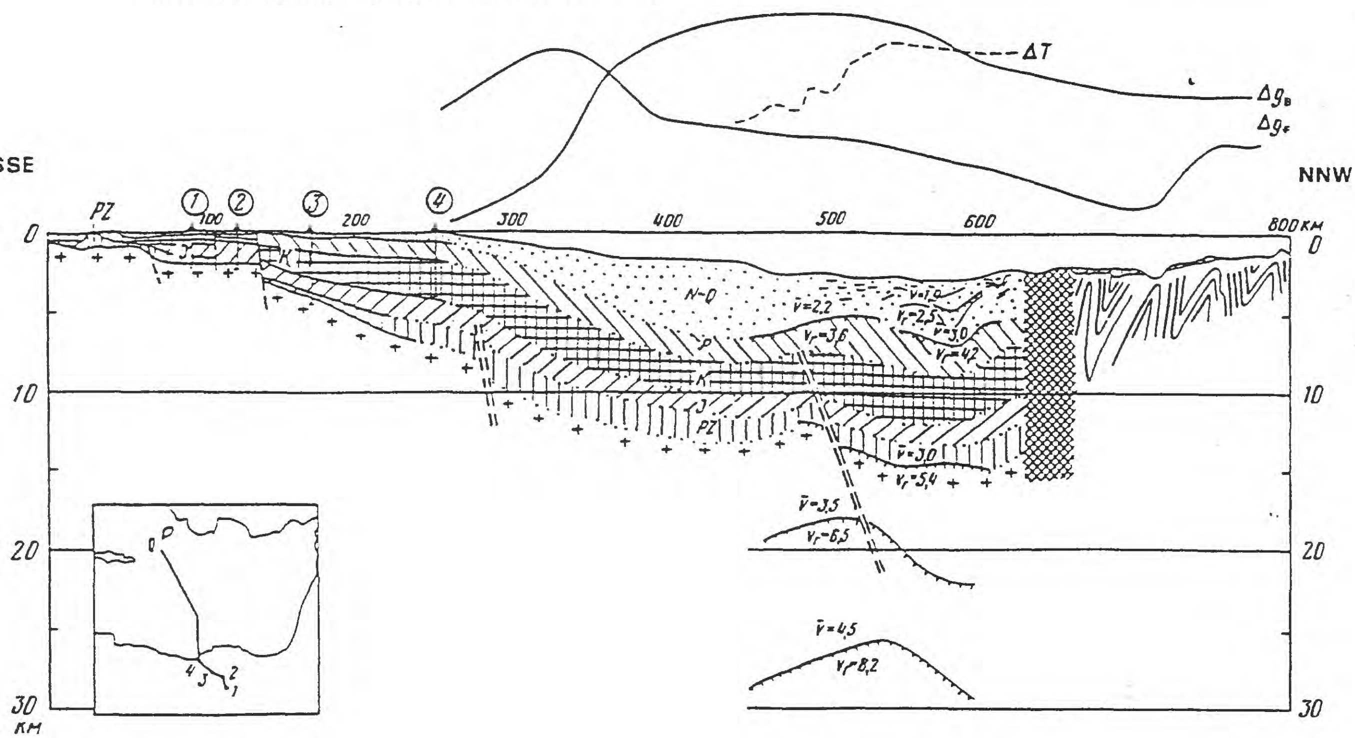


B. Schematic cross-section through East-Mediterranean chain south of Crete, based on seismic reflection data [Finetti 1976]. The structure in the Cretan margin is not controlled by seismic data, it has been completed by geological consideration. The Plio-Quaternary sediments and the evaporites are enlarged in thickness in order to display their occurrence.

Figure 49. A - Schematic southwest-northeast structural-stratigraphic cross-section offshore northeastern Libya to west of Crete. From Giese and others (1982). B - Map of lineaments, Aegean-Greece region. From Foose (1985)

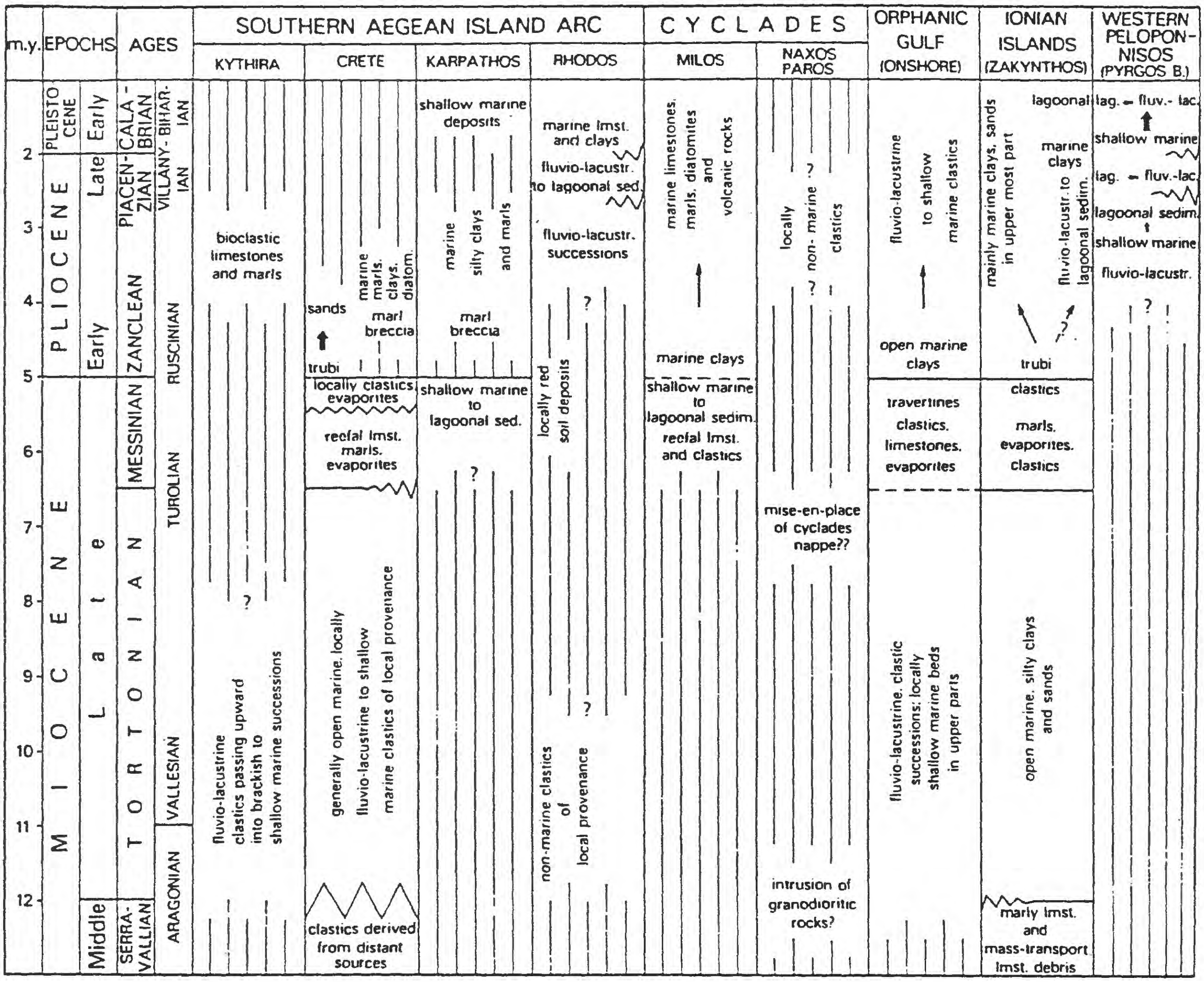


A. Nilotic and Levant margins. 1. coastal and lacustrine plain (arrow: retreating coast line); 2. continental shelf (SB: shelfbreak); 3. escarpment; 4, marginal plateau (a) and seamount (b); 5. submarine canyon and sea valley; 6, continental rise and deep-sea fan (a); 7. erosional moat; 8. basin plain; 10. halokinetic features. dome (a) and low diapir (b); 11. Levant Platform; 14. subduction trench; 16. submarine passage; 17, fracture, fault (a), shear zone (b), buried structure (c); 18, spreading axis (Red Sea). Abbreviations: AC. Alexandria Canyon; AM. Ariane Mountain; BL, Bardawil Line; D. Damietta; DS. Dead Sea; EP, Eratosthenes Plain; ES. Eratosthenes Smt; FR. Florence Rise; HP. Hecateus Plateau; J. Jordan Rift; ME, Marmarica Escarpment; Pl, Pelusium Line; PM, Ptolemy Mountains; PT, Pliny Trench; QE, Qattara–Eratosthenes Line; R. Rashid; RC. Rashid Canyon; SM, Strabo Mountain; ST, Strabo Trench.



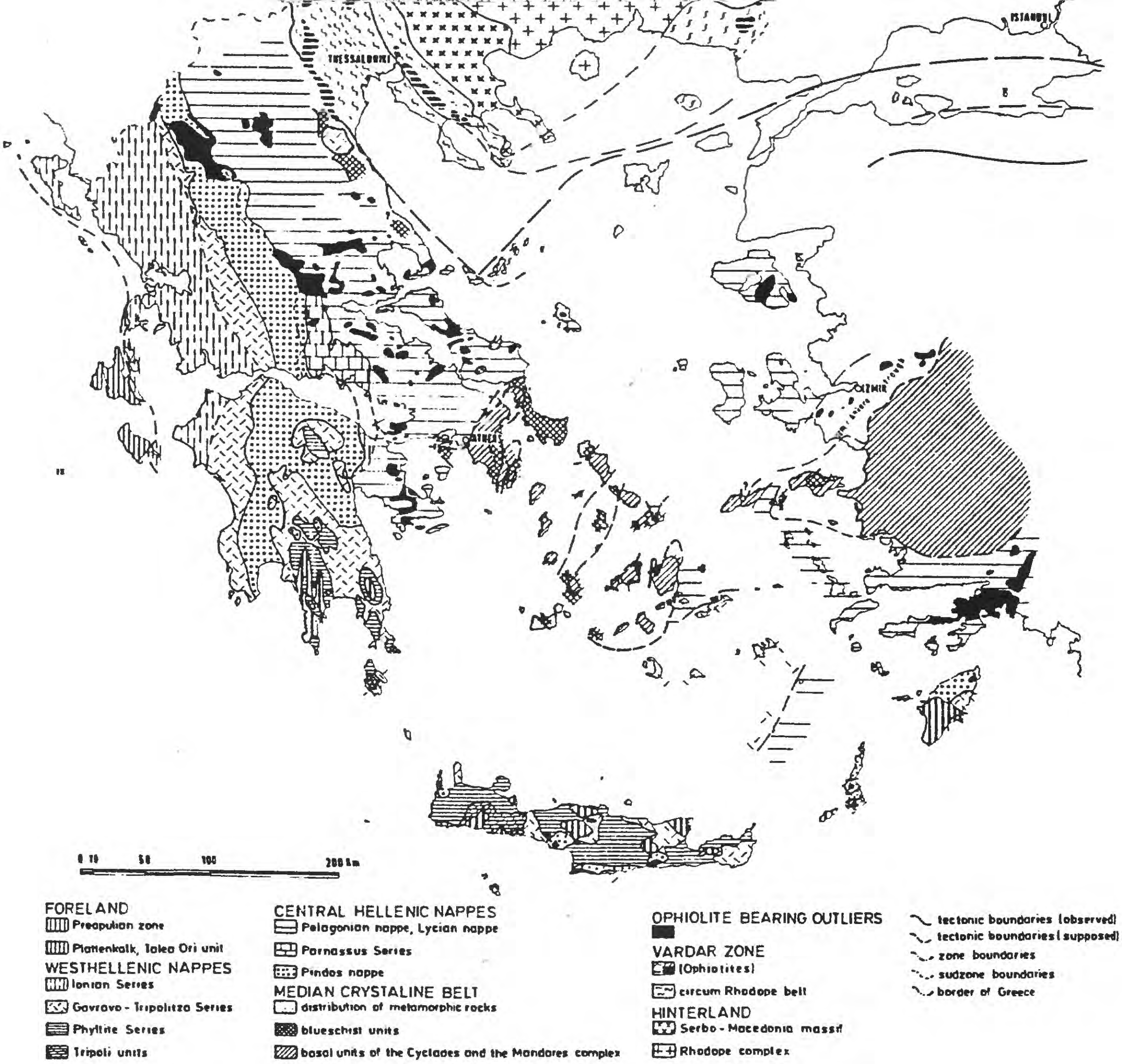
B. Geological cross section based on Soviet geophysical studies and borehole data. From Malovitskiy et al. (1975).

Figure 50. A - Sea bottom features, eastern Mediterranean. From Vanney and Gennesseaux (1985). B - SSE-NNW schematic structural-stratigraphic cross-section, Nile Delta to west of Crete. From Morelli (1985)

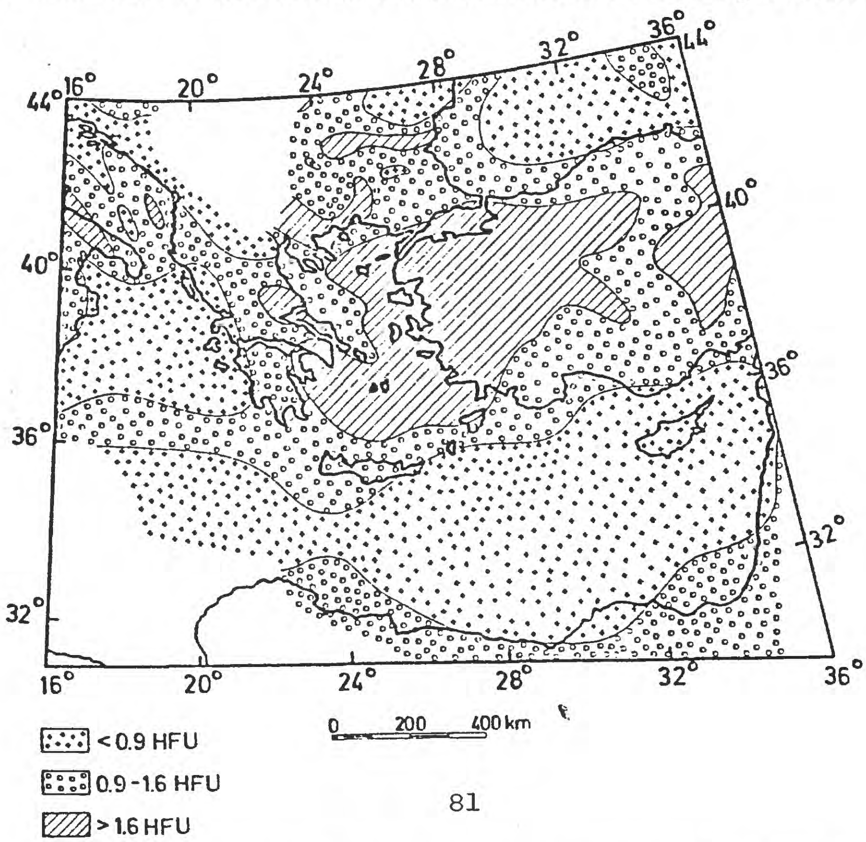


Summary chart showing characteristic aspects of late Cenozoic sequences in various parts of the Aegean region. Vertical lines refer to gaps in the sedimentary record.

Figure 51. Stratigraphic correlation chart, Greece area From Muelenkamp (1985)



A. Geological units of the Hellenides and their distribution into zones according to Jacobshagen and others (1978).



B. Heat-flow map of the Eastern Mediterranean region. After Čermák (1979).

Figure 52. A - Generalized geologic map, Greece - western Turkey-Crete area. From Makris (1985). B - Heat-flow map, eastern Mediterranean region. From Makris (1985)

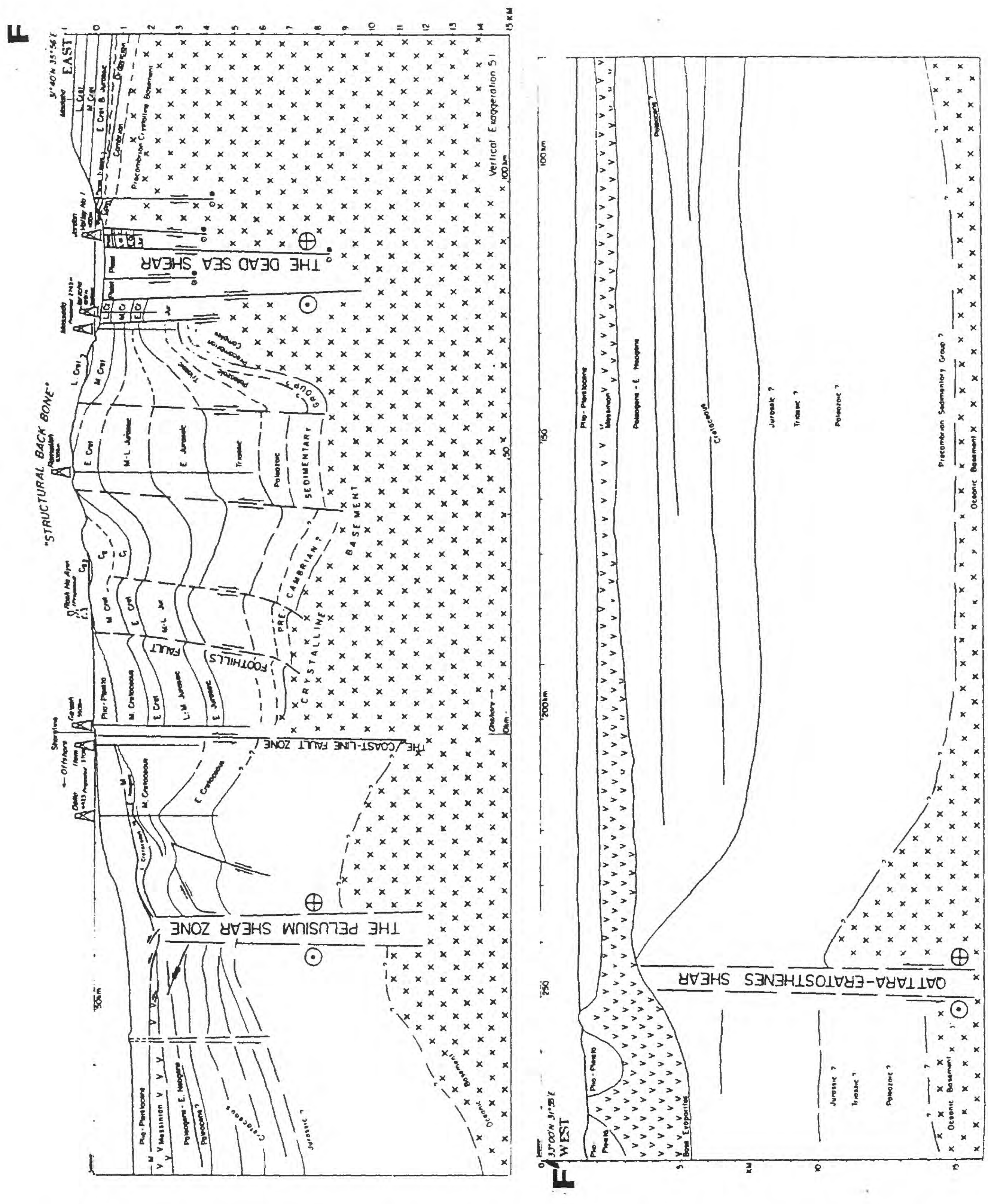
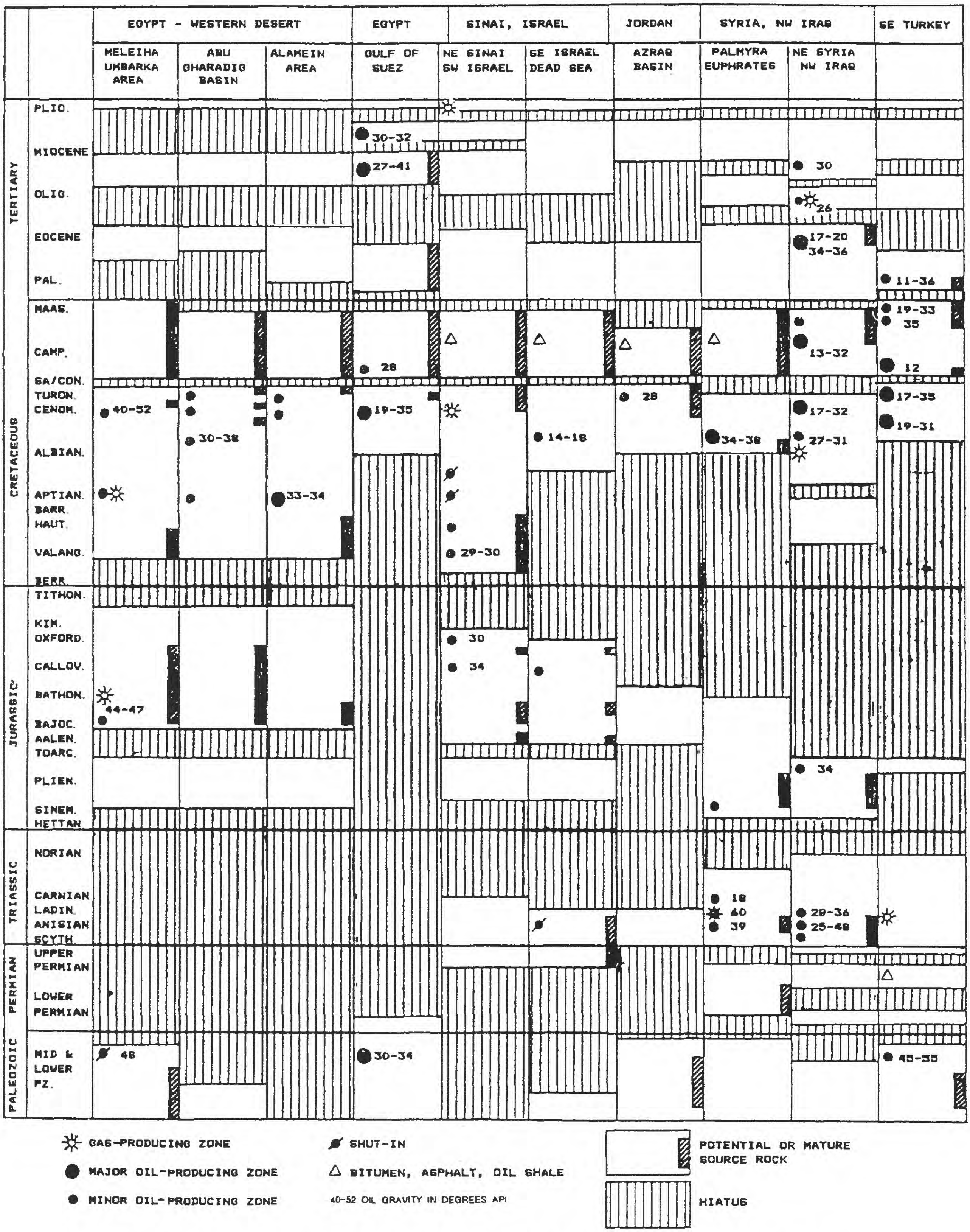


Fig. 12.4. Geological cross section from the Trans-Jordan Plateau on the east-southeast to the Qattara–Eratosthenes Shear on the west-northwest. Vertical exaggeration is 5 : 1. Surface geological and topographic data onshore are from Picard and Golani (1974) and Bender (1975). Subsurface data are from the Oil Exploration (Investments) Ltd. Sources of other data are specified in the text. Numbers beneath drillhole names represent total depth (TD) in meters, uncorrected for ground elevation. A systematic pattern of moderate westward structures rising toward the adjacent shears is recognized. Note rather abrupt structural drops to the west of the shears.

Figure 53. East-west structural-stratigraphic cross-section F - F', Levant area to southwest of Cyprus. From Neev and others (1985). Location of cross-section shown on figure 2



—Stratigraphic distribution of oil and gas production in the Eastern Mediterranean region.

54. Stratigraphic correlation chart, showing geologic occurrence of oil and gas and potential source rock occurrences, eastern Mediterranean region. From May (1991)

The Hellenic trench is interpreted as the main foredeep area of the Hellenic Arc, which extends approximately 2,000 km (1,200 mi) in an easterly direction to approximately merge with the Cyprus Arc offshore of southwestern Turkey (fig. 1). The trench consists of a series of elongated, but relatively small, deep water structural downwarps, including the Matapan trench south of Peloponnesus (figs. 1, 49, 50), containing some of the deepest Mediterranean sea floor (4.7 km, or 15,000 ft) (Vanney and Genesseaux, 1985). Subsidence rates in parts of the Hellenic trench have been calculated as high as 60 cm (23 in) per year for the Pliocene (Fabricius and others, 1985). The highest earthquake frequency and intensity of the Mediterranean region is located in and near the trench area (fig. 32).

The Herodotus basin or trench is an east-west deep water (3 km or 10,000 ft plus) abyssal plain lying west of, and merging with, the Rosetta fan segment of the Nile Cone and south of the Mediterranean Ridge (figs. 1, 2, 50). This area contains the greatest accumulation of young sediment in the Mediterranean (Vanney and Genesseaux, 1985). Sedimentary cover is as much as 12-14 km (40-45,000 ft), the upper part of which is 2-3 km (6,500-10,000 ft) of Pliocene-Pleistocene turbidites (fig. 33) (Morelli, 1985). The Neogene stratigraphic section includes thick Miocene salt. The pre-Neogene section is probably the subsided outer part of the North African Mesozoic - early Tertiary platform. Numerous gentle folds and evidence of salt structures are present.

<u>USGS Team Hydrocarbon Assessment Summary</u>::

Reservoirs - Some potential for Mesozoic and early Tertiary platform carbonates and sandstones; Neogene sandstones and turbidites; possibly Paleozoic sandstones and carbonates on fault blocks

Source Rocks - Possibly Silurian, Devonian, and Carboniferous shales, although in much of the area these may be overmature; Paleogene and Cretaceous shales and argillaceous limestones; Neogene humic shales; Jurassic and possibly Triassic shales or argillaceous carbonates in southern and southeastern areas

Seals - Mesozoic and Paleogene shales; Neogene shales and evaporites

Traps - Fault blocks in pre-Neogene section; isolated carbonate buildups in Mesozoic and Paleogene section; isolated sandstones and turbidites in Neogene section; salt structures

Thermal conditions - Unknown

Potential - Fair to good near African shelf; fair to moderate potential for gas on Mediterranean Ridge and possibly in adjacent trenches

Problems - Water depths; complex structure and need for high-resolution seismic work

Resources - No oil or gas fields in area

Estimated Undiscovered Resources					
Low Amount (95% probability)		Most Likely Amount (Modal estimate)		High Amount (5% probability)	
Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF
10	15	500	50	1,000	150

Nile Cone - Levant Platform area

The Nile Cone is an extensive submarine fan extending offshore from the Nile Delta (figs. 15, 50). To the west, the Rosetta fan segment extends into the Herodotus basin. To the east, the Damietta cone segment overlaps the westward-dipping Levant platform, an offshore subducted segment of the "Levant block," a northwest extension of the Arabian platform (Vanney and Genesseaux, 1985), which subsided in the Neogene. The platform area is occupied by growth faults and grabens (Vanney and Genneseaux, 1985). The Nile Cone sedimentary cover is 15 km (50,000 ft) or more thick (figs. 15, 30), consisting of the deeply-buried Mesozoic and early Tertiary North African platform carbonate and clastic beds overlain by Messinian evaporites and 2-3 km (6,500-10,000 ft) of Pliocene-Pleistocene Nile Delta clastics (fig. 33). Numerous submarine canyons filled with turbidites are present.

<u>USGS Team Hydrocarbon Assessment Summary</u>:

Reservoirs - Neogene sandstones and turbidites; Mesozoic and early Tertiary platform carbonates and sandstones; Paleozoic sandstones and carbonates on fault blocks

Source rocks - Neogene humic shales; Jurassic, Cretaceous, and Paleogene shales and argillaceous carbonates; possibly Silurian, Devonian, and Carboniferous shales, mostly gas prone

Seals - Mesozoic and Paleogene shales; Neogene shales and evaporites

Traps - Isolated Neogene deltaic sandstones and turbidites; fault blocks in pre-Neogene section; large anticlinal structures reported in parts of area; isolated carbonate buildups in Mesozoic and Paleogene section; salt structures

Thermal conditions - Unknown

Potential - Good especially for gas

Problems - Water depths; need for high quality geophysical work; some areas are highly mature or overmature in source rocks.

Resources - No oil or gas fields present

Estimated Undiscovered Resources					
Low Amount (95% probability)		Most Likely Amount (Modal estimate)		High Amount (5% probability)	
Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF
50	25	150	100	300	150

Hellenic Arc - Aegean Basin

The Hellenic Arc is located in the most active earthquake area of the Mediterranean (figs. 1, 2, 32) (Udias, 1985). The arc proper is a structurally complex arcuate zone approximately 100 km (60 mi) wide, extending from offshore of Peloponnesus to southwest of Turkey, where it approximately merges with the Cyprus Arc (figs. 1). The arc belt is occupied by a complex of seamounts and ridges, faulted trenches, overturned folds, salt structures, and gravity slide masses. Post-Miocene vertical faulting is prevalent, resulting in numerous relatively small block-shaped uplifts and basins with associated highly irregular sea bottom topography along the arc trend (fig. 52) (Vanney & Genesseaux, 1985).

The Aegean Sea basin is a back-arc extensional island block and trough complex located on the stretched and thinned continental crust of the European plate (figs. 1, 2, 52). The area was occupied by southward-thrusting Hellenide nappes until the early Miocene when intense fragmentation and vertical faulting occurred related to subduction of the African platform beneath the Hellenic Arc (Morrelli, 1985). Some individual basins contain as much as 5 km (16,000 ft) of late Cenozoic sediments. Vanney and Genneseaux (1985) divide the area into three main segments:

1. The Cretan basin, a west-east deep backarc basin more or less parallel to the Cretan Arc (fig. 1).

2. A central plateau, immediately north of the Cretan basin, an area of crustal shortening.

3. The North Aegean basin, an area of troughs and ridges resulting from strike-slip faulting along the northeast-southwest trending north Anatolian fault.

Late Cenozoic evolution of the area involves south to north subductions, which began in the middle Miocene, and was accompanied by breakup and subsidence of the older carbonate platform complex into a complex of relatively small horst and graben features. Deposition in the down-drop segments tends to be marine and continental clastics in the Late Miocene, followed by finer clastics and carbonates, which are overlain by Messinian evaporites with some conglomerates and breccias.

USGS Team Hydrocarbon Assessment Summary:

Reservoirs - Mesozoic and early Tertiary fractured carbonates; Neogene sandstones and turbidities

Source Rocks - Neogene, most humic shales; Mesozoic and early Tertiary shales and argillaceous carbonates; although these may be dominantly overmature.

Seals - Cenozoic shales and Messinnian evaporites

Traps - Extensional back-arc fault blocks; Neogene sandstones and turbidites; salt structures in parts of the area

Thermal conditions - High heat flow in most of area (fig. 52)

Potential - Moderate to poor for oil; fair to moderate for gas, partly biogenic

Problems - Water depths in Hellenic Arc area and parts of Aegean basin; very complex extensional fault structures in Aegean back-arc basins; complex structures on Hellenic Arc, need for refined geophysical work

Resources - A few small oil and gas fields are present in the Aegean Sea area.

Estimated Undiscovered Resources					
Low Amount (95% probability)		Most Likely Amount (Modal estimate)		High Amount (5% probability)	
Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF
30	3.0	100	4	300	15

Cyprus (Levantine) Basin - Cyprus Arc

The Cyprus basin includes the eastern Mediterranean area south of the Cyprus Arc offshore of Israel, Lebanon and Syria and north of the Levant platform (figs. 1,2). The basin comprises mainly a subducted slab of the northeast African-Arabian platform overlain by Neogene clastics, marls, and Messinian evaporites. Sedimentary cover may be 15-16 km (50-53,000 ft) or more thick, probably including a relatively complete and substantial thickness of preserved Paleozoic as well as Mesozoic and probably Proterozoic platform sedimentary rocks overlying granitic crust (figs. 53, 54) (Neev and others, 1985). Some authors, however, interpret part of the area as a remnant of the Tethys Sea with post-Triassic oceanic basalt beneath a thinner and younger sedimentary cover. Based on recent geophysical work and some drilling, Neev and others (1985) separated the eastern Mediterranean region into several tectonic blocks bounded by regional "geosutures" interpreted to be old features possibly dating back to the

Precambrian. Other interpretations consider the eastern Mediterranean tectonic patters to be post-Triassic in age.

The Cyprus Arc represents an arcuate trend offshore of Turkey, including the island of Cyprus, which underwent a complex compressional history beginning in the Late Cretaceous (Morelli, 1985). The present-day configuration of the arc is a result of late Cenozoic compression caused by southward thrusting of nappes and containing a complex of tilted ridges, accessory troughs, and seamounts, some of which may be salt structures. Cyprus Island is an emergent segment of the main arc, thrusted against obducted oceanic crust (Vanney and Genesseaux, 1985). The back-arc area is a complex of fragmented Anatolian (Turkey) nappes with west-east troughs filled by Neogene clastics.

USGS Team Hydrocarbon Assessment Summary:

Reservoirs - Mesozoic and early Tertiary platform carbonates; Neogene sandstones and turbidites; possibly Paleozoic platform sandstones and carbonates

Source Rocks - Mesozoic and early Tertiary shales and argillaceous carbonates; Neogene humic shales; possibly Silurian, Devonian, and Carboniferous shales, mostly gas prone or overmature

Seals -Mesozoic and Paleogene shales; Neogene shales and evaporites.

Traps - Fault blocks in pre-Neogene section; isolated carbonate buildups in Mesozoic and Paleogene section; salt structures

Thermal conditions - Unknown

Potential - Moderate to good in Mesozoic and early Tertiary section; moderate for deeper gas in Mesozoic and possibly Paleozoic beds; low to moderate for some gas in Neogene beds of Cyprus arc and back-arc area

Problems - Water depth; need for high quality geophysical work; probable highly mature or overmature source rocks in older beds in much of area

Resources - No oil or gas fields present

Estimated Undiscovered Resources					
Low Amount (95% probability)		Most Likely Amount (Modal estimate)		High Amount (5% probability)	
Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF	Oil-MMB	Gas-TCF
50	20	200	50	500	100

CONCLUSIONS

Because of the geologic complexity of the Mediterranean region, the USGS team assessments of undiscovered hydrocarbon resources (table 7) are subject to revision as reliable additional data becomes available. Economic factors are obviously very important in this region, despite the fact that economics has not been considered in the assessment process used in this report. Rather, the assessments have strictly centered on the potential for the presence of oil or gas accumulations in the preserved geologic complex of the Mediterranean region.

Several factors favorable for significant generation and accumulation of hydrocarbon resources are recognized in the region including: 1) widespread potential hydrocarbon source rocks in adjacent areas of the Mediterranean; 2) indications of extensive subsided pre-Neogene platform carbonate and clastic reservoir facies, as well as Neogene clastic reservoirs in large parts of the region; 3) widespread shale and evaporite seals; and 4) traps, including buried fault block and structurally-complex broad folds involving pre-Neogene potential reservoir beds. Indications of probable stratigraphic or stratigraphic-structural combination traps with clastic as well as carbonate reservoirs are also common and varied.

Uncertain or unknown factors, in some cases negative, are: 1) scarcity of drilling data in much of the continental shelf area, and in essentially all of the deep water areas, except for shallow sea bottom penetration, along with uncertainty of geophysical interpretations; 2) necessity for extensive projection and interpretations of regional factors important to hydrocarbon accumulation and preservation and, in part, based on uncertain geophysical interpretations; 3) lack of reliable geothermal data and details of geothermal history in areas of projected buried continental shelf, factors which are particularly important in oil versus gas assessments; 4) uncertainties of hydrocarbon preservation versus loss from earlier-formed traps in the pre-Neogene stratigraphic section. An important aspect in view of the complex geological history of the region; 5) economic uncertainties--exploration costs of offshore Mediterranean exploration, particularly beyond the continental shelf--contribute to unattractive economics at the present time. Although a reasonable case for significant hydrocarbon accumulations can be made for parts of the region, future exploration activity necessarily depends heavily on the world balance of supply and demand.

The assessment figures listed in this report represent a first approximation of the potential hydrocarbon resources of the Mediterranean region. No attempt is made to evaluate recognized economic factors involved, which necessarily must influence exploration programs. The higher (low probability) values attempt to recognize positive factors apparent in the geology and geologic history of the region. Lower (higher probability) values give due consideration to the many negative factors. Comparisons between U.S. Geological Survey assessments of the Mediterranean province and the North Africa and Middle East are given in tables 2, 3, and 7.

<u>MEDITERRANEAN BASIN PROVINCE</u>
<u>(Estimated undiscovered Oil and Gas)</u>

AREA	LOW		MOST LIKELY		HIGH	
	OIL	GAS	OIL	GAS	OIL	GAS
WESTERN <u>MEDITERRANEAN</u>						
Alboran-South Balearic-Algerian Basin	5 MMB	1.0 TCF	20 MMB	5 TCF	40 MMB	15 TCF
Ligurian-Provencal Basin	50 MMB	1.0 TCF	500 MMB	5 TCF	1,500 MMB	20 TCF
Corsica & Sardinia	5 MMB	0.1 TCF	50 MMB	0.5 TCF	150 MMB	1.5 TCT
Tyrrhenian Sea Basin	Neg.	Neg.	Neg.	Neg.	20 MMB	3 TCF
Total, Western MediterraneanSyria	60 MMB	2.1 TCF	570 MMB	10.5 TCF	1,710 MMB	39.5 TCF
CENTRAL <u>MEDITERRANEAN</u>						
Italy-Sicily-Adriatic Sea Basin	800 MMB	10 TCF	1,400 MMB	30 TCF	4,400 MMB	75 TCF
Ionian Sea Basin-Sirte Rise	25 MMB	15 TCF	200 MMB	50 TCF	1,000 MMB	150 TCF
Total, Central Mediterranean	825 MMB	25 TCF	1,600 MMB	80 TCF	5,400 MMB	225 TCF
EASTERN <u>MEDITERRANEAN</u>						
Mediterranean Ridge-Hellenic Trough-Herodotus Basin	10 MMB	15 TCF	500 MMB	50 TCF	1,000 MMB	150 TCF
Nile Cone-Levant Platform	50 MMB	25 TCF	150 MMB	100 TCF	300 MMB	150 TCF
Hellenic Arc-Aegean Basin	30 MMB	1.5 TCF	100 MMB	4 TCF	300 MMB	15 TCF
Cyprus (Levantine) Basin-Cyprus Arc	50 MMB	20 TCF	200 MMB	50 TCF	500 MMB	100 TCF
Total, Eastern Mediterranean	140 MMB	61.5 TCF	950 MMB	204 TCF	2,100 MMB	415 TCF
TOTAL, MEDITERRANEAN SEA BASIN	1025 MMB	88.6 TCF	3,020 MMB	294.5 TCF	9,210 MMB	679.5 TCF

Table 7.--U.S. Geological Survey estimates of conventional crude oil and natural gas, Mediterranean basin province. (Neg. = Negligible; MMB = millions of barrels; TCF = trillion cubic feet)

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