CHAPTER 1

Mediterranean Seafloor Features: Overview and Assessment

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"Trois parties du monde, c'est-à-dire trois mondes fort dissemblables, bordant ce vaste lac salé . . ."
Paul Valéry

This paper focuses on Mediterranean seafloor features in view of refining interpretations of the seabed that formed in an interplate–intercontinental system. This survey takes into account maps prepared for the International Bathymetric Chart of the Mediterranean (IBCM) and other recent investigations using various technologies (conventional and multi-narrow beam bathymetry, sonograph, seismic, side-scan sonar, and dive surveys). The study assesses the geomorphology in light of plate tectonic considerations developed during the past 15 years. Mediterranean features result essentially from (1) the long-term succession of tectonic displacement induced by continuous motion of Africa towards Europe, and (2) progressive closure of the sea involving a series of submarine-insular sills that played a significant role during the Messinian salinity crisis, climatic-eustatic changes, and erosional events.

The Mediterranean area can be subdivided into three geomorphic settings. (1) The relatively stable margins, from off Tunisia to the Middle East, correspond to the submarine prolongation of the African plate (includes the Pelagian Sea and Gulf of Sirte). The eastern sectors were influenced by Nile-derived deposition. (2) Unstable convergent (subducted) regions include compressive margins and associated deep-sea floor (i.e., Mediterranean Ridge, Arc-Trench systems, Aegean Sea, and Adriatic Sea) where the seafloor commonly includes a structurally broken, complex topography. (3) Rifted regions formed recently as a result of extension and foundering (i.e., Western Mediterranean Basin, Tyrrhenian Sea). The central part of latter sectors, particularly in the Western Basin, is occupied by bathyal plains bordered by large deep-sea fans formed by gravity depositional processes. The seafloor in such regions is locally modified by piercement features of volcanic or salt diapirism origin.

Introduction: Mare Exemplarium

The Mediterranean Sea is characterized by a noteworthy combination of attributes. These include (1) location on an intercontinental–interplate system, (2) a close relation to a young Alpine Mountain framework, (3) an almost-closed basin configuration, (4) the presence of steep, often rocky margins, and (5) a highly diverse physiographic setting. The unique overall appearance records marked geologic-environmental changes in time and space related, in part, to the Alpine orogen and to geographic influences such as deserts. The present-day physiographic configuration (Fig. 1.1) results from the interplay between two major series of relief-forming factors. The first is crustal mobility directed in both horizontal (Africa–Europe plate convergence) and vertical (downwarping and subsidence within, and in front of, a folded

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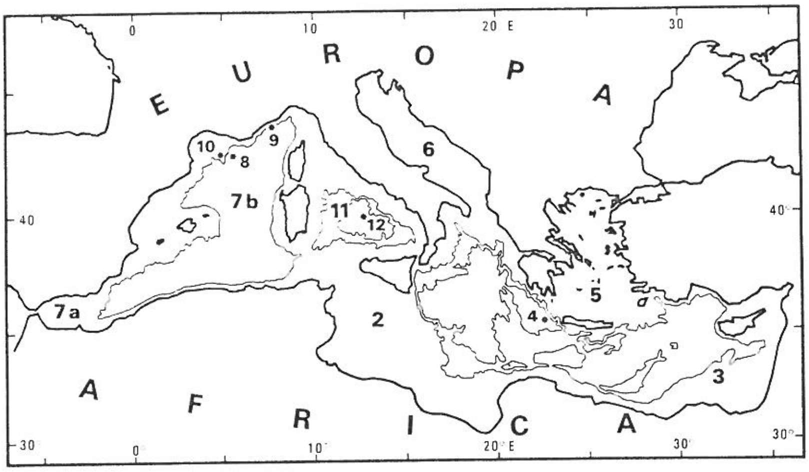


Fig. 1.1. Simplified chart of the Mediterranean Sea showing the location of Figures 1.2 to 1.12 discussed in this chapter. Depth shown by 2000- and 3000-m isobaths.

belt) directions. Thus, as an heir of the Tethys and the Mesogean Sea, the Mediterranean is an ideal example of a small sea showing marked time-variable geometry. The second set of factors is related to periodic climate (arid-humid succession) and sea-level changes. These changes have induced variations in regime of water discharge, solid-load supply, and bottom current activity. The effect of tectonic and climatic crises on the geomorphic evolution of the Mediterranean is exemplified by the Messinian events: i.e., exceptional sea-level lowering, deep cutting of the continental margin by canyons, negative water mass budget, and deposition of thick evaporite layers that have subsequently played a significant role as a result of their composition (solution features) and mobility (piercement relief structures).

During the past decade, interpretation of the Mediterranean seafloor benefited in many ways from a broad-based scientific effort: plotting of new bathymetric charts of both general (International Bathymetric Chart of the Mediterranean, scale 1 : 1,000,000) and detailed (Sea-Beam) surveys, numerous seismic and sonograph profiles, Deep Sea Drilling Project and industrial boreholes, and surveys with the submersible Cyana. The improved quality of more recently collected data has made it possible to define more precisely the major features that in this chapter are grouped in three geomorphic systems. Consideration of submarine relief in terms of a plate tectonics framework results in a somewhat different presentation than those published in valuable earlier, somewhat more descriptive analyses such as those by Mikhaylov (1965), Carter and others (1972), Łomniewsky and others (1974), and Nairn and others (1977, 1978). This overview of major physiographic features and morphological assessment is intended to serve as an additional base for the more detailed geological analyses presented in the chapters of this Mediterranean reference volume.

Relatively Stable Regions

The morphology of the southeastern Mediterranean, from the Gulf of Gabes to the coast off the Middle East, results largely from deformation of the northern rim of the African plate and alternation of humid (high clastic sedimentary supply) and arid (carbonate platform construction) conditions. The physiographic provinces, developed on a deep fractured and downwarped basement, present configurations that vary from west to east.

Pelagian Sea: A Warped-Faulted Spur

The Pelagian Sea, an advanced salient of the Africa plate abutting the Tellian Mountain and Calabrian Arc, resembles a continental borderland (Fig. 1.2). The faulted Malta–Misratha to the east and Gafsa–Jeffara (Sonshore) escarpments form its morpho-structural boundaries. This area developed from deformation and rifting of a thick sedimentary platform previously eroded and planed during the late Miocene (Colantoni, 1975; Morelli et al., 1975a; Burollet et al., 1979; Winnock, 1982; Blanpied and Bellaiche, 1983).

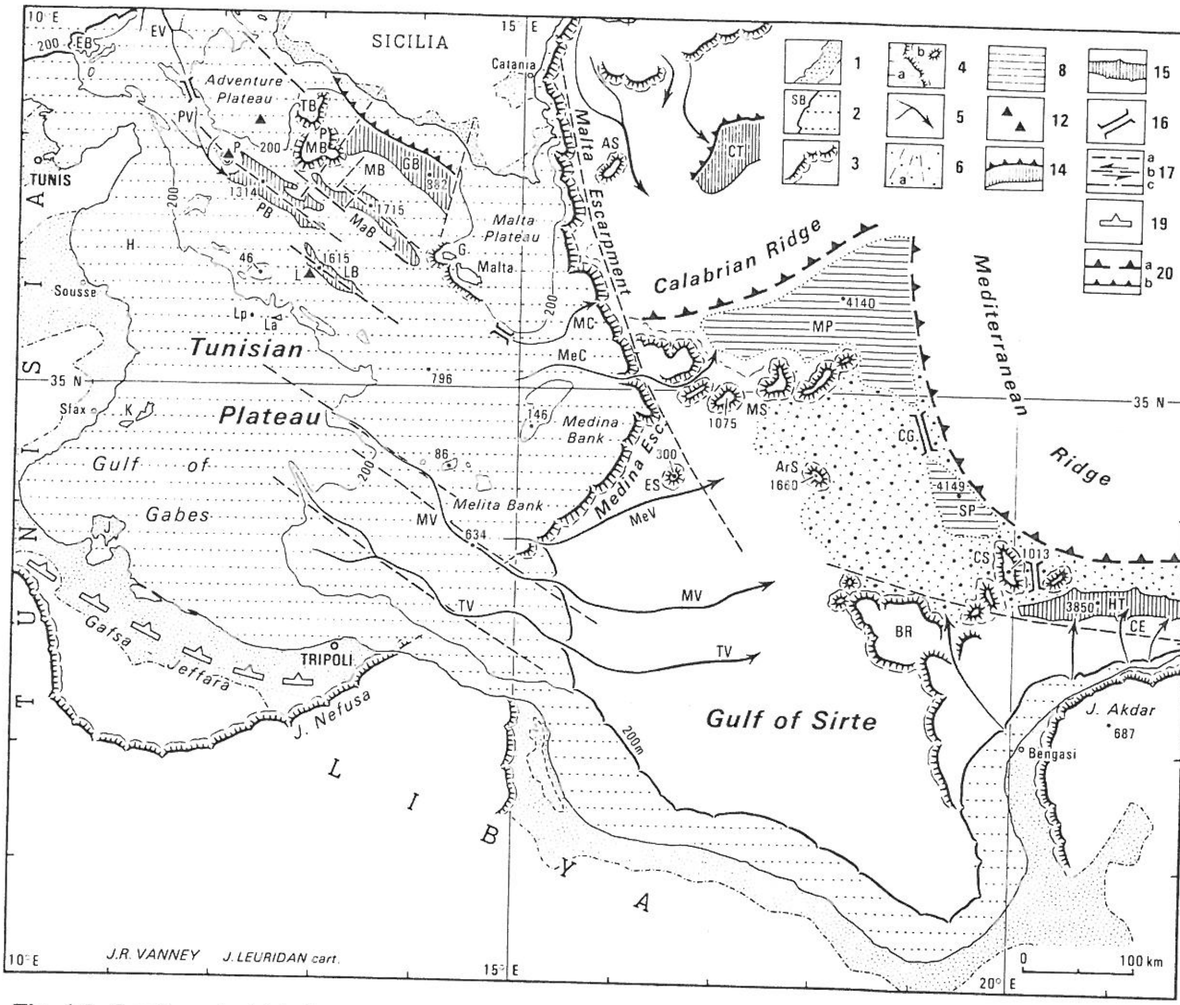


Fig. 1.2. South-central Mediterranean Sea (Pelagian Sea and Gulf of Sirte). 1, coastal and lacustrine plain; 2, continental shelf; 3, escarpment; 4, marginal plateau (a) and seamount (b); 5, submarine canyon and sea valley; 6, continental rise and deep-sea fan; 8, basin plain; 12, volcanic features; 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.

The most striking features are the northwest–southeast-trending Median troughs. These are grabens opened by rifting process (in the Pliocene, but still active) that represent an example of recent distension morphology. The best defined deeps are the South Sicily troughs (north of lat. 34°N). Three major deep en échelon basins are cut in a structurally broken ridge-and-channel landscape: Pantelleria, Linosa, and Malta (respectively 1314, 1615, and 1715 m). Their irregular floors are flanked by steep walls and volcanic cones that emerge at the islands of Pantelleria and Linosa. The still poorly defined Jaraffa and Tripolitanian troughs occur south of the gentle swells of Medina and Melita banks (shallower than 200 m) at 35° north latitude. These segmented deeps, ranging from 200 to 800 m, are probable fault-controlled submarine valleys, as suggested by the asymmetric configuration of the heads of these depressions.

The northern block, constituting the South Sicilian Plateaus, is tilted toward the north. Inside the 150-m contour, two distinct features (to the west, Adventure Bank, 15 m and Terrible Bank; to the east, Malta Plateau and islands) form tilted surfaces carpeted by a Recent sedimentary cover and punctuated by volcanic vents (Graham Bank). The intermediate Gela Basin (987 m), closed southwards by a double series of shallow tectonic dam-ridges (Pinne Marine, Madrepore Bank), is an unusual foredeep of the Caltanissetta Basin of Sicily, which has been partly filled by the offshore progression of a Mio-Pliocene olistostrome.

The third geomorphic unit is the Tunisian Plateau, the largest (300 km wide, along lat. 34°N) such feature in the Mediterranean. The triangular Tunisian Plateau displays a generally regular topography as a rather shallow (averaging 50 m), low-gradient swell with minor undulations and incisions that prolongate seaward the nearshore configuration of the Kerkennah islands area. The swell is flanked by the two west–east-trending lows, the gulfs of Hammamet and Gabes, which have served as post-Miocene depocenters. The entire plateau is delineated by a poorly defined, notched talus, prolongated by separated banks. The plateau represents a mobile block: Episodically active compressional and diapiric structures (scarps, monoclines, folds) have been subjected to long-term erosion. Thus, the plateau surface appears to have been only moderately controlled by deep structure. The flat-topped anticlinal banks, synclinal depressions (sometimes closed), and adjacent progradational–aggradational terraces show minor shaping by fluvial effects during low sea-level stands. The plateau surface is covered by biocarbonate deposits; the seafloor below 50 m is, for the most part, covered by relict lag deposits. Carbonate production and deposition predominate at shallower depths, where sands accumulate in tidal deltas and on low submarine banks (around Kerkennah, Djerba), and micrites are trapped in underwater grassy "prairies" (Cymodocia, Posidoniae) resulting in parareefal features.

Sirte Embayment

The seafloor of the Sirte Embayment, the largest reentry on the North African margin, dips gently northward and extends to the Sicilian Basin by a series of steplike notches (Fig. 1.2). The Embayment is interpreted as a wide collapsed block of the African plate (Finetti, 1982; Groupe Escarmed, 1982). It presents the following attributes:

1. The semicircular Sirte Gulf is positioned over part of the northwest-southeast Libyan horst-graben system, which is deeply buried beneath a thick Cenozoic sedimentary cover. The rather large coastal-lagoonal Sirte plain and continental shelf extend to the north by the gently inclined (1%) Sirte Cone; the surface of this latter is offset by escarpments interpreted as surface expressions of tilted block.
2. The escarpments forming the lateral margin of the embayment are essentially gigantic faulted monoclines affected by mass movement of the sediment cover. The Malta–Misratha Escarpment to the west is a steep, high-relief (2.5 km) feature dissected by a series of large submarine valleys, thus leaving spurs and elongate plateaus as high features. Sea-Beam and submersible dive surveys reveal that local oversteepening of the central segment may have resulted from a capping of limestone deposits. The eastern margin of the Sirte Embayment is formed by the Cyrenaica Escarpment. This feature is the northern rim of a southward-tilted block, as suggested by the abrupt coast bordering the Barka Mountains, the irregularly shaped narrow (~10 km wide) shelf, and the steep slope incised by large canyons.
3. The Sicilian Basin, below 2000 m, forms the north-central part of the embayment. It displays an irregular series of small hills of fault origin (Stride et al., 1977) and is bordered by a double chain of flat-topped buttes (Medina Seamounts to the west; Bengasi Ridges and Cyrene/Herodotus to the east), which may be sedimentary horsts. Turbidites have leveled and smoothed the Messina–Ionian (4100 m) and Sirte Basin plains (3900 m, connected by the Callymachus Gap), this latter being a fault-controlled prolongation of the Herodotus Trough (3000–3500 m).

The Nilotic Front: "A Gift of the Nile"

The convex-shaped Egyptian continental margin (Fig. 1.3) is the geomorphic expression of

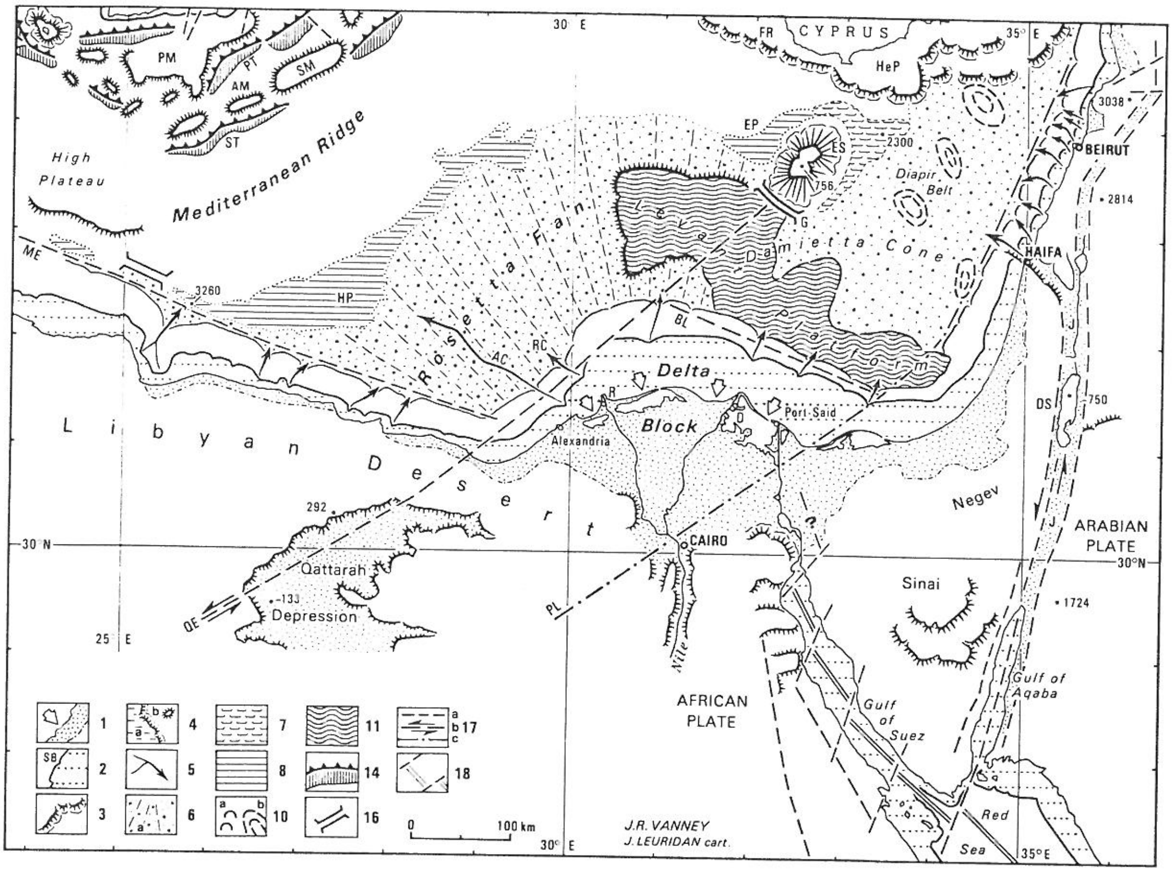


Fig. 1.3. Nilotic and Levant margins. 1, coastal and lacustrine plain (arrow: retreating coast line); 2, continental shelf (SB: shelfbreak); 3, escarpment; 4, marginal plateau (a) and seamount (b); 5, submarine canyon and sea valley; 6, continental rise and deep-sea fan (a); 7, erosional moat; 8, basin 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.

the post-Messinian deltaic sedimentary bulge that has buried the deeply dislocated African plate margin. The morphology of the basement is a block-mosaic: The main northwest–southeast-trending Marmarica and Bardawil escarpments are offset by the northeast-southwest Qattarah–Eratosthenes and Pelusium transcurrent faults (Neev et al., 1976; Neev, 1977).

Nile Delta Belt. East of El Alamein (long. 29°E), the steep rectilinear Libyan margin, defined by the Marmarica Escarpment, becomes largely protuberant as noted by both the coastline and depth contours. The "delta block" (Fig. 1.3), delimited by the Qattara, Pelusium, and Bardawil structural trends, is deeply depressed (and lowered by fault) beneath a thick prograding prodelta. Present surficial features were affected by periods of high solid discharge, mainly during late Pleistocene and Holocene (Misdorp and Sestini, 1976; Coleman et al., 1981): (1) steepened lower (75–100 m), middle (45–50 m), and upper (30–40 m) terraces, the Rosetta and Damietta offshore banks, channels, and profluvial promontories on the deltaic shelf; and (2) gravity features (slumps), ravines, and mud diapirs on the arcuate deltaic slope. This gently inclined mud surface (to about 1000 m) is surprisingly devoid of major canyons (neither the Alexandria or Rashid canyons are large or deeply incised).

The recent evolution of the coast and inner margin, an example of geomorphic recession, is the result of a sedimentary deficit resulting from several factors, some natural (diminution of discharge related to the Holocene transgression, acceleration of desertification) and some human (modification of Nile drainage, emplacement of the Aswan High Dam, etc.) (Toma and Salama, 1980; Coleman et al., 1981). Deltaic decay is recorded by a smoothing of coastal contours (i.e., retreat of river mouths and of profluvial promontories, retrogradation of barrier beaches), reduction in growth of offshore banks and mudfields, retreat of the seaward edge of the shelf terrace, and a smoothing of the slope by lateral transport of fine particles.

Nile Cone Belt. The deeper Egyptian margin (1000–3000 m) is formed by a wide (300 km west to east), extensive (200 km north to south) submarine fan. The time-spatial late Quaternary depositional morphogenesis is primarily related to Nile input load changes, deep current fluctuations, and climatic-eustatic oscillations (Maldonado and Stanley, 1976, 1979, 1981; Ross and Uchupi, 1977). The ramplike depositional topography is locally modified by gravity and halokinetic processes.

West of 30° east longitude, the Herodotus Basin and the dissected ("badlands physiography") and deformed Alexandria "paleo-fan" are deeply buried by the most extensive accumulation of sediment in the Mediterranean (70,000 km^2), which constitutes the Rosetta Fan (Ryan, 1978; Maldonado and Stanley, 1976, 1979, 1981). The 2 to 3 km thickness of Plio-Pleistocene turbidites (predominantly silty) displays a regular concave topography. There is little evidence of suprafans lobes in the upper part. The lower part is slightly dissected by small, narrow channels (10–20 m deep). The distal rim of the cone, in contrast with the Mediterranean Ridge, shows gentle folds and broad rises of subdued relief (6 km wide, 100 m high); minor superficial roughness and smooth-floored hollows are of possible diapiric origin (Kenyon et al., 1975; Ross and Uchupi, 1977; Stride et al., 1977). To the west, the fan merges with the Herodotus Basin plain surface at depths from 3000 to 3100 m.

In the Cyprus Basin, east of 30° east longitude, the surface of the Damietta Cone is much more irregular. The central and southern third of the cone is termed the Levant Platform (Ross and Uchupi, 1977) or Fault Belt (Kenyon et al., 1975; Neev et al., 1976). Sonograph surveys reveal that bottom roughness results from growth faults and grabens (3–4 km wide, over 200 m deep), sometimes crossed by sinuous channels (Stride et al., 1977). These features are interpreted as the consequence of compression (Neev et al., 1976) or gravity processes (Stride et al., 1977), locally perturbed by diapiric intrusions. Piercement relief features may result from effects of superficial dissolution of evaporites and crater formation (seismic profiles in Finetti and Morelli, 1974, and in Ross and Uchupi, 1977). The northwest scarp bordering the Levant Platform probably is the progressive displacement front of the unconsolidated sedimentary cover (Ross and Uchupi, 1977). Beyond the narrow Xenophon Gap, the Eratosthenes mount summit (750 m) rises above the plain (2755 m); the mount is bordered by a semicircular moat to the east (2300 m). This distinctive mount is the most advanced bastion of a major fault belt (Ross and Uchupi, 1977). The eastern part of the Damietta Cone, the Diapir Belt (Neev et al., 1976), displays low evaporite domes localized on a gentle incline.

Levant Margin: A Shear-Zone Morphology

The Levant margin is the submerged trailing edge of the "Levant Block," which developed in the Neogene on the northwest border of the Arabian craton (Fig. 1.3). It occupies the region between a postulated Suez Rift Zone, the Jordan–Dead Sea–Bekaa strike-slip fault, and the Pelusium Line that parallels the base of the slope. The effects of longitudinal structural control (Ginzburg et al., 1975; Neev et al., 1976; Ben-Avraham, 1978) and late Miocene erosion by canyons converging toward the "Byblos Basin" (Ryan, 1978) become gradually more apparent northward.

The southern sector, south of Haifa (lat. 33°N), appears to have nearly reached geomorphic maturity. The lower cliff cut into a prograding Plio-Pleistocene lens is preceded by a set of shore-parallel eolianite rocky walls and ridges ("kurkar") submerged by recent faulting along a coastal hinge-line. These ridges have served as dams behind which mud and sand are trapped on the inner shelf. Seaward of the 30 m contour, the median and outer shelf form a moderately wide plain (40 and 10 km, respectively, off Negev and Mount Carmel); it is relatively steep (to 1°), dissected, and covered by fine-grained Holocene deposits, except near the poorly defined shelfbreak (at about 100 m) where it is broken by numerous hillocks. On the continental slope, the rolling, gently inclined (2–4°), and incised foreset topography formed by recent westward downwarping along the shelfedge hinge-line (Neev et al., 1976). Mapping reveals oval depressions parallel to the base of the slope (for example, the subslope trough off Haifa) and downslope gravity transport-induced forms (notches, asymmetric hills, terraces, channels) that originated by slumping along the Gaza, Palmahim, and Dor margin sectors (Almagor and Garfunkel, 1979). Mass flows were triggered by fault displacement and sedimentary progradational overload above the plastically deformed evaporite substratum during the Pleistocene.

The northern sector (northern Israel–Lebanon margin flanking the high coastal ranges), in contrast to the above, remains in a youthful state of evolution as a result of strong uplift and deep dissection. The shelf lying off small coastal plains separated by elevated rocky promontories (raised beaches and wave-cut platforms up to 100 m) is narrow (less than 20 km and, locally, 10 km) and shallow (shelfbreak at 80 m), mainly off uplifts named the Haifa and Hakko noses. The shelf surface is believed to be a series of notched abrasional surfaces carpeted by Holocene eolianite ridges ("ramlé"). The continental slope, formed in part by step-fault, displays a gentle (8–10°) concave profile. It is incised by about ten canyons that are seaward prolongations of grabens and torrential wadis; most are the geomorphic expression of Messinian paleocanyons. These canyons are separated from each other by probable fault blocks and tilted plateaus such as the Tyre–Saida Bank (300–350 m). Canyons act as important dispersal paths as indicated by gravity transport bedforms noted on canyon beds. The concave lower part of the slope merges with the Eastern Mediterranean deep-sea floor at about 1500 m without development of noteworthy submarine fans.

Unstable Convergent Subducted Regions

Regions discussed below are in marked contrast with those described in the previous section. The morphology of the northern rim of the Eastern Mediterranean, for example, is the most irregular and complex mapped in this sea. Its configuration is related to convergent tectonics and, specifically, the collision between the African and European plates. Four geomorphic styles are recognized.

Mediterranean Ridge: An Extensive Fold-Fault System

This relief feature, also called the Outer Mediterranean Ridge (Stride et al., 1977) and Mediterranean Catena (Finetti, 1976; Mascle et al., 1977), forms a large median arcuate swell in the Ionian–Levantine seas and extends from Sicily to Cyprus. Of note is its undulating morphology characterized by a series of high and low structurally deformed bundles extending along a distance exceeding 2000 km. These features correspond to the recent uplift and folding of a preexisting abyssal plain into two branches (Calabrian and Hellenic) that are still of controversial origin. Ridge morphology is attributed to compression of an outer arc system, to autochthonous sliding (cf. Dickinson, 1973), or to décollement (Mulder, 1973; Biju-Duval, 1974; Biju-Duval et al., 1974); there have been considerable modification by diapirism, dissolution, and mass-wasting transport processes.

Calabrian Ridge. This short westernmost segment lies between the Messina Plain (south) and the Messina Cone (north) and extends from the Malta Escarpment to the west and Apulian Escarpment to the east. The rather irregular pattern of elongated hills (lying at a depth of about 3000–3200 m) and flat sediment-filled depressions (to 3500–3800 m, such as the Botticelli Basin and Fra Angelico Trough) is generally parallel to regional bathymetric trends. These features formed in a thin (200 m) Plio-Pleistocene sedimentary cover, folded and otherwise deformed on thick wedgelike series, probably evaporites, without coherent reflectors (Belderson et al., 1974; Rossi and Sartori, 1981; Ryan et al., 1982).

Hellenic Ridge. The length (1500 km), width (200 km), S-shaped pattern, marked relief, and compartmentalization are the main traits of this ridge segment lying further to the east. Concentrations of small-scale hummocks and lows characteristic of this region are termed "cobblestone topography" on conventional echo-sounding profiles. Rounded features, however, are an artifact of overlapping hyperbolic reflections. Sea-Beam, sonograph, and deep-tow surveys carried out in specific areas show that the topography actually consists of three more angular geomorphic configurations: (1) a ridge-and-trough pattern interpreted as foreland folded-imbricated features resulting from compression; (2) a fault-and-fissure pattern suggesting tensional morphogenesis; and (3) a pimple-and-pock pattern produced by diapirism and solution affecting the Messinian evaporite layer. These patterns, varying greatly in profile and plan-view, show the following geographic distribution (Stride et al., 1977; Kenyon and Belderson, 1978; Le Pichon et al., 1982; Ryan et al., 1982):

1. The deeper units (below 2000 m) are compound and steplike with subparallel folds and locally display sinuosity, bifurcation, and interfingering. The folded features vary according to their location: low, but well defined, on the gently inclined (about 1°) southern "deformation front"; closed and generally deformed by longitudinal faults and slump scars; high and dissected by transverse grabens, craterlike collapse depressions, and extruded (mud or salt?) dome features on the steeper (3–4°) northern "deformation front" (see Fig. 6 in Ryan et al., 1982).
2. The "Upper Plateau" (Sancho et al., 1973) designates the shallower (above the 2000 m contour), narrower (100 km) fragment of the swell. The plateau, located in front of the Cyrenaica Promontory in the central third of the Ridge, constitutes the most intensely shortened sector. The seabed is characterized by short, asymmetrically festooned, high (culminating at about 1200 m) crests interpreted as tight parallel folds dissected and broken by cross-faults and thrusts.

Arc-Trench System: Subduction or Collision?

The second convergent sector lies between the Ridge and the Mediterranean mountainous peninsula-island (Sicily–Calabria–Greece) region. It includes impressive relief features resulting from geologically recent tectonic-seismic activity concentrated along the descending African plate beneath the Eurasian microplates.

Calabrian Arc. The southernmost part of the Italian peninsula, uplifted considerably since the lower Pliocene, dominates the Calabrian margin. The most obvious part of the latter is the fan-shaped Messina Cone extending from Sicily to the Gulf of Taranto (Finetti and Morelli, 1974; Rossi and Gabbianelli, 1978; Rossi and Sartori, 1981). The highly irregular configuration of the seabed is the result of several factors:

1. A steplike configuration is noted from depths of about 3000 m upslope toward the narrow coastal plains. Different depths of basins of rather uniform topography (mainly at 1500–1600 m and 2400–2600 m) are interpreted as perched slope depocenters; sediment is trapped behind festooned damlike scarps formed by large gravity slides (or thrusts) on the southern prolongation of the Apennine chain. The upper slope and coastal cliffs are molded by young fault scarps that border a narrow, shallow shelf constructed by a series of alluvial cones.
2. This margin displays a radial dissection (by submarine valleys) pattern. Some basins on the Messina Cone are connected by V-shaped ravines. Two important submarine canyons are cut on the edges of the cone, i.e., where it is in contact with the Malta (west) and Apulian (east) escarpments. These asymmetric canyons, respectively named Reggio Valley (west) and Taranto Valley (east), have served as important sediment byways. The Reggio Valley has been well supplied by sediments transported by vigorous currents flowing through the constricted Strait of Messina (80 m deep, 4 km wide) and also by turbidity currents periodically triggered by earthquakes and tsunamis (such as the 1908 event).

Ionian Sector. The Greek margin east of the Taranto Valley presents a sublinear (northwest-southeast) pattern. This margin formed along the southeastern prolongation of the Dinaric forefolds, in Mesozoic limestones and Oligocene flysch-schist series. The amount of folding and associated deformation structures increased upward (Hinz, 1974; Rossi and Borsetti, 1974).

At the outer part of the sector, the *avampaese pugliese* or Apulian Plateau comprises a quadrangular tabular surface; locally it has been truncated by small, southeasterly tilted abrasion surfaces. The Apulian Escarpment, forming its border, consists of en echelon, linear, high-relief step-faulted slopes. The uppermost surface constitutes a rather wide (10–20 km) shelf dominated by the tectonically displaced calcareous cliffs of the Solentina peninsula.

At the median position, the Kerkira (Corfu) Trough is a broad (40 m), long (200 km), flat-floored basin interpreted as a foundered graben southeast of the Strait of Otranto. The seafloor slopes gradually from 1000 to 2500 m, toward the Kefallinia (Cephalonia) Valley. This latter is a fault-controlled transverse depression that cuts the summit of the Apulian Escarpment in the form of a hanging valley above the Mediterranean Ridge.

At the inner position, the Ionian Islands are viewed as detached blocks derived from the Hellenides. These have been intensely thrusted and fault-displaced westward as individual blocks by compressional movement which, as revealed by seismic activity, is continuing to the present. Submarine slopes, shaped by faulting, were displaced considerably during Pliocene and Pleistocene compression phases. The seafloor between the islands, a reef-islet shelf, and the mainland were formed by aligned synclines and fault valleys that now are almost completely filled by trapped detrital deposits. The coastal ranges of western Greece are dissected and offset by transverse faults that also have resulted in the formation of gulfs (Arta, Patras, and Corinth). The latter is a long (120 km), narrow (15 km), and deep (over 650 m at the easternmost terminus) cul-de-sac, bordered by rocky slopes that are still rising at a rate of 2 mm/year.

Hellenic Arc System. Perhaps the most distinct physiographic features in the Mediterranean are two zones, convex towards the south, that extend from the Peloponnesus to southwest Anatolia, over a length of about 1000 km. Much new information pertaining to the underlying structure (Hellenic nappes related to crustal plate kinematics) and shaping (influence of halokinesis, gravity, and corrosion processes) has been collected during recent years (Got et al., 1977; Jongsma, 1977; Nesteroff et al., 1977a, 1977b; Le Quellec et al., 1978, 1980; Angelier, 1979; Le Pichon and Angelier, 1979; Le Pichon et al., 1979a, 1979b, 1982; Le Quellec and Mascle, 1979; Feldhausen and Stanley, 1980; Huchon et al., 1980, 1982; Mascle and Le Quellec, 1980; Angelier et al., 1981, 1982; Dercourt, 1981; Stanley and Maldonado, 1981; Leite and Mascle, 1982).

The base of slope is defined by a discontinuous chain of mounts and trenches. The most striking characteristic of this sector is the subangular arrangement (northwest-southeast and southwest-northeast) imposed by frontal (westward) and oblique (eastward) subduction. The mounts and ridges are buttelike uplifted features (examples: Matapan and Strabo mounts, respectively 2496 and 711 m) of different size and shape. They may represent outward overturned folds, probably modified by halokinesis. Trenches are deep (to 5 km), irregularly shaped depressions. Their structural and sedimentary discontinuity is attributed to partial blocking by island flanks. The western (Ionian) trenches include the Zante or Zakynthos (4000 m), North Matapan–Vavilov (deepest in Mediterranean, 5121 m), and South Matapan (4614 m, the widest) deeps (Figs. 1.4, 1.5), filled with 0.5 to 1.0 km of terrigenous deposits. Separated from the above deeps by a transverse trough are the poorly defined Gortys Deep (about 3100 m) and the left-offset South Gavdos–Poseidon Deep (about 3000 m or less), displaying numerous diapiric structures. Trenches in the eastern Arc display a subparallel pattern: The northern Pliny deep (N65°E) is rather well defined with three main en échelon narrow segments (maximum: 4096 m). The southern Strabo deep (N55°E) is shallower (about 3500 m) and poorly developed with a thin sedimentary cover (middle Pliocene to Pleistocene). The floor of these

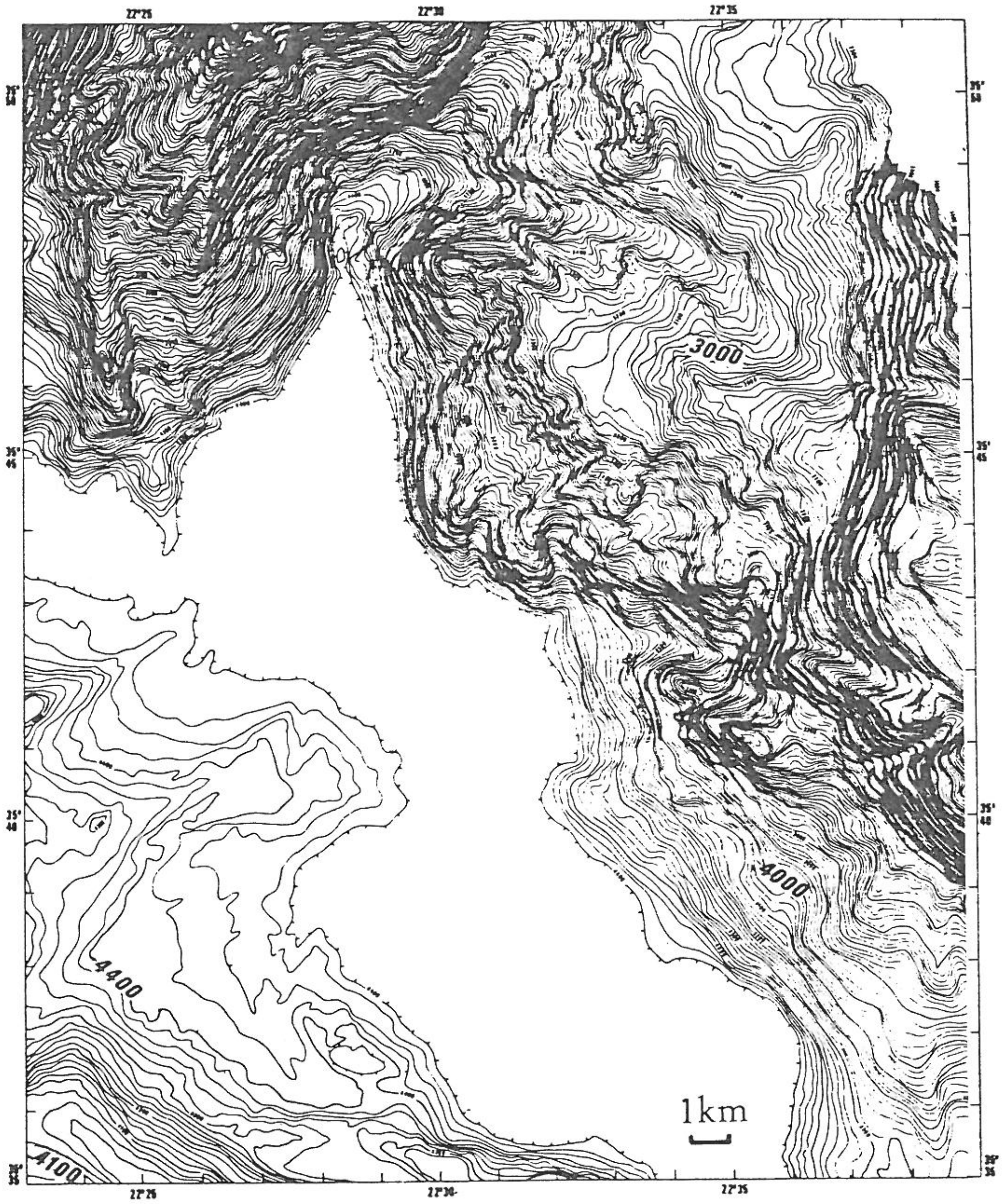


Fig. 1.4. South Matapan Trench, deepest Mediterranean seafloor, mapped with a multichannel (Sea-Beam) system (after Huchon et al., 1982; kindly provided by X. Le Pichon, Paris). Contour interval 20 m (corrected). Example of an abyssal plain on a segment of the Hellenic Trench, southwest of the Peloponnesus, at the contact between the Aegean landmass and Mediterranean Ridge. The flat bottom is the surface of 500 to 1000 m of probable upper Pleistocene terrigenous sediment (drilled at JOIDES sites 127–128). The highly irregular inner (or insular) slope was deformed by compression; locally the slope is cut by deep ravines. In the southwest corner, the trench is partly blocked by the foothills of the Mediterranean Ridge.

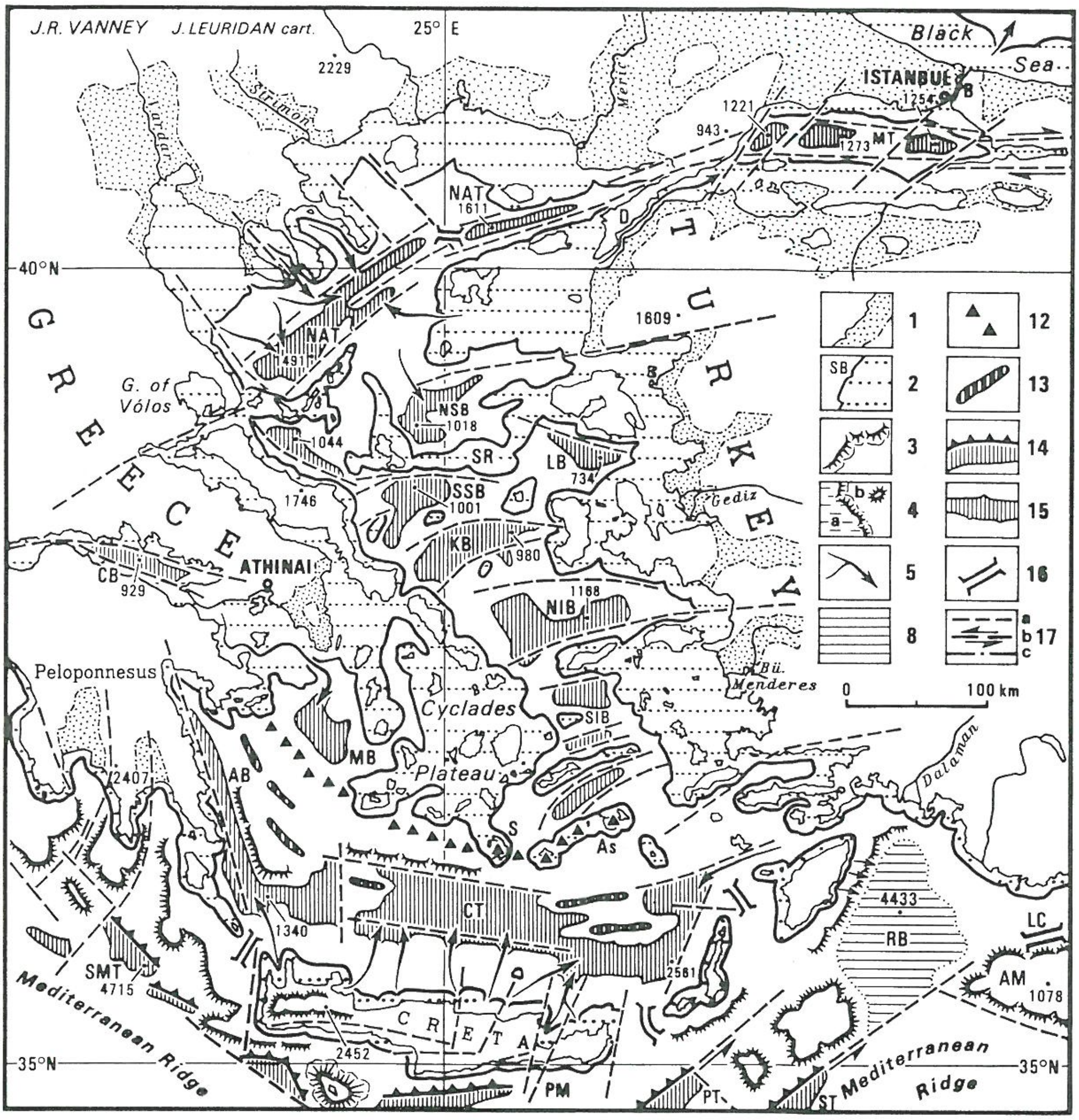


Fig. 1.5. Aegean Sea and southern approaches. 1, coastal and lacustrine plain; 2, continental/insular plain (SB: shelfbreak); 3, escarpment; 4, marginal plateau (a) and seamount (b); 5, submarine canyon; 8, abyssal plain; 12, volcanic features; 13, submarine ridge; 14, subduction trench; 15, faulted trough and ridge-basin complex; 16, submarine passage; 17, fracture. Abbreviations: AB, Argolikos Basin; AM, Anaximander Mount; As, Astipalaia; B, Bosporus; CB, Corinth Basin; CT, Cretan Trough; D, Dardanelles; KB, Khios Basin; LB, Lesvos Basin; LC, Lycia Channel; MB, Mirtoon Basin; MT, Marmara Trough; NAT, North Aegean Trough; NIB, North Ikaria Trough; NSB, North Skiros Basin; PM, Ptolemy Mts; PT, Pliny Trench; RB, Rhodes Basin; S, Santorini (Thera) Isl; SIB, South Ikaria Ridge; SMT, South Matapan Trench (see Fig. 1.4); SR, Skiros Ridge; SSB, South Skiros Basin; ST, Strabo Trench.

trench deeps is generally formed by a succession of elongated basin plains, leveled by partially deformed turbidites. The precipitous inner walls (20–40°) are fault scarps. In marked contrast, the gently inclined outer walls are interrupted by domes and terraces resulting from faulting, folding, and displacement of the sedimentary cover that slid on a plastic-type basement. Fifteen submersible dives made during the Cyanheat survey revealed the importance of solution processes (grooves, columns, and caves with pillars) in the shaping of the trench walls.

The forearc slope shows a complex partitioning and steplike topography resulting from post-Miocene vertical and extensional displacement and consequent erosion. In plan view, the distribution of features results from spurlike faulted anticlines that are bordered by rectilinear highs whose crests have been eroded; some spurs are uplifted as island blocks. Also noted are distensional transverse-oblique reentrants, i.e., foundered surfaces forming gulfs along the prolongation of the Peloponnesus basins (such as the gulfs of Lakonia and Messinia) and interinsular passages cutting across narrow submarine crests connecting the islands. Seismic profiles show that some crests and scarps have acted as dams, forming perched basins in the axis of reentrants and on the back-slopes of spurs. Locally, this irregular topography has been partially buried and smoothed by thick (>1 km in some areas) stratified terracelike Plio-Pleistocene accumulations. Gently inclined and jagged upper slopes rise to the deep (170–200 m) edge of narrow (2–5 km) peninsular shelves. These shelves locally are bordered landward by impressive cliffs, faulted and dissected in post-Villafranchian uplifted (over 2000 m) coastal horst mountains.

Cyprus Arc Sector. This easternmost arc, devoid of trenches and situated externally with respect to the Taurus Chain (Anatolia), is much less well defined than the above-cited regions. The Cyprus Arc comprises a discontinuous convex-southward trend extending from Rhodes to the coastal volcanic chains north of Latakia. The entire arc results from recent compressive movement affecting the Taurus oceanic series (Mesozoic ophiolitic suite and deep-sea deposits); structures appear to indicate southward-thrusted nappes resulting from continental collision between Africa–Arabia and Anatolia (Biju-Duval et al., 1974; Lort and Gray, 1974; Nesteroff et al., 1977a, 1977b).

The forearc, segmented as southwest overthrusts, consists of submerged mounts, disrupted as irregular separate crests. West of Cyprus, these include the Anaximander Mount (909 m) and the Florence Rise (1547 m); subcircular features associated with these are probable expressions of salt domes. South and east of Cyprus, a series of shallow northward-tilted ridges (example: Hecateus Mount, 242 m) gradually merge eastward and possibly extend to the Baasit and Amanus coastal ranges. Cyprus Island, the emerged core of this arc sector, is formed by the northern distinct arcuate Kyrenia Range (flanked by tectonic cliffs) thrusted against the obducted oceanic crust of the southern ophiolitic Troodos Cupola (1951 m). The surrounding shelf is remarkably narrow (1–2 km) and shallow (20–30 m).

Backarc basins are represented by a series of west-east troughs underlain by the Anatolian nappe substratum. The basins are partially buried beneath a terrigenous Neogene fill that increases gradually in thickness from Rhodes to Iskenderun Kürfezi. Within the 3000 m contour, the Rhodes Trough, inclined slightly southwards (maximum depth of 4482 m), is connected by the Lycia Channel to the Antalya Basin (average depth of 2200 m). The rather even bottom of this latter basin is surrounded by distinctly oriented reliefs revealed by sonograph traverses (décollement folds or evaporitic domes to the south; rugged bottom of possible diapir origin to the north). The Cilicia Basin is a shallower (by about 1000 m), narrower perched basin connected to the preceding basin by a gorge.

The Anatolia slope and shelf, the submerged southern flank of the Taurus Mounts, formed by major uplift and subsequent rejuvenation. This latter truncated the folded sedimentary series that were offset as tilted blocks. Most cliffs onshore and scarps offshore are interpreted as fault surfaces. Canyons (such as those east of Rhodes) are interpreted as fault-scarp valleys that are seaward extensions of fluvial channels on land. The shelves are generally narrow, except where important fluvial input (such as the Adana prodelta) produced wide progradational margins.

Aegean Sea: An Extensional Island Block-Trough Mosaic

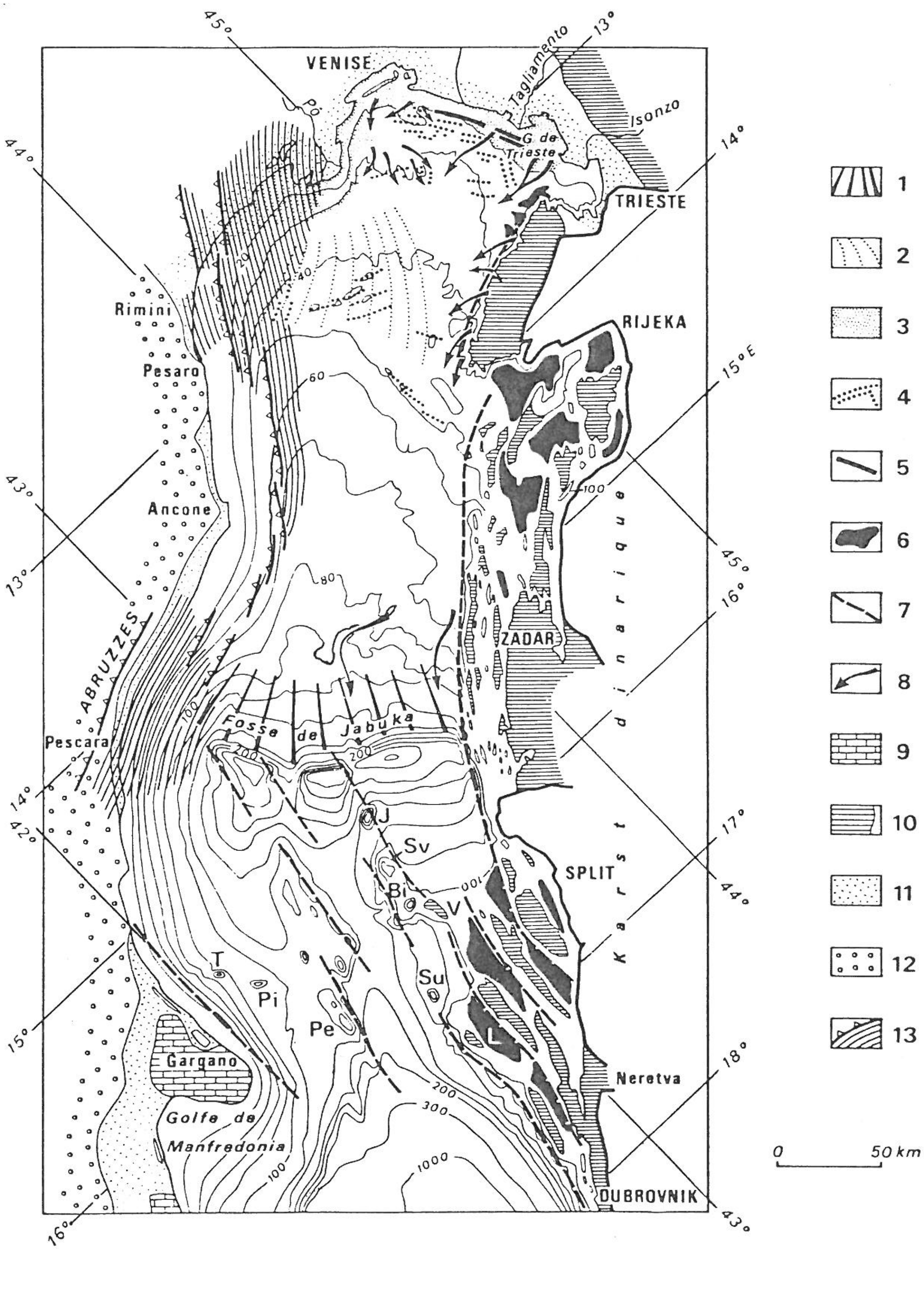
The Aegean (Fig. 1.5), connected by the Sea of Marmara to the Black Sea to the north, and by the Hellenic Arc gaps to the south, is an almost enclosed sea characterized by a basin deep-and-shallow platform pattern (Jongsma, 1977; Stanley and Perissoratis, 1977; Dewey and Sengör, 1979; Angelier and Le Pichon, 1980; Le Pichon and Angelier, 1981; Meulenkamp, this volume). This configuration is primarily the result of extensional dynamics related to subduction beneath the Hellenic Arc. After the last Hellenide nappes were emplaced (early Miocene), the eroded Aegean landmass connecting the Balkan to the Tauride Chain was subjected to strong vertical displacement and fragmentation in the late Miocene. One distinguishes the following morpho-structural zones, from south to north:

1. The Cretan Basin, a feature resulting essentially from north–south-trending extensional motion, calls to mind a backarc basin. The frequency of earthquakes in this region attests to active submarine morphogenesis. The Cretan Trough (deepest of the Aegean depressions) consists of elongated depressions increasing in depth from west (1300 m) to east (2500 m). The floor is smoothed by turbidites and flanked southwards by perched ridges and basins oriented parallel to the Cretan Arc. Northwards, some distinct high-relief features piercing the bottom include cones, such as the island of Santorini (or Thera), which form a volcanic island arc. Basins and ridges extend shoreward by a system of U-shaped graben-bays and horst-promontories.
2. In the Central Plateau, the north-south extension motion is compensated by east-to-west crustal shortening. Thus, the Plateau represents a large elevated aseismic insular platform broken by transverse and northern basin deeps. The smoothed aspect of these basin floors indicates that deposition has kept up with, or prevailed over, tectonic displacement.
3. The topography of the North Aegean Basin results largely from strike-slip faulting that has acted along the North Anatolian fault. The area comprises to the south a double set of sinuous deeps on both sides of the Skiros Ridge locally intersected by gaps, and to the north, the northeast–southwest-trending Anatolian Trough that extends from the Gulf of Volos to the Black Sea. Transcurrent movement is associated with transverse fragmentation as shown by the geographic distribution of the major physiographic features: tectonic cliffs, peninsular shelves, precipitous scarps, small and low rocky crests, and gently arched basin floors (about 1000 m, with a maximum 1468 m to the west).

Adriatic Sea: A Buried Intermontane Cul-de-Sac

The Adriatic Sea (Fig. 1.6), a shallow elongated arm of the Mediterranean, is the result of extensive deposition on a deeply foundered foreland. Long-term subsidence occurred between the relatively young orogenic belts of the Apennines, Alps, and Dinarides. Subsidence rates are considerably increased towards the Po Basin; this factor continues to be important in the northern area, in part related to man-made factors. The evolution of mountains bordering this sea has controlled the general development, shaping, and distribution of bottom features to the Recent. The present sedimentation pattern results from the large load carried by turbid layers from the Po region that flow and sink southwards, from the inflow towards the north of hypersaline warmer Ionian water, and from the important role of tidal currents and strong wind-induced currents in this region. The morpho-sedimentary transport pattern has been extensively investigated, particularly off the Venetian–Istrian coasts (Fabbri and Gallignani, 1972; Colantoni and Gallignani, 1975; Newton and Stefanon, 1975, 1982; Colantoni et al., 1979; Calaveri and Stefanon, 1980).

Features of the Adriatic Sea are summarized briefly as follows: (1) The northern lobate prodeltas extend to about 50 to 60 m; the seafloor in this region dips gently and is generally smooth with only minor irregularities protruding from the sand and mud cover. Although the role of deposition has been extensive, Flandrian transgressive coastal-deltaic features (i.e., beach rock, calcareous reef rock) are locally exposed by erosive bottom turbulence. (2) A wide ter-


VENISE
Pô
Tagliamento
Isonzo
G. de Trieste
TRIESTE
RIJEKA
Rimini
Pesaro
Ancone
ABRUZZES
Pescara
ZADAR
Fosse de Jabuka
SPLIT
Karst dinarique
Gargano
Golfe de Manfredonia
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racelike surface extends from about 60 m to about 100 m, the central part of which includes a marked broken terrain. Three small basins of the Mid-Adriatic (or Jabuka) depression, with depths to about 250 m (maximum to 268 m) extend southeastwards by a median valley (defined by the 150-m contour) bordered by scattered knolls, scarps, and islands. Deeps and valleys are the probable geomorphic expression of a highly deformed substratum incompletely buried by thick foreset beds of the Po Delta. The present-day seafloor configuration also results partially from fluvial-lacustrine and gravity transport processes active during the last low sea-level stand. (3) The horseshoe-shaped southern Adriatic is a post-Miocene downwarped basin. The large, concave central trough (maximum depth near 1260 m) is a semi-enclosed depression (north of the Strait of Otranto) partially filled by thick sequences of turbidites. The surrounding margins, progressively narrow and tilted southwards, display a crenulate form; this latter is due to canyons, fault scarps, and spurs (some of which may be submerged coral reefs) only partly buried by the sedimentary cover.

Rifted Cenozoic Basins

The Western Mediterranean Basin and Tyrrhenian Sea are two basins almost entirely underlain by young oceanic crust. Differences in the timing of contraction of this layer by cooling and in thicknesses of sediment account for the different depths of these two depressions: 2800 m in the Western Mediterranean, 3600 m in the Tyrrhenian Sea (Fahlquist and Hersey, 1969; Selli and Fabbri, 1971; Finetti and Morelli, 1973, 1974; Stanley et al., 1974a; Morelli et al., 1975b; Ryan, 1976; Watts and Ryan, 1976; Rehault et al., this volume).

Fig. 1.6. 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.

Western Mediterranean

The Western Mediterranean Basin, roughly triangular in shape, extends about 1200 km along the African coast and 850 km on the 9° east longitude meridian (Fig. 1.7). Its western corner occurs at the Strait of Gibraltar (400 m deep, 14 km minimal width), the only passage to the world ocean for salt exchange. According to general opinion, the entire basin formed mainly by long-term continental rifting followed by a short-term drift (Alvarez, 1972; Auzende et al., 1973; Dewey et al., 1973; Boccaletti and Guazzone, 1974a, 1974b; Alvarez et al., 1974; Biju-Duval and Montadert, 1977; Biju-Duval et al., 1977). Geological and geophysical data have shown that the occidental basin (of western Pacific type) was created from the late Oligocene to the upper Miocene. It would seem, however, that this aperture did not form synchronously everywhere, i.e., Aquitanian to Burdigalian in the northern part, but probably slightly younger (Burdigalian to Tortonian) in the southern part (Algerian plain). Two types of basins are recognized.

Narrow Rifted Basins. The Alboran Sea is an elongated depression (about 350 km long, 150 km wide) located within a Tertiary semicircular mobile belt, the Gibraltar Arc, enclosed by the Betic and Rif mountains. Its origin remains controversial. Recent studies show the Moho discontinuity rising to about 15 km in the central part, but these reports have not conclusively established the composition of the underlying crust. Most geomorphic features probably result from distensive motion during the upper Miocene to Pliocene. A volcanic submarine chain, comprising the Alboran Ridge and Alboran Island, divides this sea into two basins: the Western Basin (1500 m deep), separated from the Eastern Basin (1900 m) by the Alboran channel (1700 m). The major features on both margins are large plateaus (for example, Andalucia Plateau, 800 m deep) formed by foundering of faulted continental blocks. Their recent tilting resulted in the formation of salient outer banks (Djibouti Bank, 213 m; Câbliers Bank, 291 m; Alidade Bank, 44 m), highs which serve

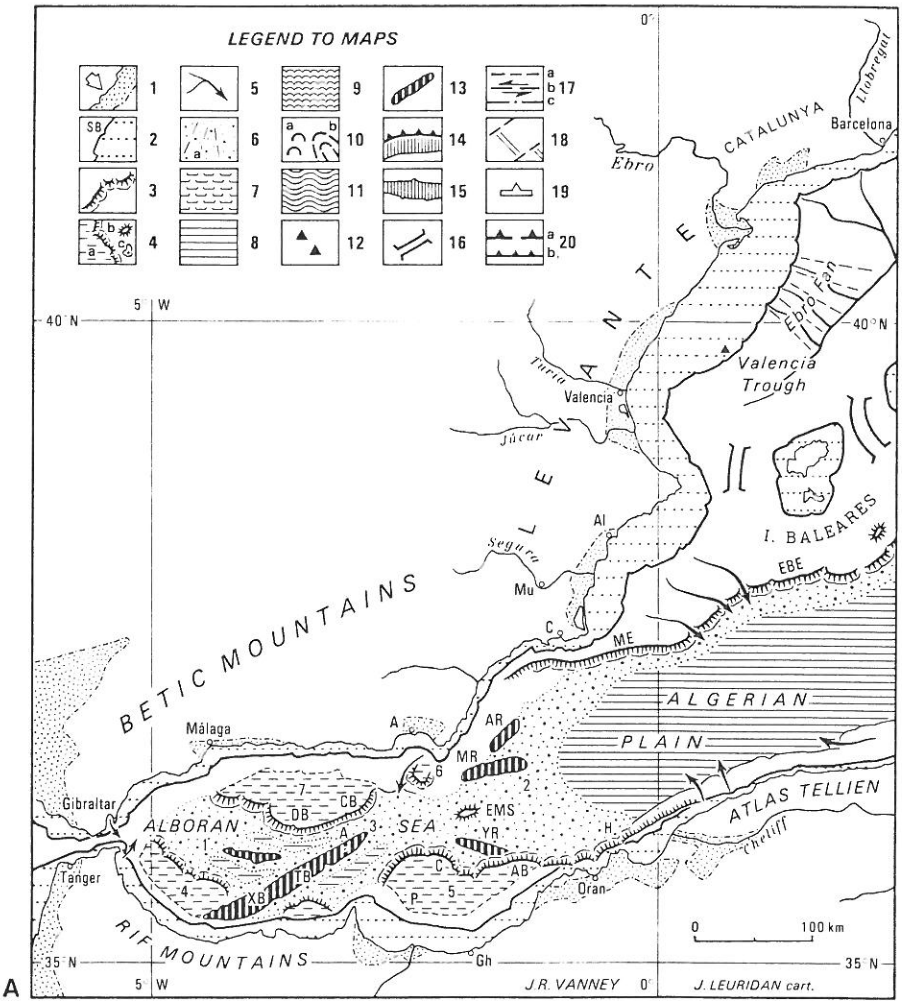

Fig. 1.7. Western Mediterranean Basin. General key (also applicable to other figures in this chapter): 1, coastal and lacustrine plain (arrow: retreating coastline); 2, continental-insular shelf (SB: shelfbreak); 3, escarpment; 4, marginal plateau (a) and seamount (b); 5, submarine canyon and sea valley; 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).

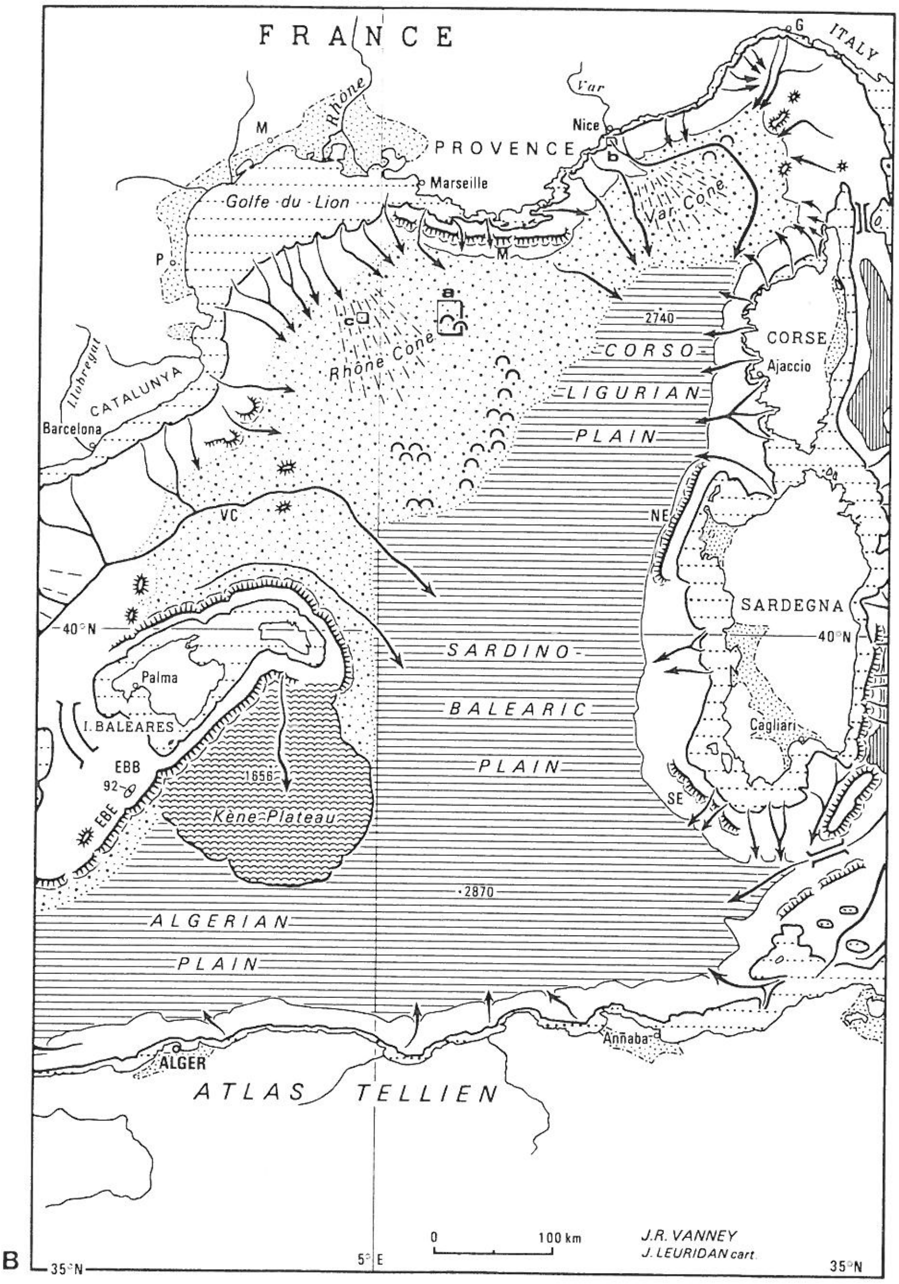

Fig. 1.7. (*continued*)

as dams modifying the dispersal of terrigenous sediments (Stanley et al., 1970; Olivet et al., 1973a, 1973b; Mulder and Parry, 1977).

The Valencia Trough is characterized by a V-shaped configuration (400 km long, 200 km maximum width). The depth of the central valley ranges from 1300 m to 2000 m. A rift origin is probably related to the opening of the contiguous Gulf of Lion, dating from the Oligocene. The two trough margins may be contrasted. The northern side bordering the continent was affected by active progradation (Plio-Quaternary buildup) of a wide continental shelf (60 km) and marked erosion of the slope. The southern side, on the other hand, comprises a narrow shelf and steep rocky slope (Tramontana Escarpment) bordering the Balearic Islands; this margin is offset by the Ibiza and Mallorca channels (800 m deep). Axial valley deposits bury some volcanic structures that formed during rifting (Mauffret et al., 1972, 1973; Bayer et al., 1973; Mauffret, 1977; Vanney and Gennesseaux, 1979).

Central Major Basins. One geographic name is commonly used for the entire Western Mediterranean depression: the Algéro-Provençal Basin. This major depression, however, includes the Algerian, Sardino-Balearic and Liguro-Provençal Basins that are not distinctly separated from each other. The three sectors are backarc-like basins, underlain below the deepest parts by normal oceanic crust; depths are nearly constant (2600 to 2800 m), and the flat basin floor is the result of smoothing by turbidites. The oceanic crust is probably of variable age. More sediments have been transported basinward from the European than from the African source terrains. During the recent past, the overall physiographic evolution has been influenced by marked normal faulting along continental slopes; thus, continental shelf build-out became limited while slope declivity increased. Transport for considerable distances of an abundant, but irregular, supply of clastic sediments (turbiditic and hemipelagic) has affected the entire basin plain configuration (Auzende and Olivet, 1974; Biju-Duval, 1974; Rehault et al., 1974; Mauffret, 1977).

Continental Margins. Shelves, slopes, and rises, irregularly distributed around the Western Mediterranean Basin, are subdivided into two main provinces: the upper margin and the lower margins.

The upper margin (shelves and slopes; cf. Bourcart, 1960) includes numerous sectors where the rocky basement is exposed (Maures, Corsica, Balearic, and African margins). Shelves tend to be narrow and sometimes absent off coastal mountain chains, capes, and cliffs (such as off Nice and many parts of the Algerian coast). The seafloor is often rocky or thinly mantled by Holocene biogenic or terrigenous sediments. Moreover, the shelfedge depth is highly variable: 90 m off uplifted coasts such as the northern Ligurian Sea and 130 m in zones of subsidence, such as the Maures margin (Fierro et al., 1973; Gennesseaux and Rehault, 1975; Gennesseaux and Vanney, 1979).

Highly irregular continental slopes contrast with the near-horizontal surface of the adjoining bathyal plain. The multiple steplike nature of the slope, probably related to normal faults, is noted on bathymetric charts. Seismic reflection records also reveal numerous lenses of Plio-Quaternary fine-grained sediment that are either deformed or displaced (or both) by slumping. Some slopes with a declivity exceeding 20% can be termed escarpments (Fig. 1.7). Some slopes are several hundreds of kilometers long, such as the Emile Beaudot Escarpment (south of the Balearic islands), Habibas Escarpment, and most of the Algerian margin. Their width, as measured between the 200 and 2000 m isobaths, does not exceed 10 km (examples: Maures, Nurra, and Habibas Escarpments). Most are parallel to the structural trend of coastal chains, and their relief, except where cut by a few small valleys (Habibas, Balearic, and Emile Beaudot Escarpments), is generally smooth. Other escarpments, in contrast, are affected by basement fractures and are deeply incised by large canyons (Corsica, Maures). These valleys are generally short, less than 60 km long, but have cut into the rocky basement so as to produce reliefs to 1500 m. This marked relief results in large part from short but intense erosion of the basement during Messinian dessication and subsequent Plio-Quaternary subsidence (Cita, 1973; Cita and Ryan, 1973; Rehault et al., 1974; Clauzon, 1975; Estocade, 1977, 1979; Bellaiche et al., 1977, 1979; Ryan, 1978; Cyaligure, 1979; Vanney et al., 1979; Gennesseaux and Lefebvre, 1980; Vanney and Bellaiche, 1982).

A second group of upper margin types has resulted from more extensive displacement of faulted blocks (Western Sardinia, Gulf of Lion, Alboran Sea). The sedimentary cover here is generally thicker, in part because of somewhat increased sediment stability on slopes of decreased declivity. Major deposits lie seaward of two major European rivers (Rhône, Ebro) that built a progradational shelf 70 km wide in the Gulf of Lion (Auzende et al., 1973; Rehault et al., 1974; Aloïsi et al., 1975; Maldonado, 1975). The shape of major deep valleys that cut these delta slopes results from important submarine incision during Quaternary low sea-level stands (Fig. 1.10). In some cases, however, canyons have resulted from a composite process involving both subaerial (during the Messinian) and submarine (Pliocene and Quaternary) processes. One such example is the Var Canyon (Fig. 1.9; Clauzon, 1978; Pautot, 1981). The origin of the Sardinia margin is considerably different. Here the shelf appears tilted basinward (shelfbreak deeper than 200 m), and its considerable width (40 km) and smooth surface may be related to lava flows or outcrops of Mesozoic sedimentary rock basement or both. Our understanding, however, of the underlying structural control is limited.

The lower margins (including the continental rise) are well developed only in the northern part of the basin (eastern Valencia Trough and Liguro-Provençal Basin) as a result of drainage and sediment input by European rivers. Continuity of the rise in the northern part of the Western Basin results from overlap of three major deep-sea fans. These are, from west to east, the Ebro, Rhône, and Var cones.

The Rhône Cone is the most important (200 km wide) and best defined. It formed largely during the Pliocene and Quaternary, and sediment supply has been reduced since the end of the Würm. Recent Sea-Beam surveys and high-resolution seismic reflection profiles serve to define several physiographic provinces: (1) an upper fan, with a raised flat-floored valley; (2) a mid-fan, with a recently formed left-trending bed on a new lateral channel (Fig. 1.10); and (3) a lower fan over which turbidites flow around salt diapir hills (Fig. 1.8) such as the Mistral Dome (250 m high) and others (Gennesseaux and Vanney, 1979; Monaco et al., 1982; Bellaiche et al., 1983).

The Var Cone, much smaller than the Rhône Fan, remains active and extends southward to the base of the Corsica slope in the Ligurian Sea. The deep Var Valley course has been strongly affected by subsidence of the central basin and associated salt diapirism.

The Ebro Fan, formed in the outer part of the Valencia Trough, is less well defined. Its configuration has been strongly influenced by the eastern margin of the trough (the Balearic continental block, which acts as a barrier) and is composed of three successive detritical cones, none of which is obvious on bathymetric charts (Maldonado, 1975; Monaco et al., 1982).

The sediment cover on the continental rise is reduced (and locally absent) in some parts of the Western Basin. Bathymetric charts clearly show that off Corsica and Algeria, for example, the 2400- to 2600-m isobath forms a sharp boundary between the lower slope and the flat bathyal basin plain. The Kene Plateau (1700 m) is another type of continental rise extending southward of the Balearic Islands, but its origin is not well defined. Large magnetic anomalies suggest the presence of a volcanic body below the sedimentary cover. A hypothesis favoring the foundering of a continental block remains to be proved (Bayer et al., 1973; Mauffret, 1977; Kelling et al., 1979).

Bathyal Plain. A long (>800 km), narrow (100–200 km) basin plain extends without interruption from the Alboran Sea to western Corsica at depths of about 2600 to 2800 m. The upper unconsolidated sediments are formed by a thick (1000–2000 m) Plio-Quaternary sequence of turbidites and hemipelagites. These bury thick series of Messinian evaporites (gypsum and halite) as indicated by seismic reflection records. Numerous, often contiguous, salt domes pierce the overlying strata and locally disrupt the sedimentary cover at the sea-floor surface. As in other Mediterranean marginal basins, the sedimentation rate is high, at least 10 cm/1000 years and locally much greater (Montadert et al., 1970; Rehault et al., 1974, this volume; Stanley et al., 1974b; Morelli et al., 1975b; Mauffret, 1977).

Tyrrhenian Sea: Youngest Oceanic Basin

The basin floor of the Tyrrhenian Sea is deep (3600 m), yet one of the smallest (230,000 km^2) in the Mediterranean (Fig. 1.11). Water exchange in this almost completely land-enclosed basin occurs across four sills: the Sardino-Tuni-

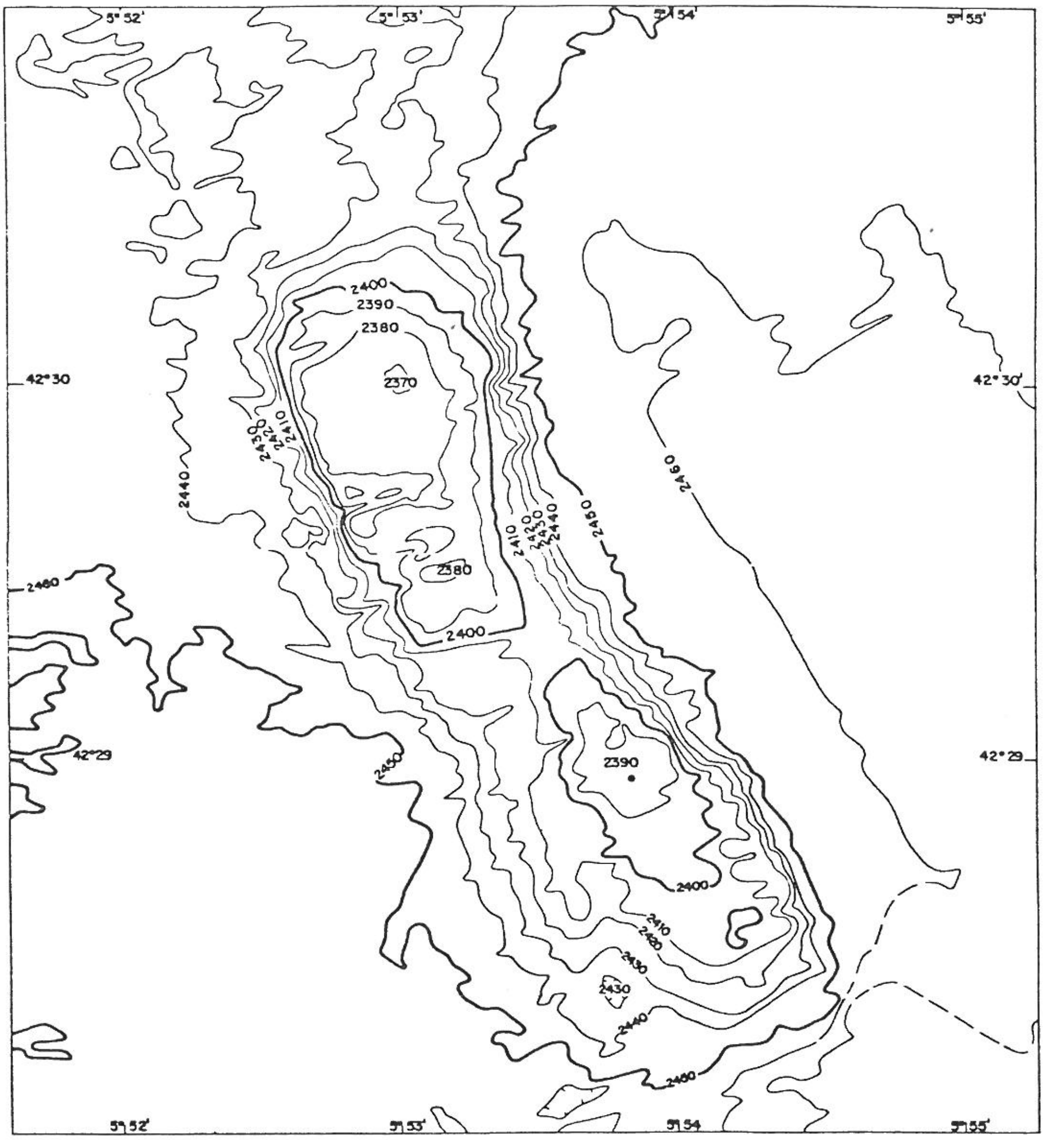

Fig. 1.8. Multichannel (Sea-Beam) map of a dome in the Des Marins group on the Rhône Cone. Contour interval; 10 m. Location shown in Figures 1.1 and 1.7. Note the linearity and asymmetric form of the hill. Kindly provided by J.P. Rehault, Villefranche-sur-Mer.

sian Strait (1950 m), the Bonifacio Strait (60 m) between Corsica and Sardinia, the Corsican Channel (400 m) in the northern Tyrrhenian, and the Strait of Messina (100 m) between Sicily and Italy (Morelli, 1970).

Recent geophysical and geological studies, undertaken primarily by Italian institutes, have shown that the present geomorphic pattern results from rifting motion dating from the upper Miocene and subsequent rapid foundering of newly created oceanic crust (Selli and Fabbri, 1971). Tectonic displacement has been largely controlled by north-south fault trends, such as the major Faglia Centrale. Depressions located behind the Calabro–Sicilian Arc are viewed as marginal basins on the basis of volcanic and seismic criteria. Recent foundering and continuing structural activity help explain the marked relief of both the margins and the basin floor of this sea (Alvarez, 1972; Boccaletti and Guazzone, 1974a, 1974b; Wezel, 1974, this volume; Biju-Duval and Montadert, 1977).

Continental Margins. During subsidence of the Tyrrhenian Basin, continental margins were

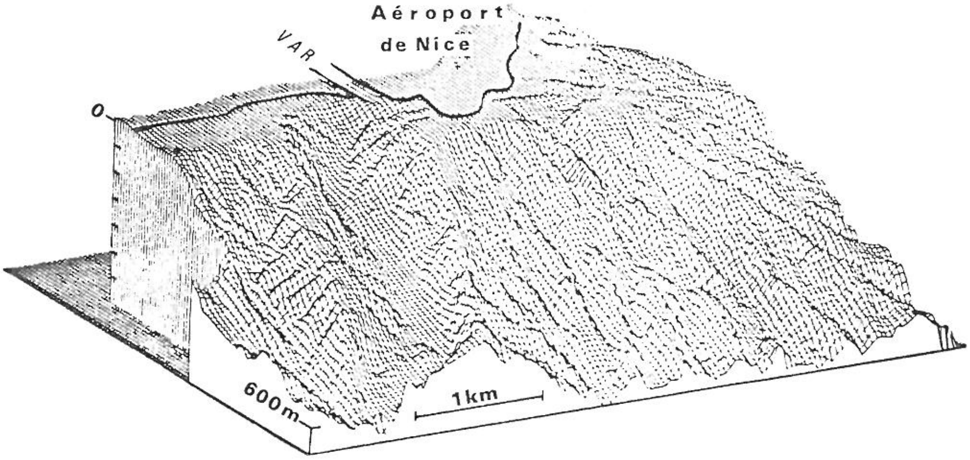

Fig. 1.9. Chart of the Quaternary prodelta of the Var River (Provence), kindly provided by Decca-Survey France. Location shown in Figs. 1.1 and 1.7. The block-diagram has been computer generated from a digital data bank. The original contour map (at a scale of 1 : 10,000) was prepared from a dense bathymetric line survey (50 m apart), using a narrow beam (6°) echosounder. The chart depicts the narrow deltaic shelf, deep and intense dissection by a radial ravine system, flat bottom of the Var Canyon (on the left of the diagram) contrasting with the sharp and crenulate crests, and the near-continuity between the subaerial and submerged segments of the Var Valley.

displaced and vertically offset along a dense network of normal faults. Two structural orientations are highlighted by the topography (Fabbri et al., 1981):

1. Some physiographic features are indicative of predominant faulting parallel to the coast line. The configuration of Sardinian, Sicilian, and southern Italian margins can be related to basement structure as emphasized by Selli (1970). A semicontinuous succession of seamounts and ridges of crustal derivation divides most of the slope into two segments (Fig. 1.11A). Although not all sectors of such margins have been sampled, study to date indicates that their underlying geological configuration as well as their shapes are diverse. Off the Sardinia, Baronie, and Quirra seamounts lie two elongated (100 km in length) and very narrow chains; these latter occur up to 50 km from the coast and are separated by the Orosei Canyon. Relief features are mainly formed by Paleozoic crystalline series (such as the Sardinia crust) and have resulted from large normal fault displacement and tilting during the Plio-Quaternary. The Baronie highs were eroded during the Würm by subaerial processes (170 m depth); the much deeper (866 m) Quirra Seamount remained submerged during this period.

On the Italian margin, the most important intraslope ridge extends along the Paola Basin from 41° north latitude to Calabria in the south. Elsewhere, individual seamounts and short ridges and chains (allochthonous series and/or basaltic volcanoes) appear on some of the typical Tyrrhenian cross-section profiles as depicted schematically in Figure 1.11A. The greatest effects of tectonics, however, are noted on the Sicilian margin where volcanoes abound (Eolian islands, Ustica Island). These relief features served as dams, with the deep basins behind them retaining gravity-induced deposits. In some cases, these intraslope basins (Fig. 1.11B) have become entirely filled with detrital sediment (Calabrian, Paola Basins) which then overflow and by-pass the structural barriers. When such tectonically controlled basins lie near the coast, complete filling by sediment eventually results in the formation of a continental shelf; one such example is the midsector of the Italian coast north of Naples. In other regions, partial filling of a basin results in a wide terrace separating the two slope segments, i.e., a good example is the southern Sardinia margin (Wezel et al., 1979; Borsetti

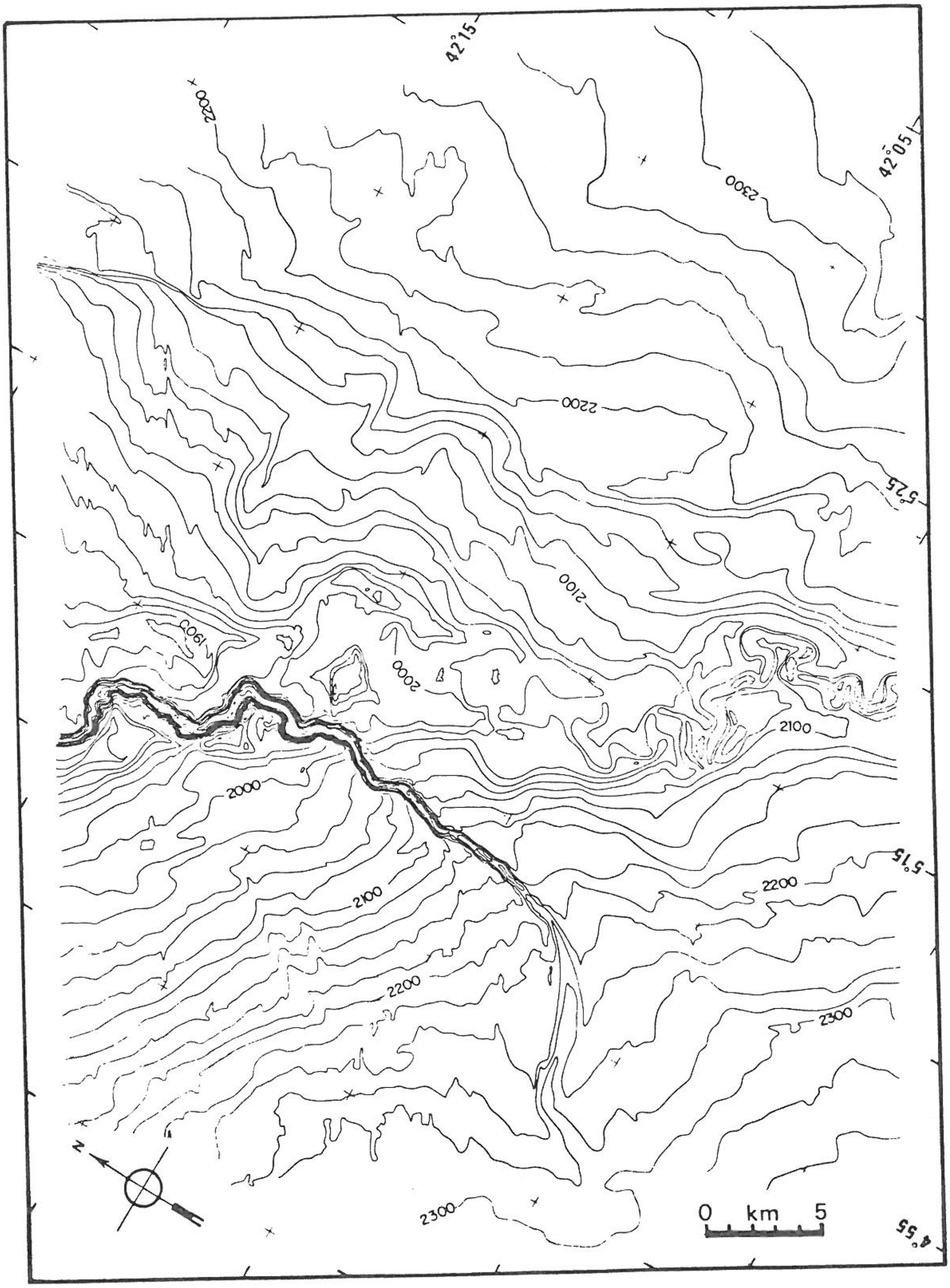

Fig. 1.10. Channels and fan of the Rhône Cone plotted with multichannel (Sea-Beam) data (for location, see Figs. 1.1 and 1.7). Contour interval, 20 m. Kindly provided by G. Bellaiche (Villefranche-sur-Mer). The Vieux Rhône Channel, approximately delineated by the 2050-m contour, is characterized by a sinuous, flat-floored segment; a deserted south-southeast-trending channel appears as crescentic depressions and flat-topped crests. At 2210 m, the new channel, south and southwest-trending, is bordered by levees on the lower cone. This recent distributary channel and associated fan surface formed by incision of the western levee and channel overflow.

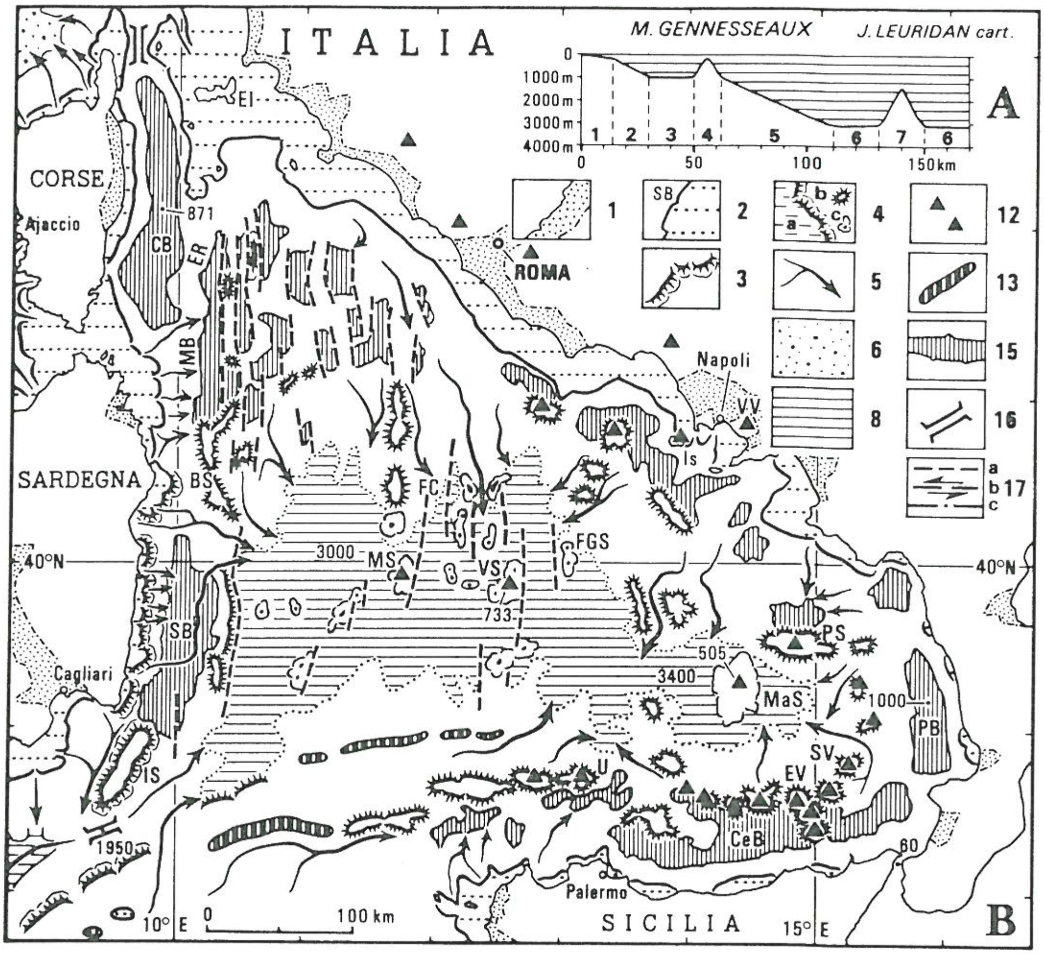

Fig. 1.11. Tyrrhenian Sea and surrounding areas. Legend for cross-section, in A: 1, continental shelf; 2, upper slope; 3, intraslope basin; 4, midslope smt; 5, lower slope; 6, central plain; 7, central smt. Legend for the chart, B: 1, coastal and lacustrine plain; 2, continental/insular shelf (SB: shelfbreak); 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).

et al., 1980). In some sectors, crystalline or volcanic strata have merged largely above the slope and delineate shallow basins (Cefalu Basin) or deep furrows, some open at each end (near Baronie Seamount).

2. Other physiographic features or margins result from oblique normal faulting abutting against a horst and graben system. The northern margin of the Tyrrhenian Sea is the direct southern continuation of the Tuscany landmass. This sector comprises a dense series of north–south-trending horsts and grabens with a configuration recalling a continental borderland (Viaris de Lesegno et al., 1978; Wezel, this volume). To the west, the Corsican Basin, comprising a thick accumulation of Cenozoic sediments, is similar to a relict forearc basin (Rehault et al., this volume).

Both canyon distribution and axial trends are dependent on fault systems. Some valleys end in midslope basins, while others only appear on the lower slope. A few Tyrrhenian canyons such as Orosei Canyon,

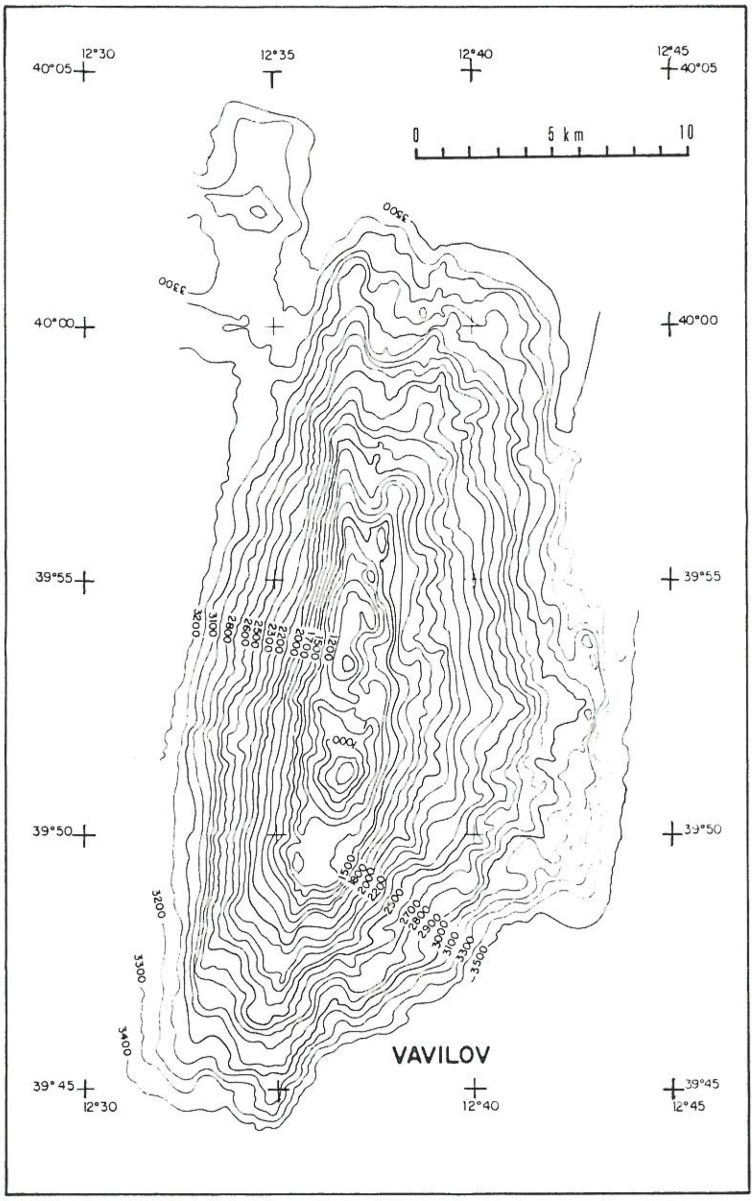

Fig. 1.12. Vavilov Seamount (central Tyrrhenian Sea) based on multichannel (Sea-Beam) data (location shown in Figs. 1.1 and 1.11). Contour interval 100 m. The mount, clearly delineated by the 3300-m contour in the Tyrrhenian Plain, is one of the most important seamounts in the Mediterranean. It is a thick tholeiitic lava build-up along a north-south fracture. Noteworthy are the west-east asymmetry of the slopes, low number of large erosional ravines, and craterlike knobs on the crestline.

near the Baronie Seamount, and Stromboli Canyon are similar in shape to those of the Western Mediterranean Basin.

Central Basin. The deep Tyrrhenian basin sector exceeds depths of 3500 m owing to its oceanic structure covered by a thin sedimentary cover and geologically recent foundering that has progressed from west to east since the Messinian (Fabbri and Curzi, 1980). Its topography is characterized by two major features:

1. A flat plain (Fig. 1.11A, 1.11B) in the deepest part of the basin has resulted from turbiditic deposition during the Plio-Quaternary. Salt diapirism here is less active than in the Western Mediterranean. No deep-sea fans have developed although an abundant sedimentary supply as been provided from the Apennines.
2. Large, asymmetric mounts and ridges (Fig. 1.11A) emerge above the flat seafloor. These are generally elongated and oriented N10°W, parallel to major distension fault trends. Some are tilted continental crust blocks, others are volcanic features, sometimes of tholeiitic origin (Vavilov Mount, 2600 m,

Fig. 1.12, and Marsili high, 3000 m), rising above the basin floor.

Concluding Remarks

A few of the salient points raised in this chapter can be summarized as follows:

1. Shelves: The generally narrow nature of Mediterranean continental shelves and variable depths of shelfbreaks are largely a function of Plio-Quaternary tectonics.
2. Slopes: The generally high slope declivities may reflect a recent overall compression that has affected the entire Mediterranean basin. A characteristic attribute resulting from geologically recent tectonics is the offset of the slope into two or more sectors, as exemplified by the Tyrrhenian margin.
3. Canyons: Mediterranean canyons have long served as type examples of submerged V-shaped valleys. New techniques (Sea-Beam, deep submersible dives), however, indicate that flat floors, sometimes wide and U-shaped in profile (Var Canyon, for example), often prevail. As to their morphology, some canyons appear to have been cut by subaerial erosion during the Messinian and then subsequently modified by Quaternary deepening.
4. Continental rise: The two largest sedimentary depocenters, the Rhône and Nile cones, are composite submarine deltas formed by superposed fans. Classic levees and lobes are much better developed on the Rhône deep-sea fan than on the Nile Cone.
5. Active compressive margins: New technology, Sea-Beam surveys in particular, show the great physiographic complexity of Mediterranean tectonic arcs. The Hellenic Trench, for example, is not one continuous trough as often depicted in some typical Pacific arcs but consists of a series of deep, variably shaped and distributed structurally separated basins.
6. Deep-sea floor: Each of the three major basin systems described herein (Western Mediterranean, Tyrrhenian Sea, Ionian Sea–Levantine) constitutes a different morphology. The Ionian–Levantine Basin, recording effects of long-term compression, is characterized by a "youthful" (sharp, small, high-relief, broken) topography. The Western Mediterranean basin, in contrast, displays a vast, smoother surface formed by gravity-flow deposits locally deformed by salt tectonics. The small plain surface of the Tyrrhenian Basin is covered by a relatively thin sediment series that has not yet buried numerous offset and tilted continental blocks and submarine volcanoes.

In 1972, D.J. Stanley aptly surnamed the Mediterranean Sea a "modern sedimentation laboratory." Our overview shows, once again, that its complex physiography offers a magnificent field for morphogenetic study, particularly since the Mediterranean has undergone almost continuous "metamorphosis" since Jurassic time. As a response to the structural framework, for example, the Tunisian Plateau–Pelagian Sea is continuing to break apart. The Adriatic Sea is deformed between the evolving Apennine and Dinaride chains. Continental slopes record different stages of evolution: complex, broken configuration in young distension Tyrrhenian margins; high declivity in some Western Mediterranean Basin sectors, probably owing to recent compressive movements (Mauffret et al., 1981); and disorganized high-relief features that characterize much of the tectonically active (largely compressive deformations) Eastern Mediterranean margin.

Similar successive stages are recorded by the deep-sea floor. Deep portions of the recently rifted Tyrrhenian, for example, display numerous seamounts formed by both crystalline and volcanic series. In contrast, basin relief features of this type in the Western Mediterranean Basin are mantled by thick horizontal sedimentary layers (Auzende et al., 1972, 1975a, 1975b; Mauffret et al., 1981). The surficial cover of the Eastern Mediterranean Ridge, on the other hand, is progressively deformed by subduction processes. Our morphogenic classification may perhaps be used to help evaluate changes induced by the progressive disappearance of the Mediterranean Basin.

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