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Catalonian, Eastern Betic, and Balearic Margins: Structural Types and Geologically Recent Foundering of the Western Mediterranean Basin

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ABSTRACT

Stanley, Daniel Jean, Henri Got, Neil H. Kenyon, André Monaco, and Yehezkiel Weiler. Catalonian, Eastern Betic, and Balearic Margins: Structural Types and Geologically Recent Foundering of the Western Mediterranean Basin. *Smithsonian Contributions to the Earth Sciences,* number 20, 67 pages, 33 figures, 1976.—A high-resolution seismic study of the Catalonian, eastern Betic, and Balearic regions in the western Mediterranean emphasizes the importance of large-scale post-Miocene vertical displacement of upper Miocene and overlying unconsolidated sediment sequences. The structural configuration of the Pliocene and Quaternary series observed on subbottom profiles indicates that the geologically recent margins in these sectors have subsided along preexisting (Oligocene or older) as well as more recent (post-Miocene) tectonic trends. The post-Miocene movements are not necessarily synchronous and marked differences of structural styles are identified. The origin of the three major types of margins—abrupt, intermediate (or steplike), and progressive—is closely related to tectonic trends on land. Subsidence of the sub-Pliocene seafloor on the order of 1500 m is estimated on the basis of seismic profiles presented here.

The abrupt margin type, exemplified by the Emile Baudot and Mazzaron escarpments, occurs in areas where the edge of the basin parallels the major structures on land and where vertical displacement has developed in a relatively restricted structural zone. Intermediate margins, such as the sector southeast of the Betic chain, are localized in areas where two major structural trends converge (NE-SW and NW-SE fractures predominate), and show a steplike (growth fault) displacement landward. Progressive margins, such as off Catalonia, display a flexing of the Pliocene and Quaternary cover and are related to Pliocene foundering followed by more gentle subsidence from the upper Pliocene to the present. This type of margin occurs seaward of Tertiary basins where older (Hercynian to Miocene) tectonic trends have been reactivated. Seismic evidence indicates that submarine canyon development on these different margins is associated with the post-Miocene tectonics as well as with Quaternary eustatic events.

The Balearic Rise, a large continental block detached from the southern part of the Balearic Platform, foundered largely in post-Miocene time, but this feature has not yet completely subsided to the level of the Algéro-Balearic Basin plain. It is possible that large continental blocks beyond the base of slopes that are presently buried by a thick Pliocene-Quaternary cover may have a structural origin analogous to that of the Rise. Margin formation and the evolution of the western Mediterranean Basin bear some similarities to the structural development of rift zones.

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Contents

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Introduction

The origin of the western Mediterranean Basin is a complex and extremely challenging subject. The rapidly growing number of studies concerned with the Tertiary evolution of this deep enclosed sea are based mainly on analyses of deep penetration seismic profile, gravity, and magnetic data coupled with interpretations of the results of the Deep Sea Drilling Project D/V *Glomar Challenger* (1970 cruise, leg 13) and of the geology of adjacent land regions. Considerable discussion has revolved around the age of the basin and the mechanisms responsible for its formation, including oceanization (de Roever, 1969), and sea floor spreading (Le Pichon et al., 1971). Some workers, for instance, have proposed that the Mediterranean already had its extensive deep basin configuration at the end of the Miocene and was essentially a desert environment at that time (Benson, 1972; Hsü, 1972; Cita, 1973; Ryan et al., 1973b). However, most geologists and oceanographers, including us (Got et al., 1973; Stanley et al., 1974a), favor the more classic view expressed by Bourcart (1950, 1963), Glangeaud (1962, 1968, 1970), Storetvedt (1973), and earlier workers, i.e., that the configuration of the Mediterranean as presently observed and the nature of the sediments which fill it are related to geologically recent foundering. This sea-floor subsidence, initiated in the Oligocene and perhaps earlier, is thought to have accelerated in post-Miocene time. The geological and geophysical arguments pertaining to the origin and time of formation of the present western Mediterranean Basin are presented elsewhere (Hersey, 1965; van Bemmelen, 1969; Pannekoek, 1969; McKenzie, 1970; Hsü, 1971; Vogt et al., 1971; Dewey et al., 1973; Drooger, 1973; Mauffret et al., 1973; Auzende and Olivet, 1974; Biju-Duval et al., 1974; Sonnenfeld, 1975; and others).

Although bearing on these problems, this investigation has a somewhat different and more specific purpose, i.e., to define selected margins bounding

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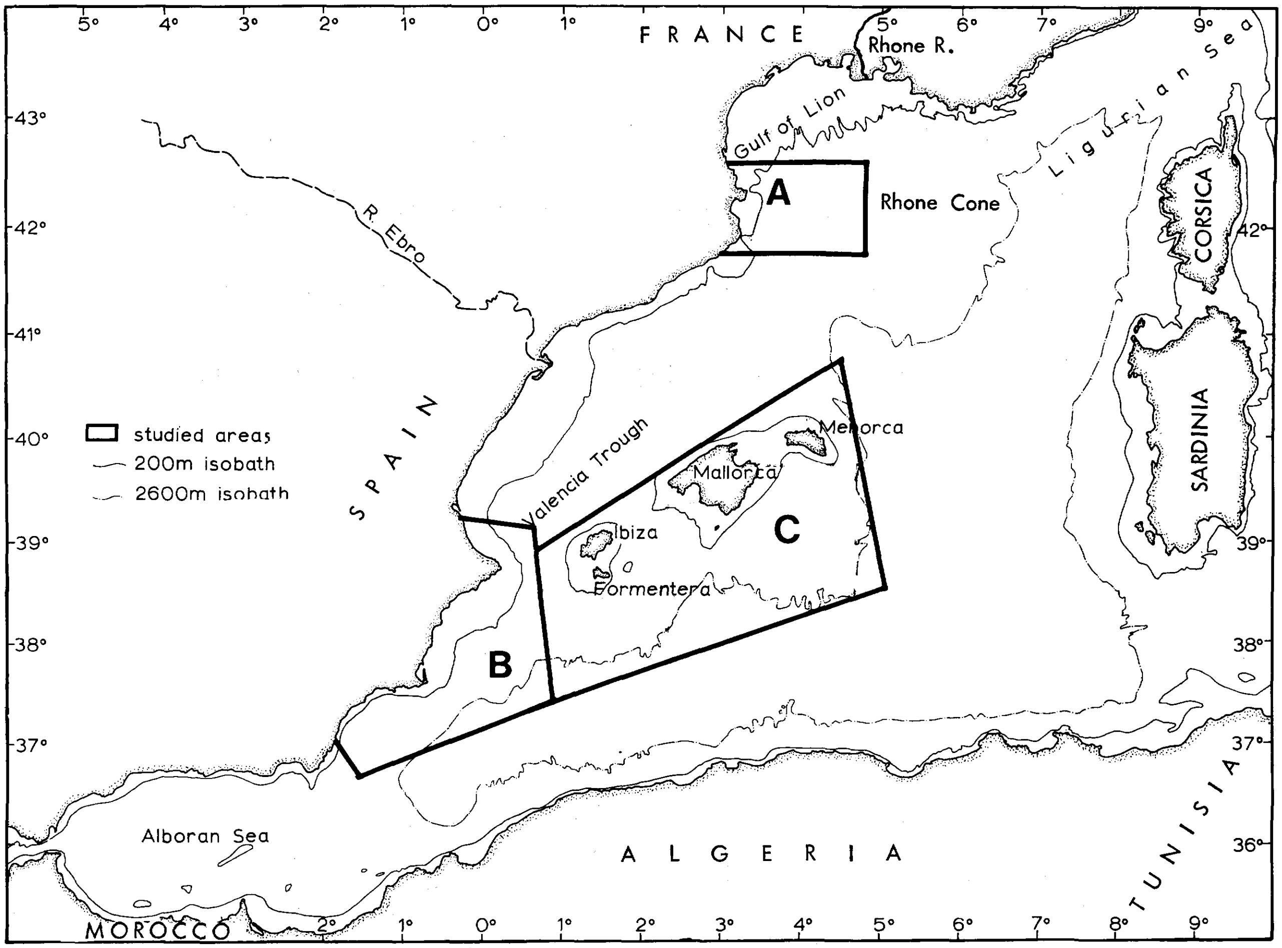

FIGURE 1.—Chart of the western Mediterranean showing the three study areas: A, Catalonian margin; B, eastern Betic margin; C, Balearic Platform and adjacent margins. (Topographic details shown in Figures 3 and 22.)

the western part of the Balearic Basin. Particular attention is paid to the late Miocene to recent evolution of structure, stratigraphy, and physiography in three regions: the Catalonian margin east of the Pyrenees, the eastern Betic margin southeast of Spain, and the Balearic Platform and its contiguous margins (Figure 1). An attempt is made to relate these margins to the structural framework of the adjacent land.

In these respects, the three continental margins have received little attention to date. Among the points considered here are the regional distribution and thickness variations of Pliocene and Quaternary sequences, and the modification of these young series by post-Miocene tectonic events. The origin of submarine canyons as related to margin evolution and the role of these features in sediment transport in the study areas are also evaluated. The configuration of the Pliocene and Quaternary units is detailed with low- to moderate-penetration seismic profiling systems which provide higher-resolution subbottom detail than that obtained with more powerful systems used to study the deeper (late Miocene salt and infrasalt) sequences underlying the basin (cf. Mauffret et al., 1973). Our subbottom investigations are supplemented by coring and deep drilling surveys in several sectors of the study area.

The three areas were initially examined independently by the different authors who used roughly comparable subbottom profiling methods.* Although these areas are topographically and geologically quite distinct, a joint investigation was subsequently conducted with the expectation that a comparison of the Catalonian, eastern Betic, and Balearic margins would shed light on the related problems of margin origin and basin evolution. We also believe that a comparison of our results with those compiled by others in the other parts of the western Mediterranean Basin would provide insight into post-Miocene history of the Mediterranean.

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We are indebted to a number of organizations for their generous backing including financial aid, ship-time, equipment and materials, and facilities provided which made this investigation possible: Centre National pour l'Exploitation des Océans (CNEXO), Centre National de la Recherche Scientifique (CNRS), Institut für Geophysik (University of Kiel), Institute of Oceanographic Sciences (Wormley, U. K.), Lamont-Doherty Geological Observatory (Columbia University), Musée Océanographique de Monaco, National Geographic Society (Research Committee), New York State Maritime College, Smithsonian Research Foundation, and the U. S. Naval Oceanographic Office (NAVOCEANO). Bottom and subbottom surveying was conducted on the N/O *Catherine Laurence,* R/V *Conrad,* RRS *Discovery,* T/S *Empire State IV,* N/O *François Blanc,* USNS *Lynch,* N/O *Professeur Lacaze-Duthiers,* D/S *Terebel,* and N/O *Winnaretta-Singer.* The captains, officers, and men of these ships are thanked for support so efficiently given in the work at sea.

We acknowledge with gratitude the many persons with whom we have had an opportunity to discuss the various problems raised in this study. We thank, in particular, Dr. O. Leenhardt, Institut für Geophysik (Kiel); Dr. A. H. Stride, Institute of Oceanographic Sciences (Wormley); and Commandant J. Alinat, Musée Océanographique de Monaco, who made special contributions to this undertaking. We also shared pleasant and productive hours at sea and in the laboratory with Dr. J.-C. Aloisi, University of Perpignan; Mr. R. Belderson and Mr. B. S. McCartney, Institute of Oceanographic Sciences, Wormley; Dr. A. Blackman (deceased) and Mr. R. S. Anderson, U. S. Naval Oceanographic Office; Professeur M. Gottis, University of Bordeaux; Mr. G. Serra-Raventos, University of Barcelona; and Dr. F. Theilen, Institut für Geophysik (Kiel.)

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Drs. B. Biju-Duval, Institut Francais du Pétrole, and G. Kelling, University of Wales at Swansea, read the manuscript and provided helpful suggestions improving the text. We also thank Dr. W. B. F. Ryan, Lamont-Doherty Geological Observatory, for his thought-provoking review of the manuscript. Although we clearly stand on opposite sides of an important scientific argument discussed in this monograph, we welcomed the opportunity to consider his comments. The data interpretation and conclusions presented here, however, reflect the views of the authors.

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Methodology

The data presented in this study were collected on numerous cruises conducted independently by the authors and their colleagues during the past decade. Reasonably dense bathymetric and sub-

* The initial investigations of the Catalonian margin were made by Monaco (1971) and Got (1973); the eastern Betic by Kenyon (unpublished); and the Balearic Platform and adjacent areas by Weiler and Stanley (1973) and Kenyon (unpublished).

bottom seismic coverage is available in the three study areas as a result of these surveys. Numerous profiles are supplemented locally by other data including cores, grab samples, and observations made during submersible dives and bottom camera and side-scan sonar surveys.

Bottom and subbottom data on the Catalonian margin east of the Pyrenees and the French-Spanish border were collected between 1965 and 1974 on the N/O *Catherine Laurence*, N/O *François Blanc*, N/O *Winnaretta-Singer* and N/O *Professeur Lacaze-Duthiers*. Positioning was made by radar and RANA navigation (precision of within 500 to 1500 m) and the following systems were used:

1. 12 kHz transducer for bathymetry
2. EG&G Boomer (300 and 500 J), with a HP–60B hydrophone and EG&G 254 recorder (ship's speed of 4 knots, a total of about 1000 km)
3. EG&G Sparker (3000 J), with a HP–60B hydrophone and EG&G 254 recorder (speed of 8 knots, a total of about 500 km)
4. EG&G Sparker (9000 J), with a Chesapeake M-16 hydrophone and EG&G 254 recorder (speed of 6 knots, a total of about 1500 km)

Other seismic data in this area have been published by Alla (1970), and Got et al. (1971). The methods used and results obtained during these surveys are detailed in Monaco (1971) and Got (1973). Also available were data from piston cores, grab samples, and submersible dives (Reyss, 1964; Reyss and Soyer, 1965; Got and Stanley, 1974). Stratigraphic interpretations of seismic profiles in this region are based on correlation with exploratory petroleum drilling on land (Gottis, 1958) and on the adjacent Gulf of Lion continental shelf (Cravatte et al., 1974).

Bathymetric and seismic coverage on the margin east of the Betic range off southeastern Spain is less dense than on the Catalonian margin. Among the profiles used are 9000 J sparker lines obtained on the 1969 cruise of the D/S *Terebel* (EG&G Sparker 9000 J; Chesapeake M–16 hydrophone; EG&G 254 recorder; ship's speed 5 knots) and air-gun profiles from the R/V *Conrad* 9 (August 1965) courtesy of W. B. F. Ryan (Lamont-Doherty Geological Observatory). These were complemented by seismic data collected on cruises 27 and 28 of the RRS *Discovery* (June–July 1969) of the Institute of Oceanographic Sciences, Wormley, where the following equipment was used:

1. Precision Echo Sounder for bathymetry
2. A free-running type air gun (28 cu. in), with a 200-ft-long hydrophone, trailed at ship's speed of about 6 knots
3. 36 kHz short-range, side-scan sonar on the shelf and upper slope

The largest of the three areas studied, the Balearic Platform and adjacent margins, has been surveyed during several cruises:

2. RRS *Discovery* (cruises 27 and 28, 1969) using equipment described above, and in addition GLORIA (6.5 kHz geological long-range inclined ASDIC)
2. RRS *Discovery* cruise 35 (11 July to 19 August 1970), where positioning was made by satellite and radar; seismic gear similar to that of 1969 cruise, but ship's speed 8 knots and length of hydrophone 300 ft
3. USNS *Lynch-I* (cruise January–February 1972) used satellite, Loran-C, and radar for positioning; 3.5 kHz and 12 kHz transducers used for bathymetric profiling (G. Kelling, A. Maldonado, and D. J. Stanley, in preparation), and 30,000 J Teledyne Sparker with Precision Electrographic Recorder (Raytheon) used for subbottom profiling at ship's speed of 10 knots; additional material collected includes piston and gravity cores that provide sediment sound velocity data (NAVOCEANO velocimeter equipment); bottom photographs obtained at 8 stations on the Balearic Rise
4. T/S *Empire State IV* cruise (June 1972) provided additional coverage of Balearic region south of islands of Menorca and Mallorca using EG&G 8000 J sparker
5. *Conrad-9* (1965) air gun transect provided information on area east and southeast of Menorca (cf. Ryan et al., 1970); ship's speed 10 knots

Stratigraphic interpretations are based on correlation of seismic profiles with those that traversed JOIDES 13 site 124 (Ryan et al., 1973a) immediately east of the Balearic Rise. The thickness of the upper (Quaternary) acoustic layers takes into account the sediment velocity measurements made on cores collected on the *Lynch-I* cruise, i.e., about 1.7 km per second. Recent sound velocity estimates for the entire Pliocene and Quaternary sequence range from 1.7 to 2.8 km per second and from 3.5 km per second (Hinz, 1972) for the underlying salt ("couche fluante") (including M or K reflectors); velocities to as high as 4.3 km per second are attributed to some older consolidated infrasalt layers above acoustic basement (Mauffret et al., 1973). Considerably lower values (3.0 km/sec.) have been recorded in some cases, thus resulting in a velocity inversion below the salt layer (Ryan, pers. comm.). In this study we assume a 2.0 km per second value in our calculations of the Pliocene and Quaternary thickness.

The Catalonian Margin

Geological Framework

The Catalonian margin extends between the southwestern part of the Gulf of Lion and the northern extremity of the Catalonian Chain (Gavarres Massif, Spain) off the eastern Pyrenees (Figure 1A, 41°50′ to 42°50′N lat.). The Gulf of Lion shelf and slope form the broadest and most extensive margin in the western Mediterranean, and this crescent-shaped borderland extends from the eastern Pyrenees near the French-Spanish border to the Provence region east of Marseille in southern France. The shelfbreak between Port-Vendres and Marseille is approximately 200 km long, and the widest sector of the Gulf of Lion shelf (65 km) occurs along a transect extending SSE from the Gulf of Aigues-Mortes west of the Rhône delta.

The emerged terrain bounding the Catalonian margin can be subdivided into several well-defined regions on the basis of morphology, stratigraphy, and structure. These four emergent Catalonian terrains, illustrated in Figure 2, are described below (from north to south):

1. The *Roussillon coastal plain,* a low-lying sedimentary basin consisting of Neogene deposits, is separated from the Languedoc region to the north by Cape Leucate, a headland comprising Mesozoic rocks. The continental margin off the Roussillon coastal plain is the southern extension of the Gulf of Lion.

2. The zone of the *eastern extension of the Pyrenees* includes primarily metamorphic units, including schists of the Albères region and gneissic rocks of the Canigou Massif; the latter forms the point of highest elevation (2785 m) on the emerged Catalonian region. This sector is bounded to the north and to the south by a complex network of faults.

3. The *Ampurdan coastal plain,* a sediment-filled basin, is morphologically similar to the Roussillon coastal plain. However, a topographic high, the Montgri Massif, separates this low-lying region into two zones: the Haut Ampurdan lies north of the massif, and the Bas Ampurdan to the south. The Montgri Massif, the remnant of a laterally thrusted mass of Cretaceous limestone, is presently exposed along the coast south of the Gulf of Rosas.

4. The *Gavarres Massif,* forming the northern part of the Catalonian Massif of northeastern Spain, comprises primarily crystalline and metamorphic (largely schist) sequences. This topographic high is separated from the Ampurdan region by a set of E–W trending faults.

The structural orientation southwest of the study area is NNE–SSW; faults define the Palafrugell zone ("Couloir de Palafrugell") in the northeastern Gavarres Massif. The predominant fault trend (Pyrenean) in the study area, however, is NW–SE (Figure 2). The evolution of the Catalonian margin is to a large degree related to the complex fault network cited above, and this structural configuration is discussed in subsequent sections.

Physiography

The physiographic configuration of the Catalonian continental shelf (Figure 3) is directly related to that of the contiguous emerged terrains described above. The Roussillon shelf (Figure 3), which forms the southwestern extension of the Gulf of Lion shelf is, for the most part, a broad, gently seaward dipping surface; topographic relief is subdued in the zone between 30 m and 110 m. The Pyrenean shelf, farther to the south (Figure 3, B) is narrower and the topography considerably more irregular. Here, three physiographic provinces are recognized between the coast and the shelf break: (1) a relatively steep margin extends from the coast to about 30 m depth; (2) the shelf slopes gently and uniformly in the zone between 30 and 90 m; and (3) an undulatory surface occurs between 90 to about 110 m. The outer shelf is bounded by the slope with an average gradient of 6 degrees. The lower Catalonian slope merges with the western part of the Rhône submarine fan (also called the Rhône Cone, Menard et al., 1965).

The continental margin off the Ampurdan coastal plain (Figure 3, C) is relatively deep, and the 100 m isobath is located only about 12 km from the coast. The gradient increases progressively seaward so that a transect across the margin in this sector appears as a convex-up profile; both shelf and shelf break are poorly defined. The degree of convexity of the profile increases to about midslope depths.

The physiography of the margin seaward of the Gavarres Massif in the southern portion of our

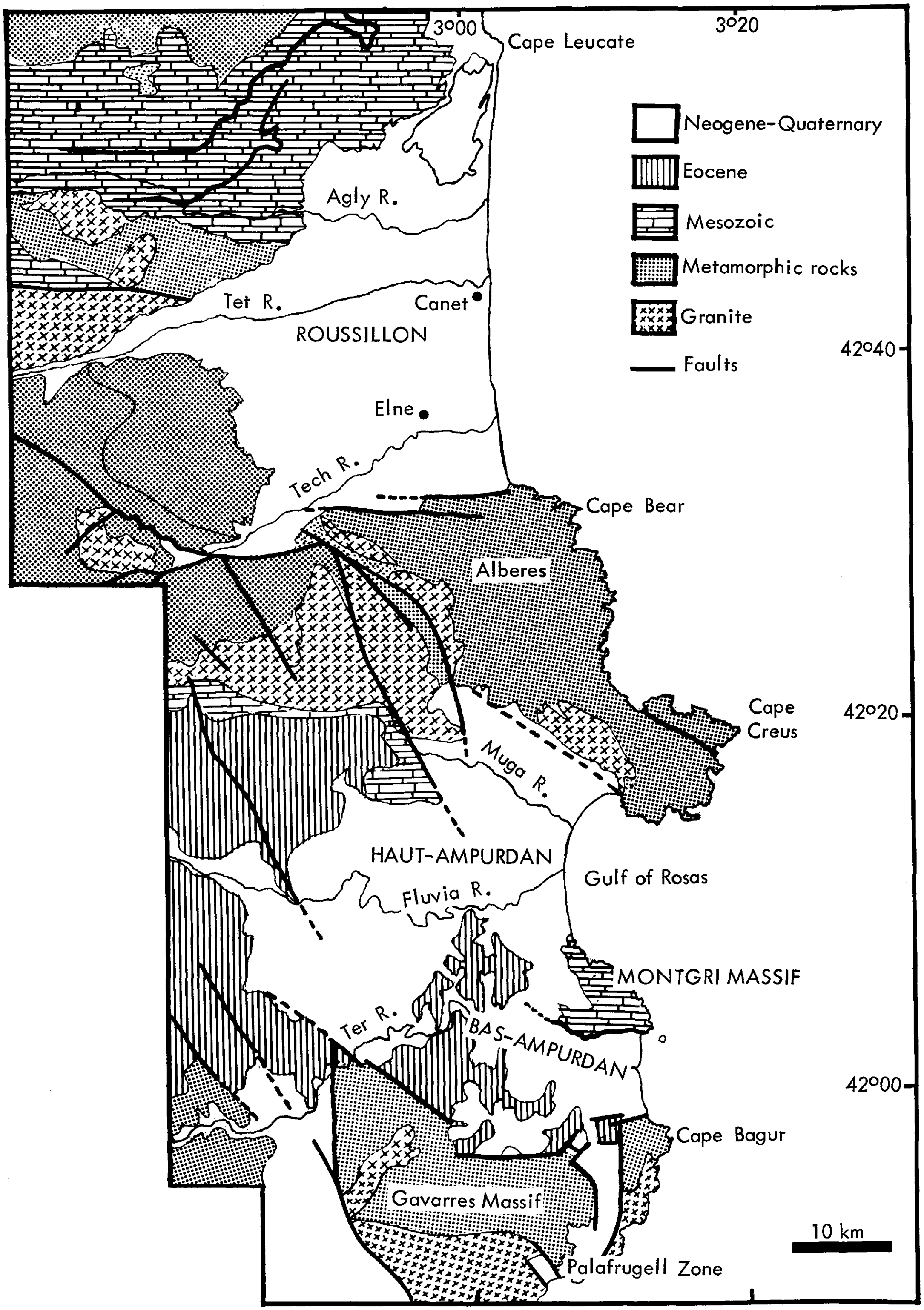


FIGURE 2.—Simplified geologic map showing major structural trends on land bordering the Catalonian margin.

study area (Figure 3, D) is similar to that of the Pyrenean shelf described above.

The Gulf of Lion submarine canyons have been mapped by Bourcart (1959, 1960a) and other workers. Several large submarine valleys also occur on the Catalonian margin, and include the following, from north to south (cf. Figure 3):

1. The Lacaze-Duthiers Canyon heads at a depth of 120 m, trends NNW–SSE, is slightly sinuous and is dissected by numerous tributary valleys along both canyon walls. Its general orientation becomes WNW–ESE at a depth of about 1000 m and the lower valley can be traced to about 1700 m. Cross-valley profiles are V-shaped and the configuration is typical of classic canyons described by Shepard and Dill (1966). Steplike terraces and other topographic irregularities along the canyon walls reflect, to a large degree, erosion and exposures of indurated bedrock (Got and Stanley, 1974).

2. The Cap Creus Canyon is oriented WNW–ESE and it heads, at a depth of 150 m, close (6 km) to Cape Creus. The trend is less sinuous than that of the Lacaze-Duthiers Canyon, but the axial gradient is greater. Cross sections reveal a wider profile and a flatter canyon floor than that of the preceding canyon (Reyss, 1964). The lower valley has been mapped to a depth of about 1700 m.

3. The La Fonera Canyon trends E–W and differs from submarine valleys lying farther to the north in possessing a U-shaped profile with a well-defined flat canyon floor. The canyon head is cirquelike and highly dissected, and the axial slope is high (to 10°). The lower valley can be followed to a depth exceeding 2000 m. Submarine canyons are absent on the margin off the Ampurdan coastal plain.

Stratigraphic Interpretation

Certain seismic reflectors in subbottom profiles on the Catalonian margin (Figures 4A and 4B) can be correlated with surface and subsurface strata; the latter have been mapped in petroleum drill holes on land and in the Gulf of Lion (Cravatte et al., 1974). The following is a brief analysis of the major subbottom sequences examined.

Paleozoic Basement.—The Gulf of Lion shelf is formed by Tertiary and Quaternary sedimentary sequences lying above the Hercynian basement. Cores of the Paleozoic basement have been recovered in four wells (*Sirocco, Mistral, Tramontane,* and *Autan*) (Cravatte et al., 1974), and these show that the Pyrenees extend geologically eastward to the Maures Massif on the Provence coast of southeastern France (Arthaud and Mattauer, 1972; Burollet and Dufaure, 1972).

The substratum in the Roussillon coastal plain has been penetrated at two petroleum (Compagnie Française de Pétroles) exploratory drill sites (Gottis, 1958), Elne and Canet, at depths of 2140 m and 1785 m, respectively. The basement is shallower in the Ampurdan coastal plain (1300 to 1600 m). Seismic profiles obtained on the shelf in the study area (Figure 5A, B) enable us to follow, in continuous fashion, the basement between the north Pyrenean margin and the Gavarres Massif. As in the Gulf of Lion (Alla et al., 1972), this basement deepens rapidly seaward, and deep seismic work has enabled this horizon to be followed to the base of the slope (Delteil et al., 1972).

Pre-Pliocene Sedimentary Sequences.—Although the subbottom penetration by various seismic systems used has been relatively low (500 m), units of probable pre-Pliocene age are occasionally recorded. The oldest Tertiary series crop out on the edge of the Ampurdan coastal plain and also have been cored at several drill sites in this area. Seismic profiles obtained on the Catalonian shelf and slope reveal several units that are interpreted to be older than Pliocene. The oldest stratigraphic horizon above the basement, noted on records collected north of the Gavarres Massif, appears as a concentrated sequence of reflectors (Figure 6B) showing distinct stratification and an unconformable contact with the underlying basement. It is possible that these seismic reflectors are of equivalent age and composition to calcareous and marly sandstones of Eocene age that are exposed above older metamorphic units on adjacent land sequences.

On the shelf south of La Fonera Canyon (off the Catalonian Massif) there occurs locally a sequence of subparallel reflectors that are well stratified and offset by a fault complex. The upper part of this unit displays a sharp surface (Figure 6C) believed to be erosional in origin. The penetration by seismic profiling is considerably more extensive than in the series described above. These reflectors are tentatively interpreted as Miocene strata (Serra-Raventos and Got, 1974).

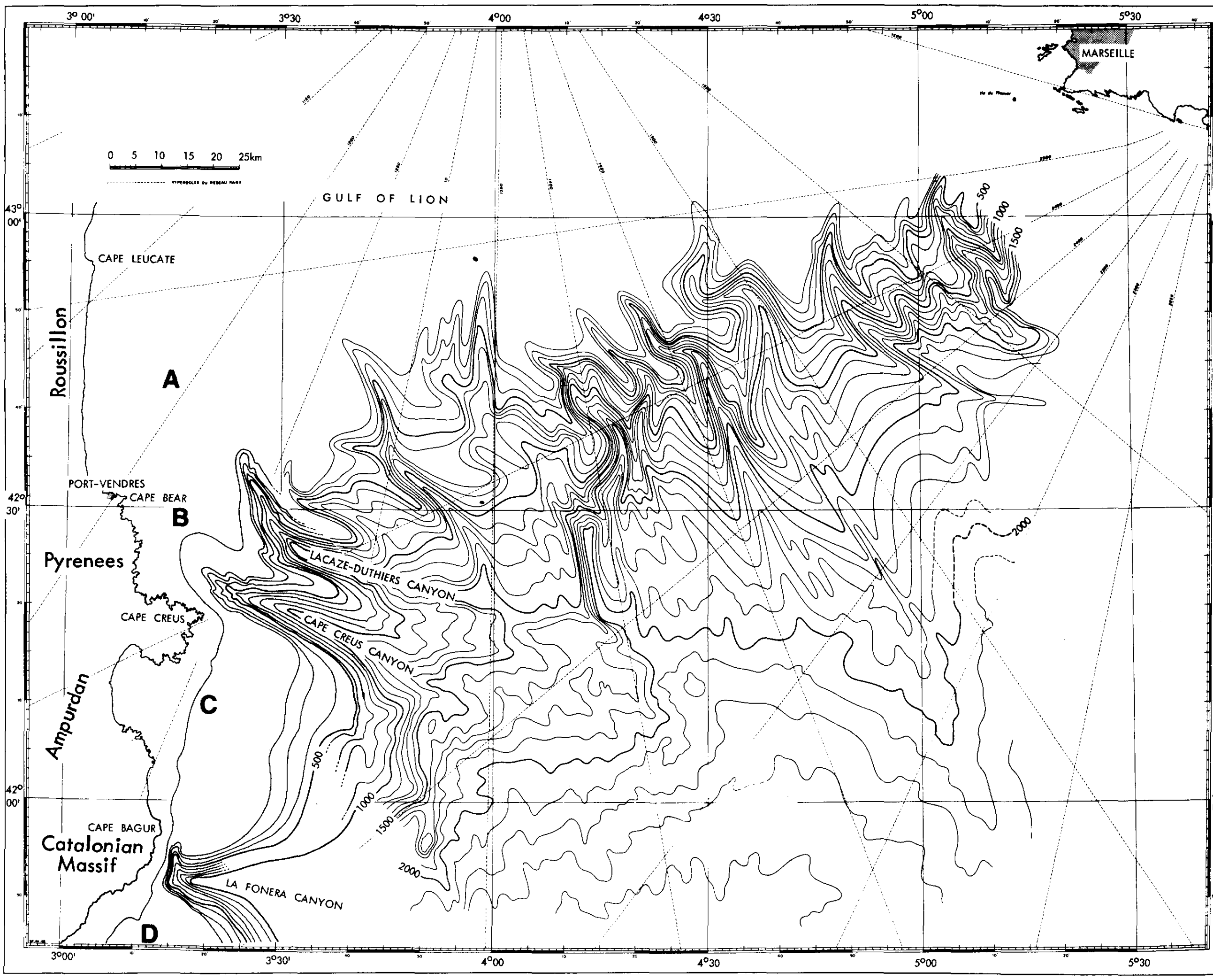
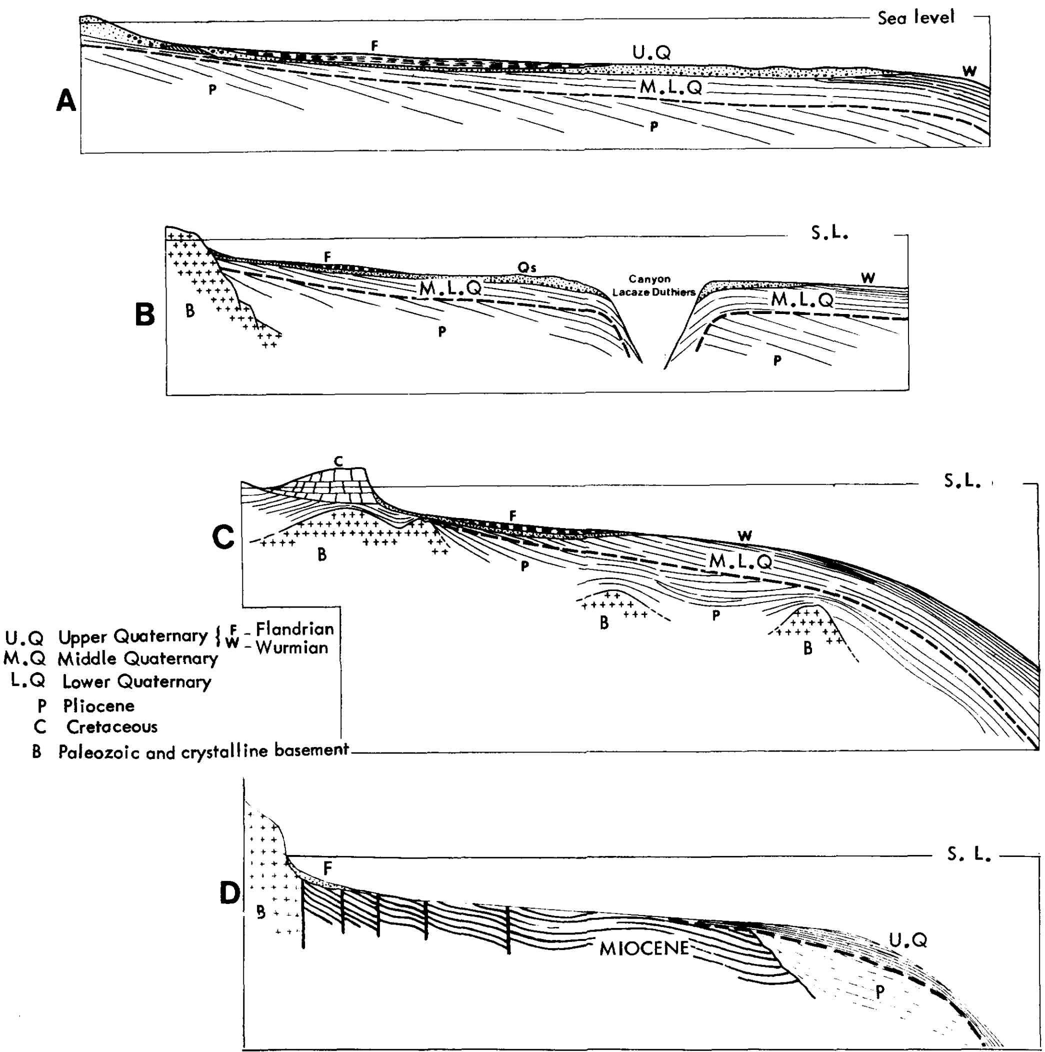


FIGURE 3.—Catalonian margin southwest of the Gulf of Lion: left, chart showing major topographic features discussed in text (depth in meters), modified after Bourcart (1959, 1960a) and Alla et al. (1969); right, schematic profiles oriented E-W across (A) Roussillon shelf, (B) Pyrenean shelf, (C) Ampurdan margin, and (D) Catalonian Massif margin.

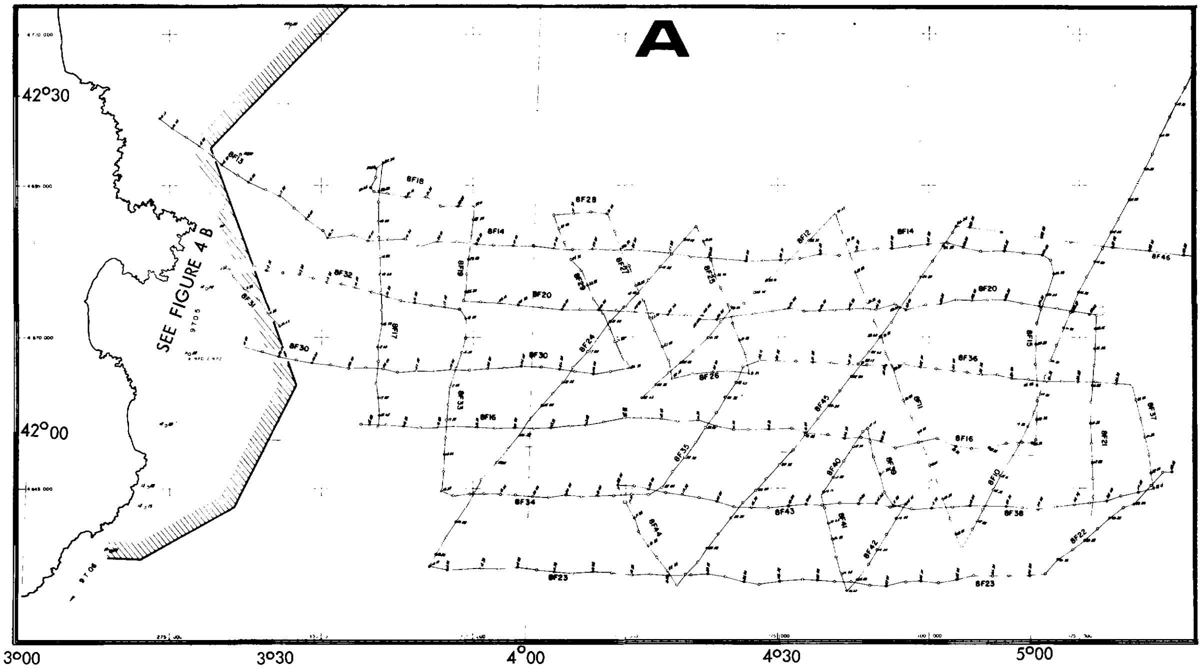
The presence of deep cores increases the reliability of correlation in the Gulf of Lion shelf. Here the basement is buried by a conglomerate unit of Aquitanian age which, in turn, is covered by hemipelagic sediments of Burdigalian and middle Miocene (undefined) age. Farther to the south, in the Balearic Basin plain, this sequence is covered by evaporites of Messinian (uppermost Miocene) age (Burollet and Byramjee, 1974). These suprasalt (?) sequences appear to pinch out toward the base of the slope; they are replaced laterally on the slope and shelf by an unconformable erosional surface. This hiatus, dated as Pontian (≅ Messinian) by Glangeaud et al. (1966, 1967), may be equivalent to what is designated elsewhere in the western Mediterranean as Reflector H and Reflector K (Alla et al., 1972); this band of reflectors is also called Reflector M or M reflectors (Biscaye et al., 1972 and Ryan et al., 1973b).

PLIOCENE SEDIMENTARY SEQUENCES.—Reflectors attributed to the Pliocene on the basis of correlation with drill sites on land occur throughout the study area; they are absent only in the immediate vicinity of crystalline massifs (i.e., Pyrenees and



Gavarres massifs) and on topographic highs underlain by Miocene deposits off the Catalonian coast (Figure 6c). The acoustic characteristics of these Pliocene units change in a direction away from the coast, i.e., from oblique, well-stratified reflectors truncated at the top by a near-horizontal erosional surface, Reflector G (Figure 7A), to horizontal, acoustically less well-defined reflectors termed the "transparent layer" (Figures 14–16). Unlike the pre-Pliocene units described earlier, the Pliocene sequence is characterized by an undulose folded (but not faulted) structure (Figure 6c).

Quaternary Sedimentary Sequences.—Quaternary units are distinguished by a succession of well-defined subhorizontal reflectors on the shelf as well as on the slope and in the Balearic Basin plain. Several key horizons on the shelf are defined by means of shallow, high-resolution profiles (300 J Boomer) coupled with coring of the uppermost sedimentary sequences. A basal unit above Reflector G consists of a succession of conformable reflectors of low amplitude (a_1 and a_2, Figure 7A) of probable lower Quaternary age. This sequence is followed upward by a series of well-marked reflec-



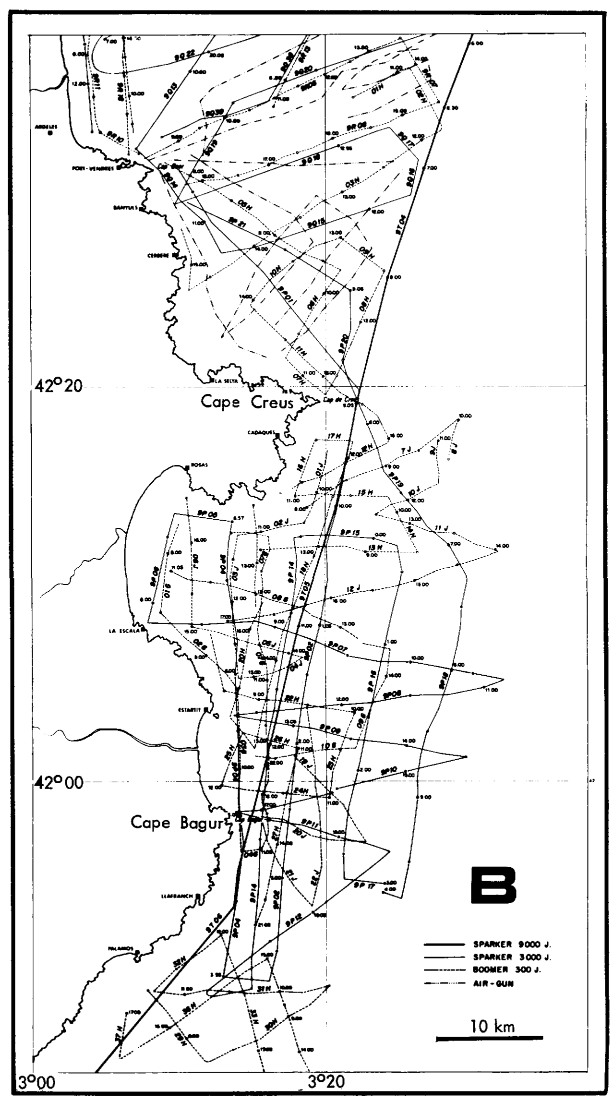


FIGURE 4.—Charts showing position of available seismic records on the Catalonian margin: A, coverage on slope and basin plain (9000 J sparker); B, track lines on shelf.

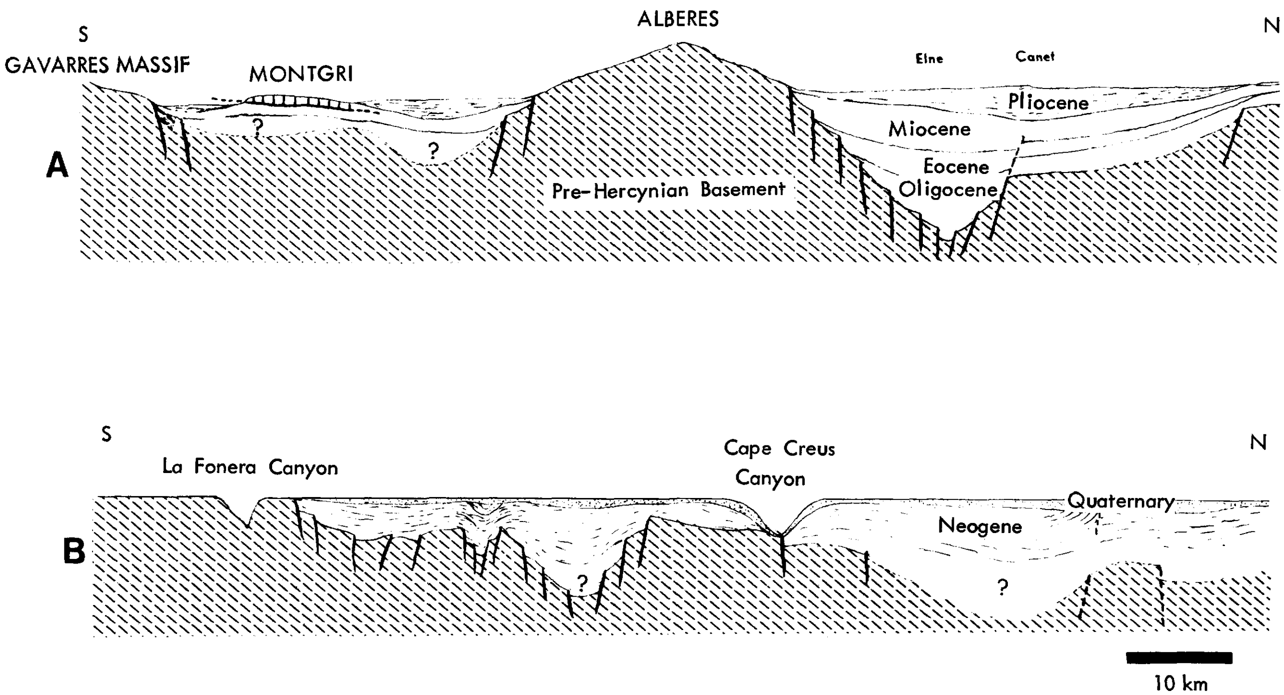


FIGURE 5.—Two roughly parallel sections oriented N-S showing general stratigraphic and structural configuration: A, transect on land from the Gavarres Massif to Cape Leucate; B, submarine profile off the same region. (Approximate vertical scale: 1 cm = 1000 m.)

tors (a_3) of probable Riss age. This latter sequence is capped by an undulose, discordant surface (Reflector J) that cuts units a_2 and a_3; these latter units are eroded by the oldest fluvial channels off the Roussillon coastal plain (Monaco, 1973).

The upper Quaternary sequence comprises a series of low amplitude and oblique reflectors (a_4) that fill irregularities and depressions of the J horizon. The upper part of this horizon has been cored and consists of muds of early Würm age (Würm II–III). In turn, these are covered by conformable reflectors of low amplitude (a_5) dated by carbon 14 as upper Würm to postglacial. On the midsector of the shelf, the preceding Quaternary sequence is covered by a discontinuous transparent layer (a_6) of Holocene (Flandrian) age (Figure 7B). These surficial muds thin on the continental slope.

STRUCTURAL CONFIGURATION

GENERAL.—Deep drilling and mapping on land show that the underlying structure of the Ampurdan and Roussillon coastal plains is controlled, to a large extent, by the Pyrenean fault complex. A major E–W fault delineates the Roussillon plain and a series of NW–SE trending faults controls the orientation of the Ampurdan coastal plain. Thus, these coastal plains are interpreted as tectonic depressions whose maximum downthrow is located on the margins of the Pyrenean chain. The depth of the crystalline basement underlying these depressions is irregular, i.e., apparently displayed by a series of normal faults as a result of vertical tectonics (Figure 8). The basement rises gently northward toward Cape Leucate and southward toward the Gavarres Massif. A seismic profile (9000 J Sparker) trending parallel to the coast demonstrates this structural displacement (Figure 6A).

DEFORMATION OF THE PALEOZOIC BASEMENT.—The seismic surveys on the shelf reveal the irregularities of the uppermost basement surface (Figure 8). As on land, (cf. Fontboté and Guitard, 1958; Mattauer, 1968) the position of the basement is directly controlled by a network of fractures with a predominant Pyrenean (WNW–ESE) orientation.

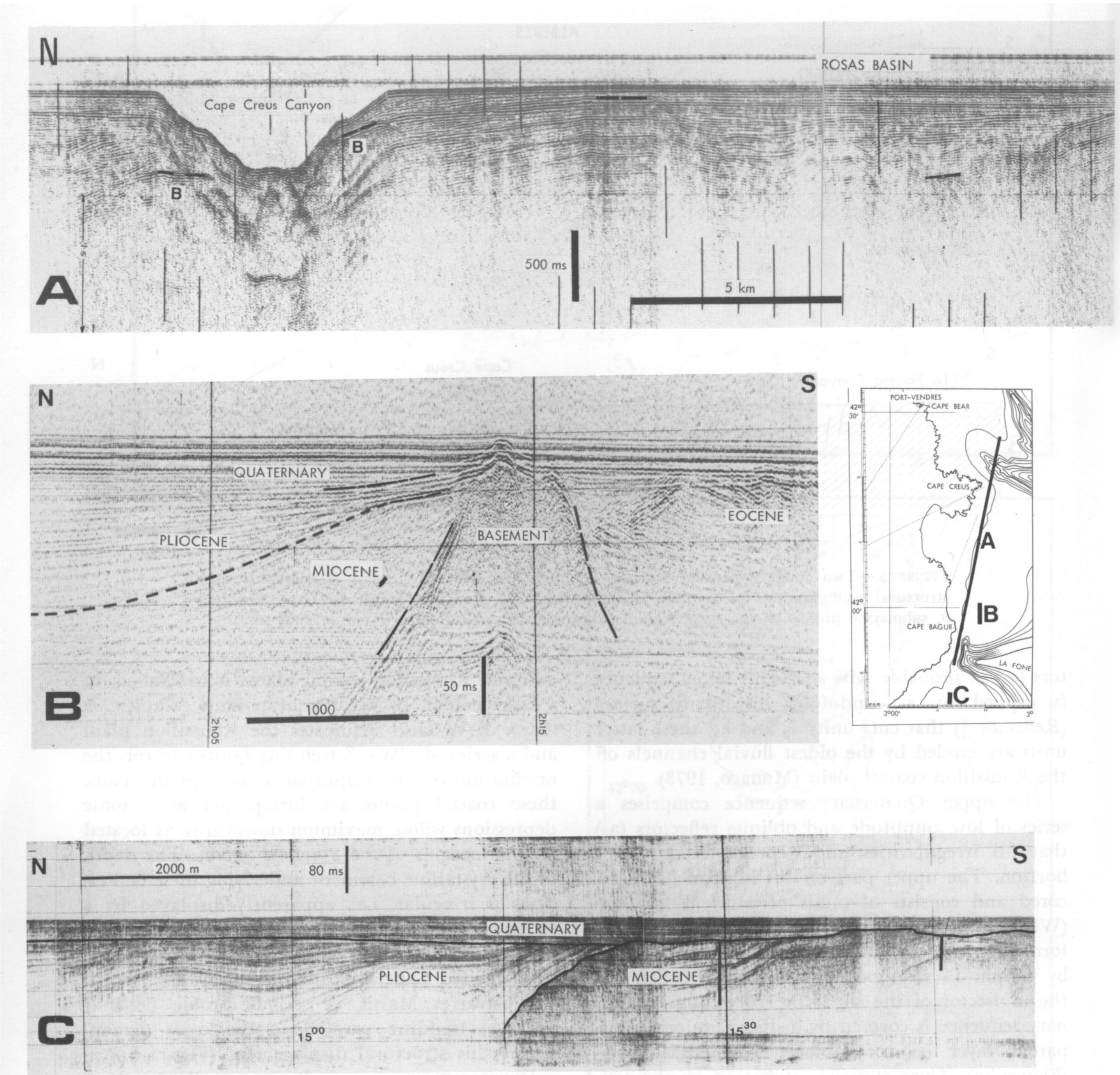
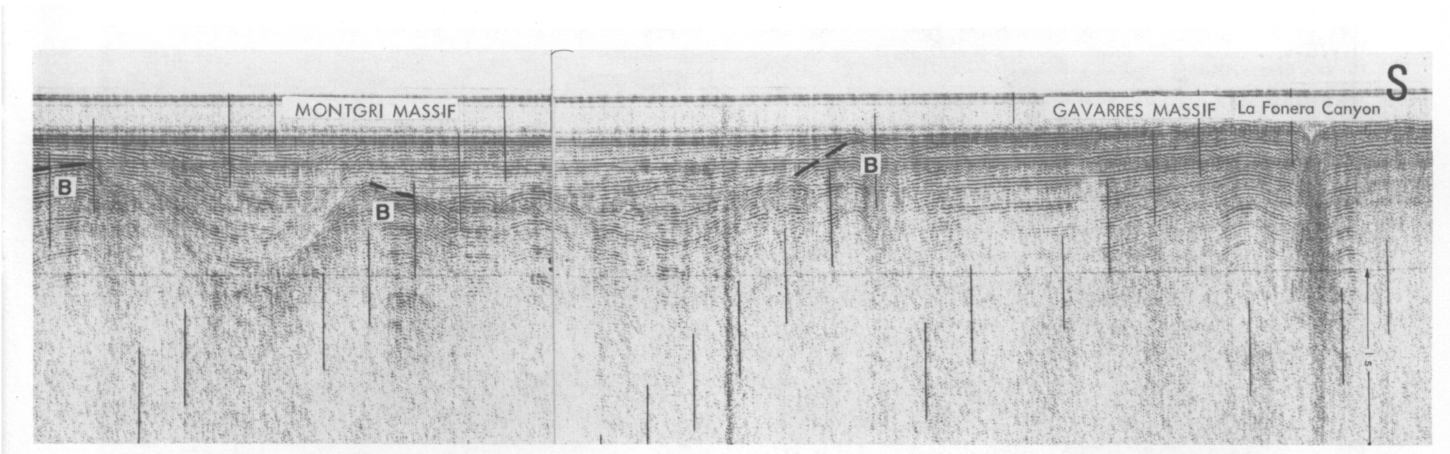


FIGURE 6.—Seismic profiles selected to show major acoustic reflectors on the Catalonian margin and their stratigraphic interpretation: A, 9000 J sparker profile (see interpretation on Figure 5B); B, 3000 J sparker; C, 300 J Boomer. (B = acoustic basement.)



Seaward, the basement rises locally as a result of N–S trending faults.

The basement can be followed seaward to the Basin plain by means of deep penetration (Flexotir, Flexichoc and other) systems; it deepens rapidly by a series of stepfaults, and the total tectonic throw approximates 4000 m (Delteil et al., 1972). This complex of faults is oriented N–S in the study area; the fault trend changes suddenly to an E–W orientation north of 41°30′N latitude.

Deformation of the Neogene Sequences.—The structural displacement of pre-Pliocene units offshore in the study area remains poorly defined as a result of the limited acoustic penetration of the equipment used. On the other hand, subbottom data are sufficiently abundant to define the attitude of Pliocene sequences. These latter units appear to be depressed rapidly seaward as shown by the progressive downwarping of deeper acoustic reflectors and the apparent bending (or flexuring) of these reflectors away from the coast (Figure 9). This phenomenon, referred to as the "flexure continentale" by Bourcart (1950, 1960b), has been attributed to subsidence of the Basin plain basement with accompanying depression (and seaward depositional progradation) of the overlying sedimentary series. Regional mapping of the Reflector G (Pliocene-Quaternary boundary) (Figure 10) shows that this surface is cut by the three previously described submarine valleys (Lacaze-Duthiers, Cape Creus, and La Fonera canyons) and a presently buried valley (La Escala Canyon) off the Ampurdan coastal plain. The downwarping phenomena affecting Reflector G have been particularly intense off Ampurdan, between the Cape Creus and La Fonera canyons, submarine valleys that follow major fault trends. Movement along these faults has apparently resulted in important vertical displacement of the Reflector G isochrons between the canyons and pronounced lowering of the Ampurdan shelf relative to the other sectors of the Catalonian margin.

The tectonic displacement that offset the basement and overlying series lessened at about the time of Reflector G; this is demonstrated by the undulations of the G Reflector in zones where faults offset the underlying basement, i.e., in the head of the Cape Creus Canyon and off Puerto-de-la-Selva, La Escala, Estartit, and Palamos. This observation suggests that the major movements are Pliocene in age and occurred along older (pre-Tertiary) tectonic lineaments. Some pre-Pliocene movement cannot be excluded. Displacement involving local readjustments along these same fault trends has occurred during the Quaternary (i.e., Canet fault and the Canet-Agly anticline in the Roussillon shelf cited in Monaco, 1971).

The G Reflector can be traced laterally and appears to correlate with the Pliocene-Quaternary surface in the Roussillon and Haut-Ampurdan coastal plains. Elsewhere, this acoustic horizon is directly transgressive above the basement offshore and it is absent in near-coast sections. Erosion of this sedimentary section is related to regressive phases of sea level in the Quaternary.

Deformation during the Quaternary.—The

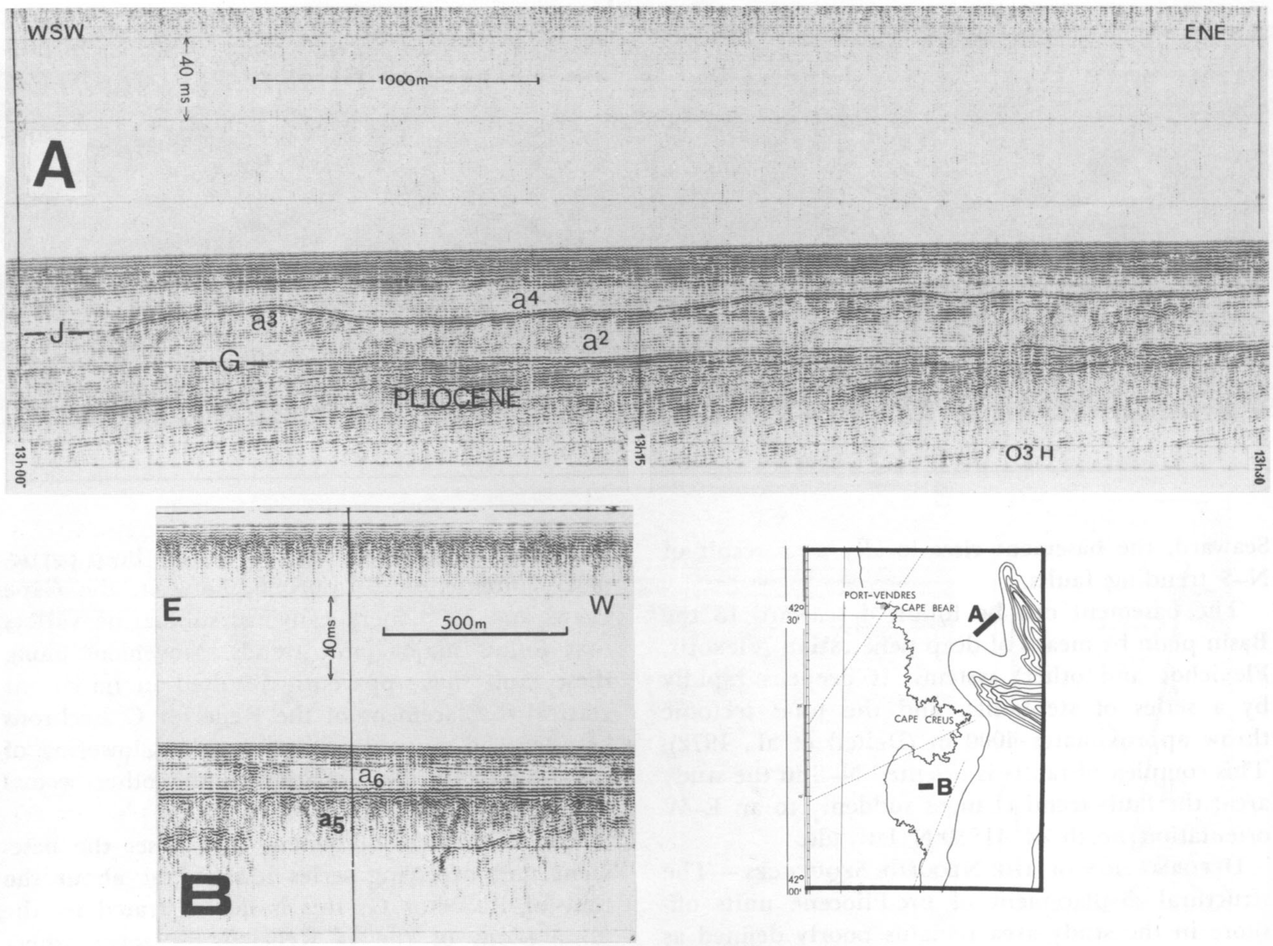


FIGURE 7.—Two (A,B) seismic profiles (300 J Boomer) selected to show major acoustic reflectors above the Pliocene. (G = Pliocene-Quaternary boundary; a2 and a3 = lower Quaternary; J = lower-upper Quaternary boundary; a4 = Riss; a5 = Würm; a6 = Holocene.)

structural map of Reflector J (Riss age) (Figure 11) differs from that of Reflector G. The position of the three major Catalonian canyons is noted on this map, while that of the now-buried La Escala Canyon is completely absent. The position of the latter is denoted only by a gentle depression of the 150 to 200 ms isochrons and by the appearance seaward of large undulations that probably resulted from structural deformation of the basement. However, the central margin off Ampurdan, displaying the greatest differential downwarping, is apparent. The major change observed is the lateral displacement seaward of the "zone de flexure" that occurred during the time between the G and J reflectors; the process involved in the downwarping was explained in the preceding section (cf. Figure 9). Reflector J can be traced laterally and correlated with equivalent units on land, as in the case of the Pliocene-Quaternary boundary (Reflector G). The absence of this horizon in the sector north of Cape Creus is due to the relatively more intense tectonic displacement and related erosional phase affecting this region toward the end of the Quaternary.

STRUCTURAL MODIFICATION OF LATE QUATERNARY SEQUENCES.—Regional mapping of the Late Quaternary horizons (Figure 12) shows that structural modification continued during the Late Quaternary and Holocene. Deposition accompanied subsidence in the three offshore Catalonian sectors.

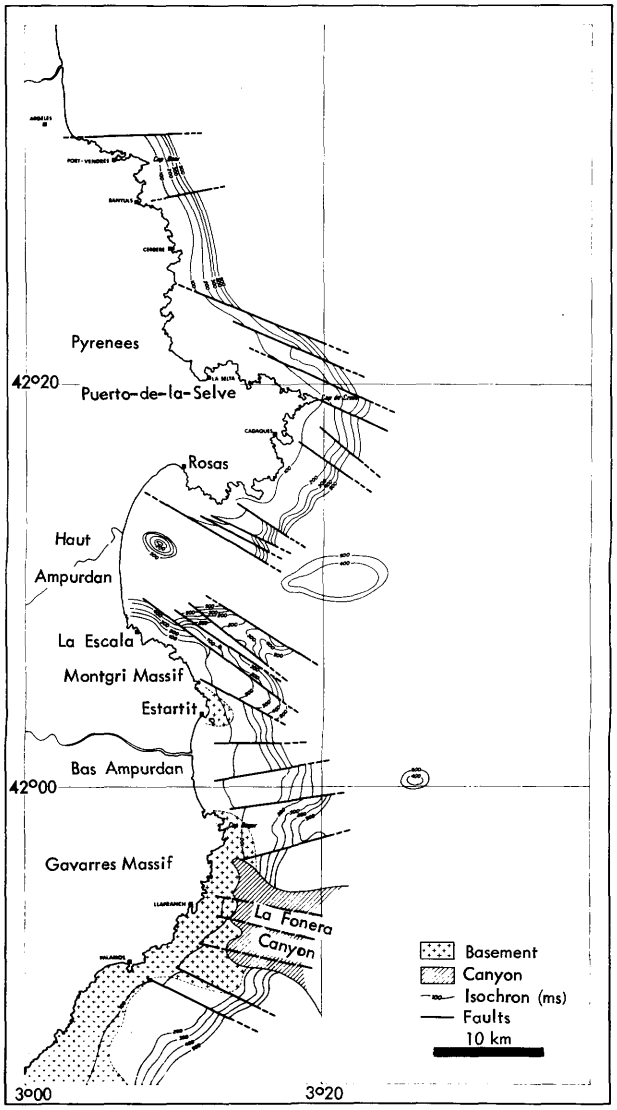


FIGURE 8.—Isochron map of upper acoustic basement surface reveals major fault trends (in milliseconds, two-way travel time).

Coring demonstrates that these movements affected not only the lateral extension and thickness of each of the dated (by carbon 14, Monaco, 1971; Got, 1973) horizons, but also the lithological nature of the deposits (Got et al., 1975). For example, on the margin off Ampurdan where subsidence has been most intense (Figure 13), the deposits are thick and consist essentially of marine mud sequences accumulated during the Würm III–IV (a_5IIb) while on the Roussillon and Pyrenean shelves, littoral sand and gravel sequences (a_5IIc) were deposited during this same period (dated at about 18,000 years B.P., Got, 1973). Furthermore, Holocene muds appear lithologically uniform off Ampurdan. In adjacent regions, subtle textural variations, including gradual vertical grain-size changes, are observed. These lateral variations resulted from differential downwarping of the Catalonian margin during the late Quaternary. Subsidence maintained the Ampurdan margin surface well below sea level during the Quaternary, while sectors undergoing less downwarping off the Roussillon coastal plain, off the Pyrenees, and off the Catalonian Massif more clearly reflect the effects of transgression and regression related to the eustatic oscillations in late Pleistocene-Holocene time. It appears that the vertical displacement of the Catalonian margin has continued until the present.

Outer Margin Evolution during the Neogene and Quaternary

SLOPE STRUCTURES.—The network of subbottom seismic lines on the outer Catalonian continental slope and contiguous Balearic Basin plain is less dense than on the shelf and uppermost slope (Figure 4A,B); mapping of individual reflectors in the outer sector is not feasible. The seismic equipment used (9000 Joules sparker), however, provides deeper penetration of subbottom series and thus enables us to interpret in a general way the major depositional and structural events affecting these more distal environments during the Neogene and Quaternary.

The region extending seaward of the Ampurdan coastal plain (margin displaying a convex-up profile) shows a marked thickening of the Quaternary sediment section, and this depositional sequence is deformed by large-scale undulations (lateral wavelength amplitude of 2000 m). On the slope proper, this undulatory structure is replaced by a series of large, discontinuous, lunate features interpreted as a sequence of displaced slump masses that have modified the otherwise well-stratified Quaternary units (Figure 14). Some of these allochthonous slump tongues (see arrows, Figure 14B) are about 5 km wide and approximately 450 m thick. The underlying Pliocene and uppermost Miocene sequences locally are offset by stepfaults

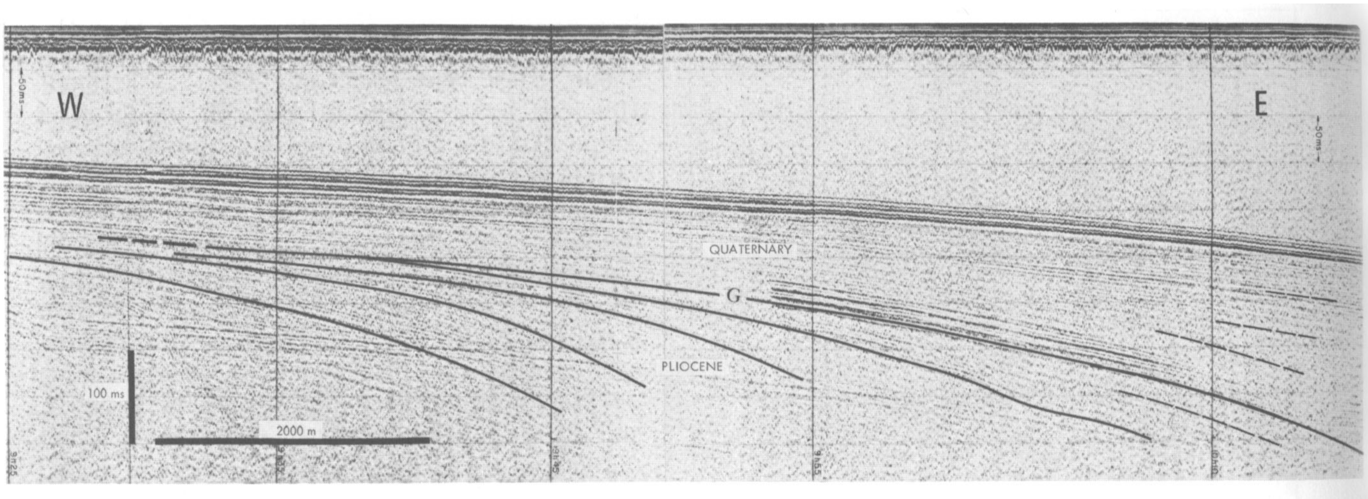


FIGURE 9.—An E–W profile (3000 J sparker) across the Ampurdan margin showing seaward-tilted Pliocene and Quaternary reflectors related to subsidence ("flexure continentale") mechanism.

(Figure 14c). Growth faults affect the upper Pliocene and Quaternary deposits. Another type of structural deformation that affects the Quaternary series is noted locally: subbottom highs in the form of anticlinal folds and horsts, produced by early Quaternary displacement. The thickness of Quaternary sequences is reduced over these highs (Figure 14c).

We interpret the different types of structures affecting the surficial sequences as the result either of downwarping of the "continental flexure" type, or growth faults that have offset the underlying Pliocene sequences, or both (Aloisi et al., 1974). Subsidence has triggered slumps and other mass movement of younger, less well-indurated Quaternary horizons above the more cohesive underlying sequences on slopes of 5 degrees. These displacements of Pliocene and Quaternary units are concentrated in zones where older series have been offset by movement along faults. Uplifted zones serve as topographic barriers (tectonic dams, T. D., Figure 14c) that stop the downslope movement of slump tongues. After continued sedimentation has leveled the slope behind a tectonic dam, slump masses can, once again, bypass such a sector and be deposited farther downslope.

Thus, each episode leading to failure and displacement of an allochthonous mass modifies the sea-floor topography. All of the displacement phenomena described here that modify sediment thickness and morphology have affected primarily the Quaternary series. The irregular nature of the surface topography of the Catalonian outer margin reflects the importance of continuing mass gravity movements on the slope. Somewhat analogous deformation also has occurred in canyons (i.e., on the walls of the Bourcart Canyon north of the study area); the resulting modification of the seafloor has been described by Glangeaud et al. (1968) as "phénomènes pelliculaires et épidermiques." Comparable features are observed in the Catalonian canyons (Got and Stanley, 1974, fig. 4).

BASE-OF-SLOPE STRUCTURES.—The marked thickening of the Quaternary section in the base-of-slope environment results, in part, from the accumulation of downslope-moving slump masses that accumulate near the break in slope between the continental slope and the basin plain. In some instances, seismic profiles show Pliocene and Quaternary strata which dip toward the slope (Figure 15). This phenomenon appears to be independent of the structural configuration of the underlying (M or K) reflector. This particular type of structure is interpreted as follows: the pre-Pliocene evaporite sequence, including Messinian salt (Burollet and Byramjee, 1974), pinches out toward the base of the slope. The movement of salt by doming and diapirs (salt tectonics) locally uplifts and laterally displaces (by sliding) the unconsolidated Pliocene-Quaternary sedimentary

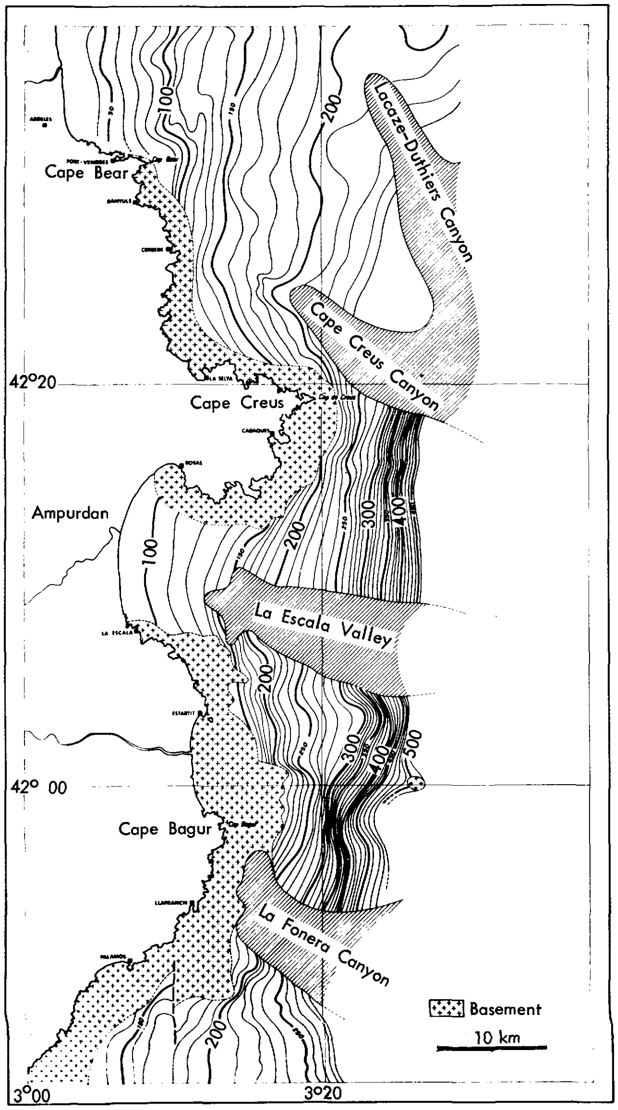


FIGURE 10.—Isochron map of the G Reflector (Pliocene-Quaternary boundary) in milliseconds, two-way travel time. (Note seaward tilt off Ampurdan and trend of the buried La Escala Valley.)

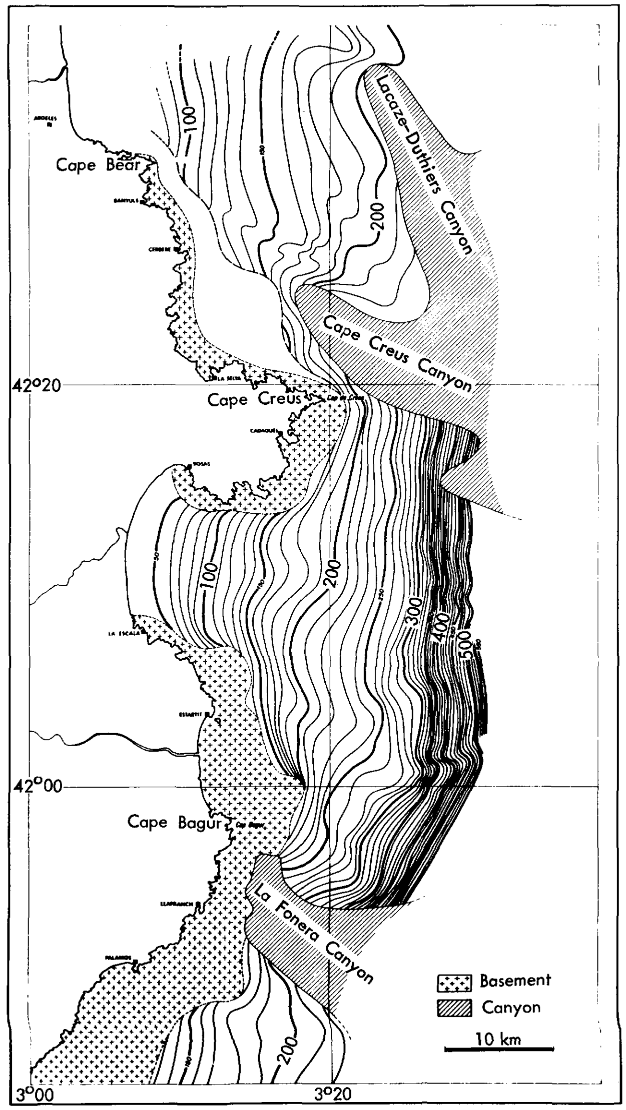


FIGURE 11.—Isochron map of the J Reflector (lower-upper Quaternary boundary) in milliseconds, two-way travel time. (Note extensive seaward tilting off Ampurdan between Cape Creus and La Fonera canyons.)

cover toward the base of the slope. Strata dipping toward the slope as a result of this salt-withdrawal phenomenon have been observed on several E–W seismic traverses across the base-of-slope environment between the Catalonian margin and the Balearic Basin plain south of the Gulf of Lion.

BALEARIC BASIN PLAIN STRUCTURES.—The structure of the Basin plain seaward of the slope is considerably less complex as demonstrated by the near-horizontal and subparallel attitude of the acoustic reflectors between the sediment-water interface and the K (or M) Reflector. Reflectors in these basinward zones are locally deformed into swells and depressions of low amplitude (Figure 16A), in some cases by salt tectonism (Mauffret, 1969). Structural displacement is more clearly apparent on Basin plain seismic sections than on those of the slope due to the relatively thin and

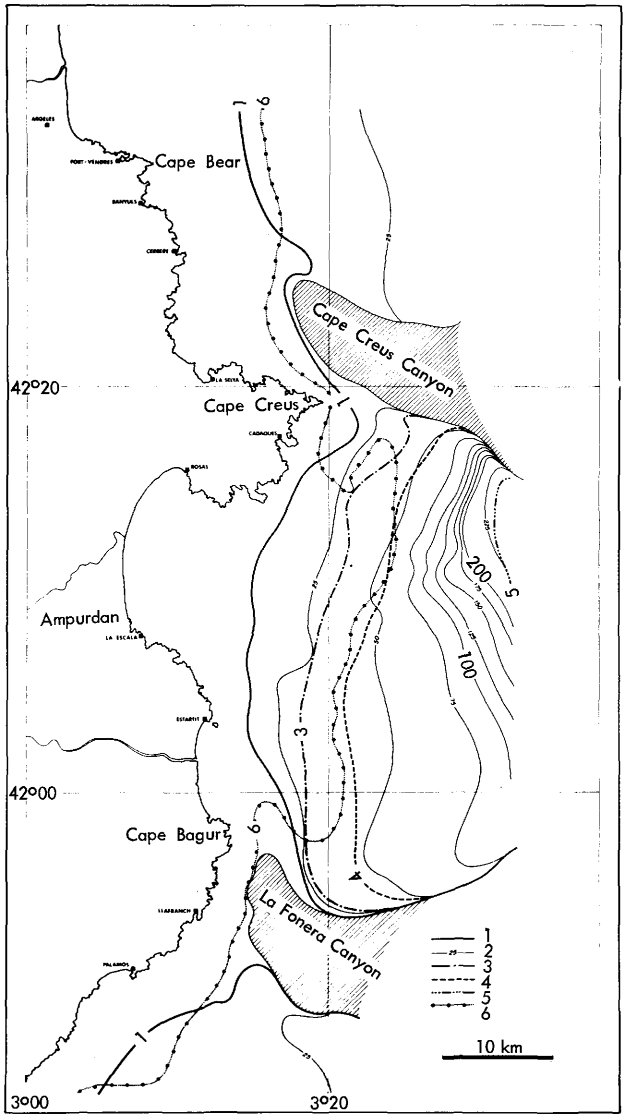


FIGURE 12.—Map showing details of the extent of the late Quaternary sedimentary sequences at different time intervals: 1, landward limit of sediment at about 27,000 years before present (B.P.); 2, isopach of the sediments dated between 23,000 and 27,000 years B.P. (contoured at 25 ms (25 m) interval); 3, landward limit of sediment at about 23,000 years B.P.; 4, landward limit of sediment at about 20,000 years B.P.; 5, landward limit of sediment at about 15,000 years B.P.; 6, seaward limit of the Holocene sequences. (The upper Quaternary sequence is thicker and more complete in the rapidly subsiding zone off Ampurdan than north of the Cape Creus Canyon and south of the La Fonera Canyon; see Figure 13.)

near-horizontal upper sediment section. Particularly visible are faults that displace the Quaternary reflectors and which thus modify the surface topography (Figure 16B); vertical offset of strata ranges to 40 to 50 ms (40 to 50 m).

The position of the different structural zones described above is depicted on the chart in Figure 17. Three major arcuate tectonic zones are apparent and these are oriented roughly parallel to the Gulf of Lion margin, i.e., oriented NE–SW in the study area and trending E–W farther to the east. The boundary between the zone of slope-tilted strata and the less tectonically deformed Basin plain sequence coincides rather closely with the outer edge of the evaporite sequence in the Balearic Basin. The boundary between the middle (or slope-tilted strata) zone and the slope proper corresponds to an area where some large vertical fault displacement has been recorded on deep-penetration seismic profiles (Delteil et al., 1972; Burollet and Byramjee, 1974). It would appear that these faults, some of which can be traced upslope, are closely related to the subsidence and foundering of the sea floor to its present depth (>2400 m).

As is apparent from the above observations, structural patterns in the region off the Catalonian margin have been influential in the present distribution pattern of the Pliocene and Quaternary cover. The thickness of sediment on the shelf and in the Basin plain provides a means to interpret both the dispersal pattern and volumes of sediment deposited. In the former environment, two factors control the sediment distribution: proximity and availability of sediment from terrigenous (fluvial) sources on the adjacent land, and the contemporaneous subsidence of the margin during sedimentation (cf. Ampurdan margin). In the Basin plain, where sedimentation rates are generally lower, the geologically recent subsidence of the basin floor and formation of the slope has accelerated sediment transfer from land seaward by downslope entrainment, largely slumping. The movement of these allochthonous masses downslope has resulted in the irregular sediment thicknesses and increased relief on the slope, and in considerable thickening of the Pliocene and Quaternary sequences at the base of the Catalonian slope. Significant amounts of terrigenous material also have been transported by mass-gravity processes to this deeper environment by way of the submarine canyons, which act

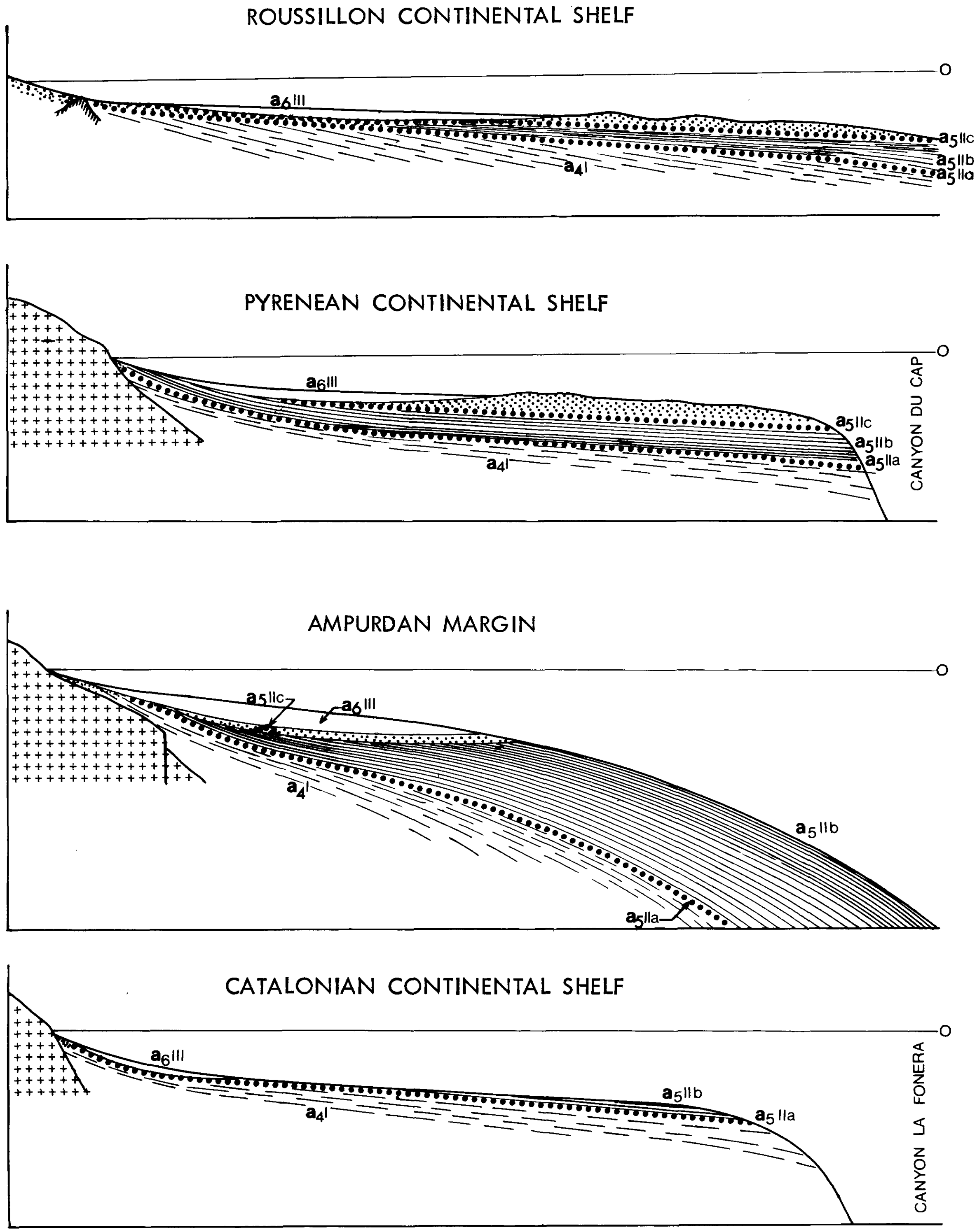


FIGURE 13.—Schematic cross-margin profiles along the four major Catalonian sectors showing variations of thickness, lithology, and distribution of the Würm to Holocene sediments. (These profiles detail the surficial sequences shown in the transects in Figure 3.)

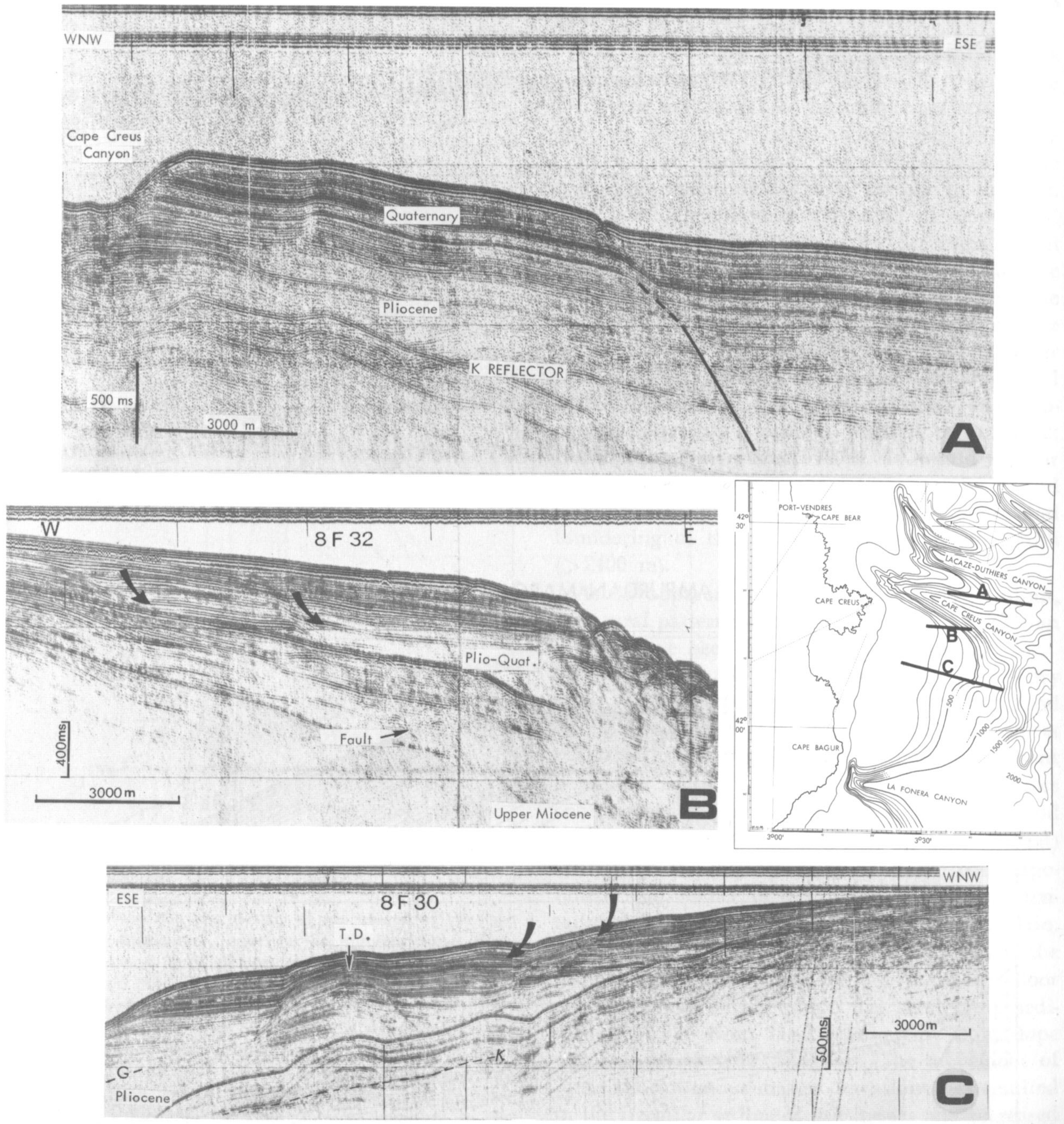


FIGURE 14.—Selected 9000 J sparker profiles on the Catalonian slope showing evidence of slumping (arrows) of Pliocene-Quaternary sequences related to faulting and growth-faults of underlying layers (see Figure 17). (On C note fault-bounded tectonic dam (T.D.) behind which are trapped Quaternary units.)

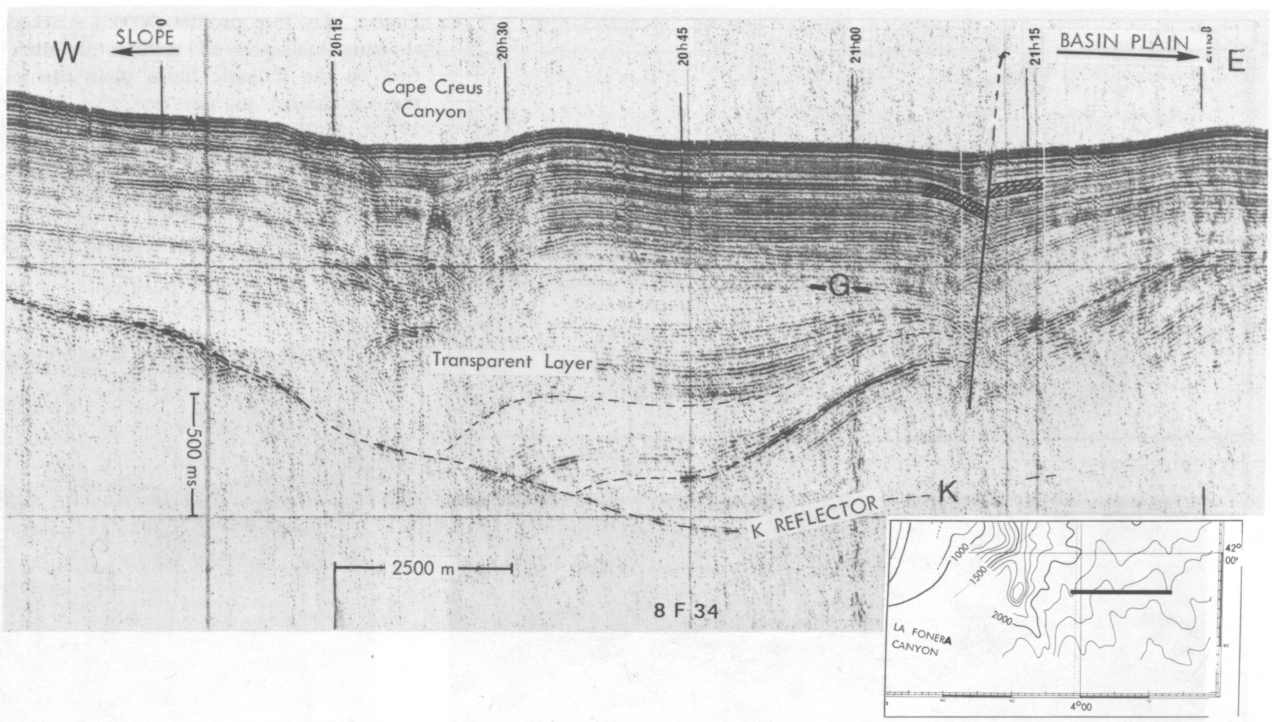


FIGURE 15.—An example of Pliocene and Quaternary strata dipping landward at the base of the slope (see also Figure 17). Note fault (f) extending to the sediment-water interface, the Quaternary-filled Cape Creus Canyon, and an erosional surface defined by the small hyperbolae characteristic of the K Reflector (= M reflectors, uppermost Miocene) on left of profile. (9000 J sparker profile.)

as funnels in the transfer of sediment from land to the basin (Got and Stanley, 1974).

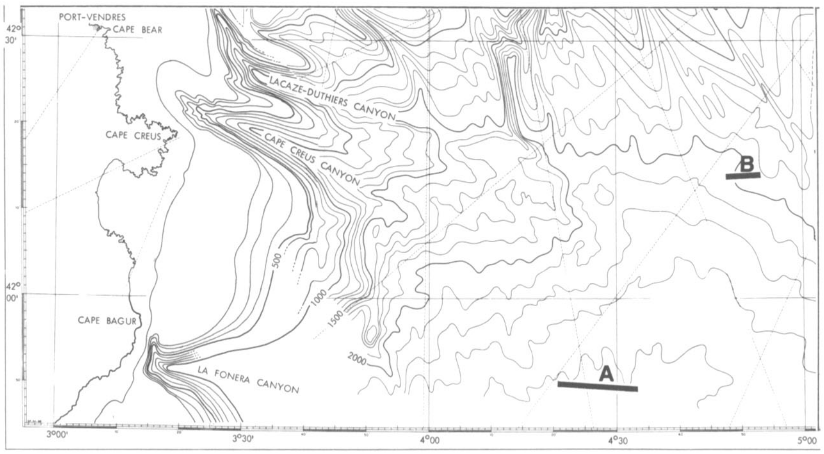
SUBMARINE CANYONS

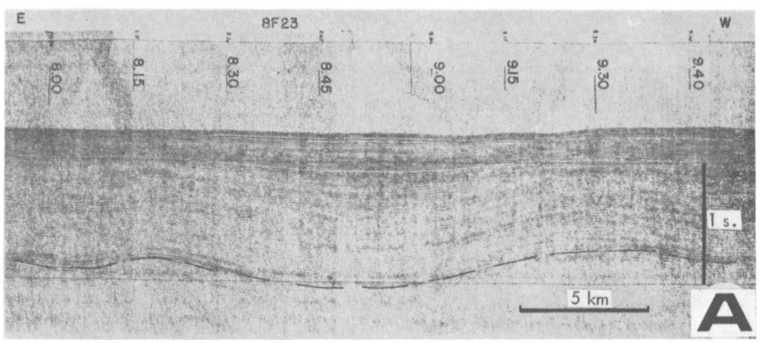
STRUCTURAL CONSIDERATIONS.—Many of the submarine canyons of the western Mediterranean, particularly those incised on the northern margin of the Balearic Basin, have been intensively surveyed (Bourcart, 1959, 1960a, 1963). Among the more recent studies are those of Reyss (1964, 1969), Reyss and Soyer (1965), Gennesseaux (1966), Glangeaud et al. (1968), Bellaiche (1970), Pautot (1970), and Mascle (1971). Many of these investigations consider both the tectonic origin of canyons and their role in the transportation of sediments from land to the deep basin plain. The result of our bathymetric and seismic surveys of the Catalonian canyons is summarized as follows:

1. Canyon physiography is characterized by steep canyon walls, a sinuous axial trend, and a network of tributary canyons that call to mind a subaerial fluvial system. The relief between canyon axis and intercanyon ridge exceeds 900 m along most of the slope off the Gulf of Lion.

2. In spite of the apparent subaerial configuration of the canyon morphology, there does not appear to be any major visible connection between the canyon axes and present valleys on the adjacent coast. The absence of continuity is the result of erosion that occurred during the recent Würm eustatic lowstand of sea level when a large sector of the continental shelf became truncated. Nevertheless, a buried channel, extending 1 to 2 km landward from the canyon heads, is observed on high-resolution seismic profiles (Figure 18A).

3. The initial downcutting of the canyons occurred in Pliocene or Quaternary time as demonstrated by the erosion of Pliocene sequences. In some cases pre-Pliocene sections, including the crystalline Paleozoic basement, are eroded (Figure 18B). In other instances, Pliocene reflectors do not





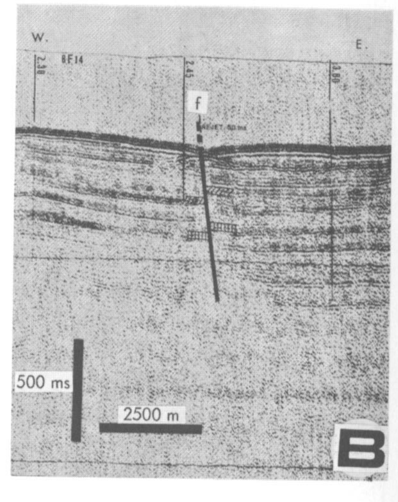


FIGURE 16.—Two profiles (9000 J sparker) showing examples of tectonic deformation on the Balearic Basin plain east of the Catalonian margin (see also Figure 17): A, gentle undulatory configuration of the Pliocene-Quaternary sequences; B, fault (f) with a throw of 40 ms (40 m).

appear to be truncated below the lowest canyon axis incision, and no earlier pre-Pliocene (including Miocene) incision appears (Figure 19.) The major canyon cutting phase in this region appears to be dated at, or about, the Pliocene-Quaternary boundary, i.e., recorded by the Reflector G unconformity surface.

4. Submarine valleys originate along the major fault fracture zones that offset the basement. These fault systems include the NNW–SSE Cape Creus faults and the E–W faults in the La Fonera area.

5. Each of the valleys displays several distinct phases of successive cutting and filling between the head and the midsector of the canyon to depths of about 1000 m. The canyon axes migrated laterally and progressively in a predominant direction during these Quaternary phases (Figure 20), i.e., away from the Pyrenean axial zone. An analogous migration of fluvial systems on land during the Quaternary is also recorded (Got, 1967).

6. The lateral migration of the canyon axes is related to the uplift of the Pyrenees during most of the Quaternary. The role of uplift is recorded topographically, i.e., the canyon walls on the Pyrenean side lie at shallower depths than the opposite canyon walls.

ORIGIN OF SUBMARINE VALLEYS.—Geologists concerned with the evolution of the western Mediterranean Basin, including Bourcart et al. (1961) and others, in recent years have suggested that an extremely important phase of regression exposed the shelf and adjacent shallow margin at the end of the Miocene. In support of this theory, some workers propose that submarine canyons presently observed on the Mediterranean margins were formed in Pontian (≅ Messinian) time and subsequently have been filled with Pliocene and Quaternary sediments. Thus, if one follows this line of reasoning the present physiography of the western Mediterranean is one directly inherited from "relict" (pre-Pliocene) events, without important changes in earlier periods.

One such example frequently cited is the Lacaze-Duthiers Canyon whose structure and origin have

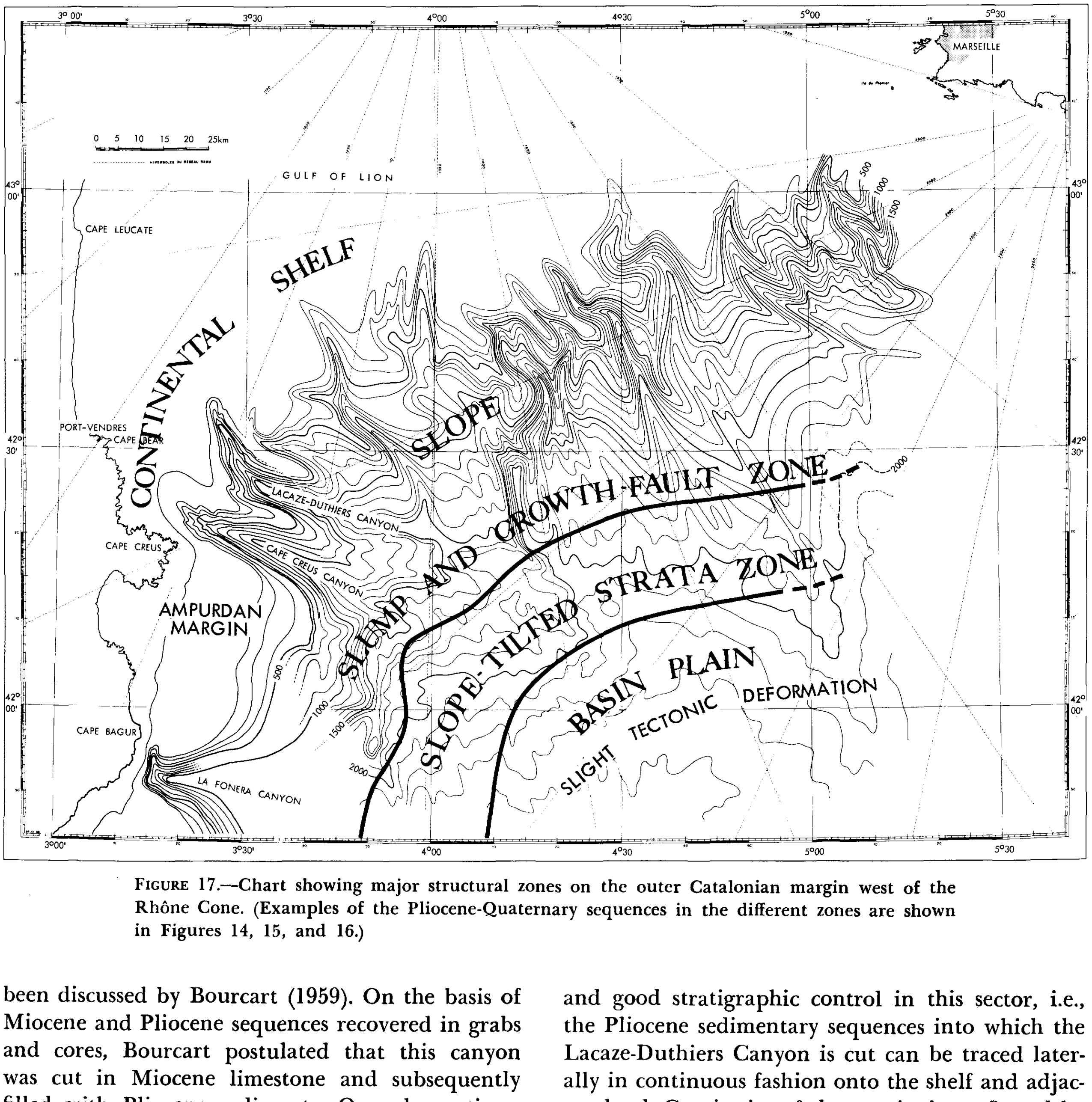
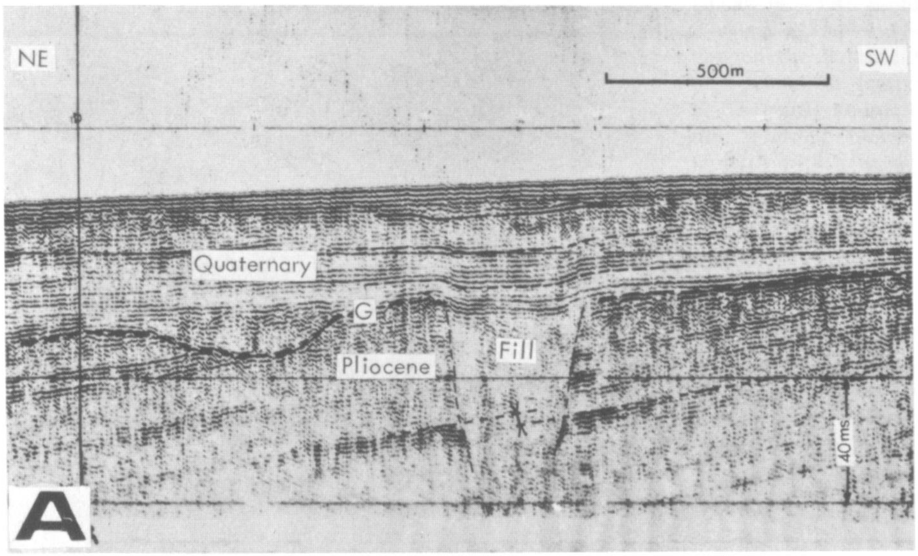
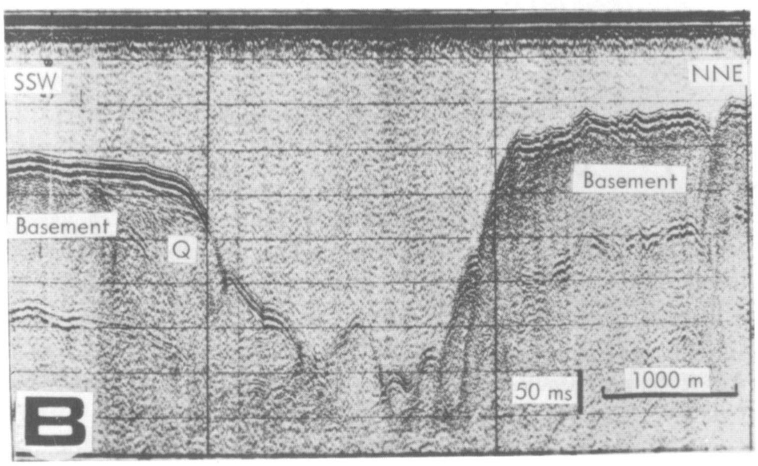


FIGURE 17.—Chart showing major structural zones on the outer Catalonian margin west of the Rhône Cone. (Examples of the Pliocene-Quaternary sequences in the different zones are shown in Figures 14, 15, and 16.)

been discussed by Bourcart (1959). On the basis of Miocene and Pliocene sequences recovered in grabs and cores, Bourcart postulated that this canyon was cut in Miocene limestone and subsequently filled with Pliocene sediments. Our observations, based on numerous seismic traverses across the canyon, do not support this hypothesis but indicate instead that the initial and most important erosive phase in the Catalonian region took place at the end of the Pliocene. This first phase of canyon cutting is associated with the G Reflector, which is an unconformable erosional surface delineating the boundary between the Pliocene and the Quaternary. This is confirmed by the dense seismic net and good stratigraphic control in this sector, i.e., the Pliocene sedimentary sequences into which the Lacaze-Duthiers Canyon is cut can be traced laterally in continuous fashion onto the shelf and adjacent land. Continuity of these units is confirmed by drill sites on the coast. The seismic profiles show no evidence of pre-Pliocene cutting in the lower part of the canyon.

The important period of erosion at the end of the Pliocene was followed by successive episodes of Quaternary sea level oscillation, which resulted in repeated migration of the sea across the shelf. On the Catalonian margin, sedimentation patterns record these eustatic events as well as the almost





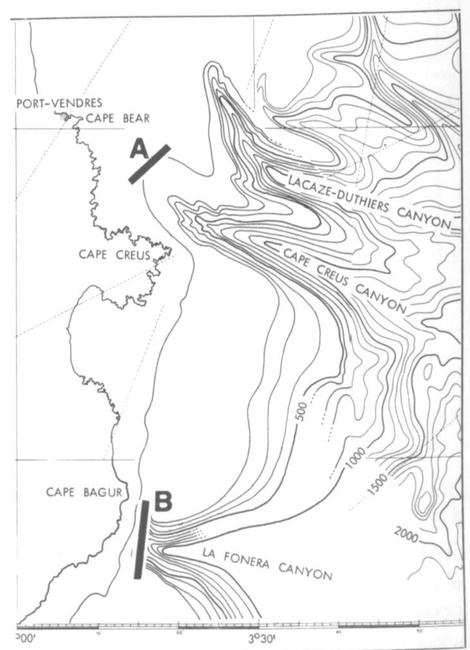


FIGURE 18.—Seismic profiles: A, record (300 J Boomer) reveals the filled head of the Cape Creus Canyon, which is cut in inclined bedded Pliocene units and follows a fault (note offset reflectors on opposite canyon walls); B, record (3000 J sparker) across the head of La Fonera Canyon cut into basement.

continuous downwarping of the western Mediterranean Basin. Perhaps the most important eustatic phases occurred in the middle to upper Quaternary (Mindel and Riss) as recorded by Reflector J. This is clearly the case in the region off Ampurdan, where the erosional effects associated with the Riss horizon are apparent and indicate the final major erosive event in this sector. After the Riss, the La Escala Valley no longer was eroded; the platform on which it was cut was lowered and remained submerged as a result of tilting and subsidence. The La Escala Valley was buried by sediment in post-Riss time.

The above and other considerations serve to

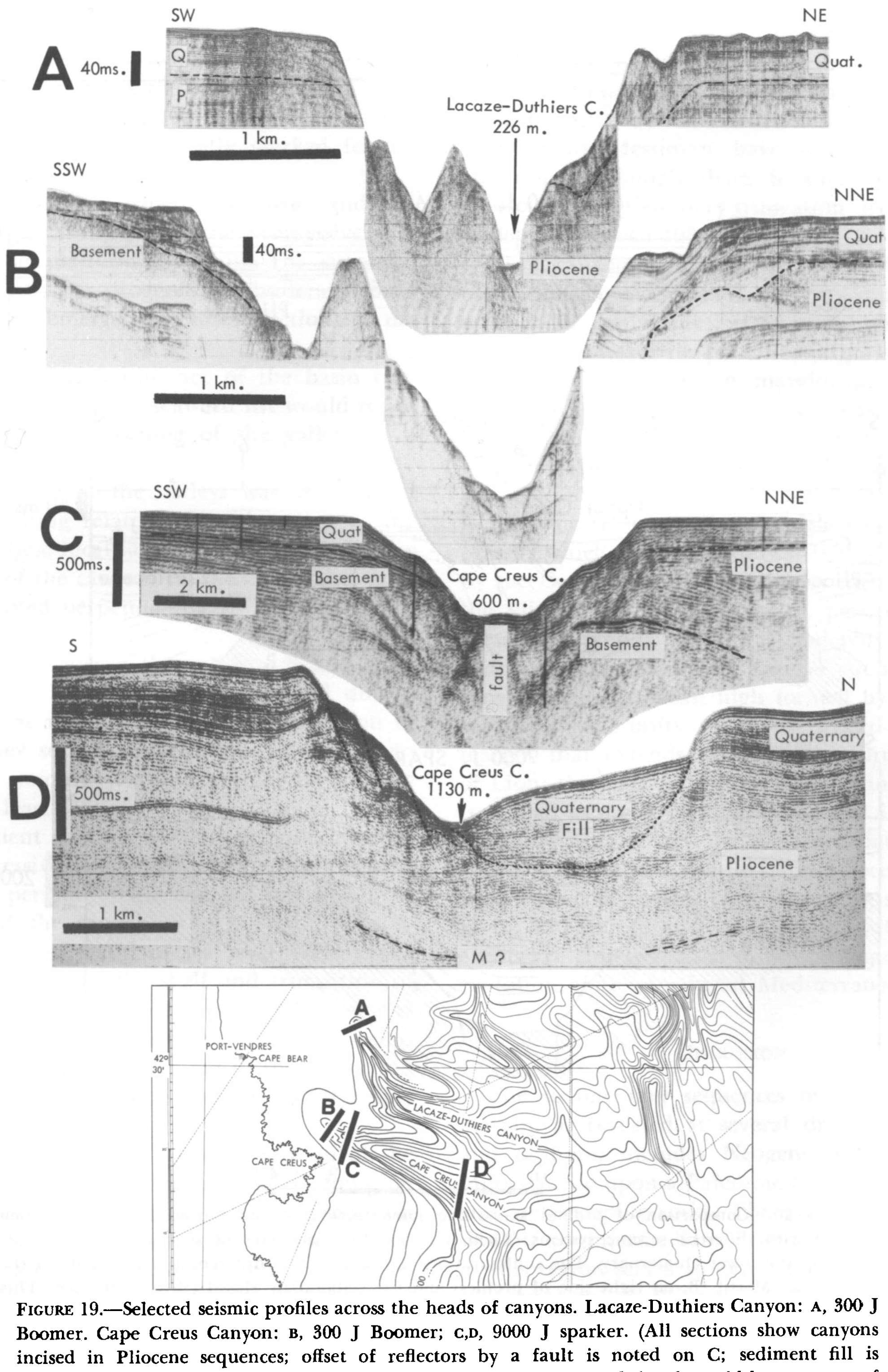


FIGURE 19.—Selected seismic profiles across the heads of canyons. Lacaze-Duthiers Canyon: A, 300 J Boomer. Cape Creus Canyon: B, 300 J Boomer; C,D, 9000 J sparker. (All sections show canyons incised in Pliocene sequences; offset of reflectors by a fault is noted on C; sediment fill is reduced in canyon heads (A–C); a thick Quaternary fill is noted in the midslope sector of Cape Creus Canyon (D).)

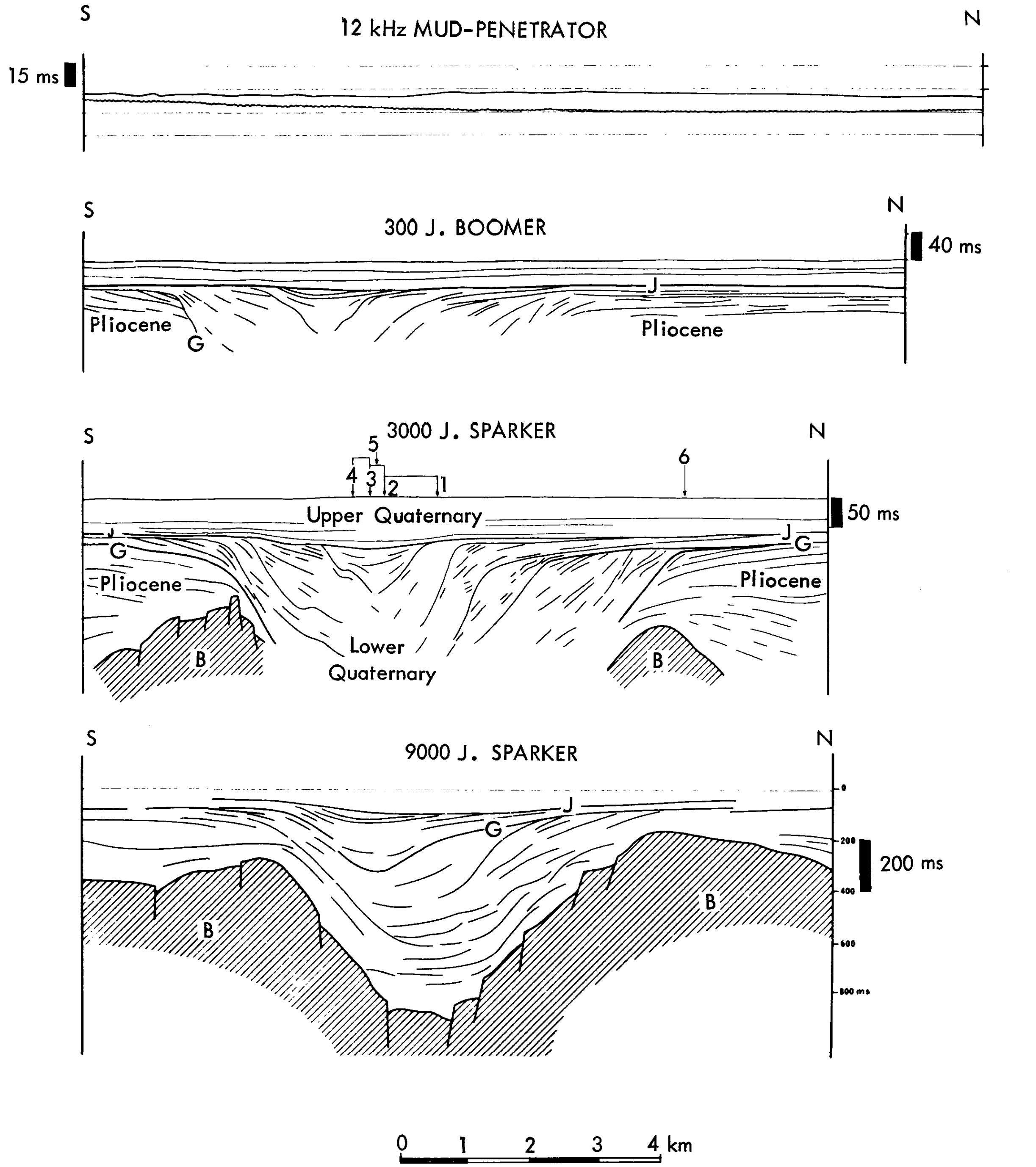


FIGURE 20.—Comparison of profiles across the same section of the buried La Escala Valley made with different seismic systems. These profiles show the axes of successive canyons cut during the lower Quaternary. The configuration of strata reflects differential movements of the Pyrenean Massif (B, on right side of profiles) and the Catalonian Massif (B, on left side). This differential movement has produced a migration of the canyon axes toward the south during the lower Quaternary (axis positions 1 to 4) and subsequent thickening toward the north of the upper Quaternary strata (5 and 6) after the canyon-cutting phase. The thickening of strata to the north (upper profile) results from the continued subsidence of the margin from the upper Quaternary to present.

interpret the sequence of events which led to the formation of Catalonian submarine canyons:

1. At least some relief was needed for the initial cutting of the canyons at the end of Pliocene time. A relief of at least 200 to 300 m would have been sufficient to incise a significantly marked feature such as a subaerial valley.

2. The ongoing "continental flexure" and tectonic tilting have resulted in the progressive subsidence of the platform on which the subaerial valleys were cut; this progressive subsidence would have initially submerged the lower sections of the valleys.

3. As the general subsidence of the basin continued, the accompanying seaward tilt would result in the progressive drowning of the valleys in a landward direction.

4. Submergence of the valleys was accentuated locally by faulting related to the lowering of the basin floor; these local fault trends, responsible for the location of the canyons on the Catalonian margin, are oriented perpendicular to the major N–S faults.

5. The relief between the valley axes and adjacent intervalley highs became accentuated during submergence as a result of enhanced deposition in the intervalley sectors; this buildup of the intervalley highs accounts for the present-day canyon relief of at least 900 m.

6. Subsequent eustatic oscillations superimposed on the progressive submergence of the margin have resulted in periodic reincision of the upper to midsectors of the canyons.

7. The last low stand of sea level (Würm IV) resulted in erosion of the shelf and truncation of connections between the canyon heads and the adjacent subaerial valley systems; an exception is the preservation of a channel cut in the a_2 horizon between the Lacaze-Duthiers Canyon and the Agly River.

8. Since the last rise in sea level, erosion of the canyon heads has prevailed as a result of slumping and other mass-gravity processes, while deposition has occurred primarily in the lower canyon sectors.

This generalized Pyrenean-Catalonian tectonic-paleogeographic canyon evolution is not applicable to all sectors of the northwestern Mediterranean margin. There is evidence, for instance, of pre-Pliocene erosion on the Provençal margin to the northeast, and in the sector south of the Catalonian margin. In this latter region, late Miocene erosion appears to have occurred primarily on structural highs, and the best evidence of pre-Pliocene truncation is recorded on the continental shelf proper. Pre-Pliocene reflectors (such as the M reflectors, Messinian) have not been eroded on the slope, although there is ample evidence of Pliocene and Quaternary truncation in some sectors at depths between 100 and 1700 m.

Thus canyon formation, physiography, eustatic oscillations, and structural configuration are closely related. In this respect, it is useful to recall the irregular "touches de piano" configuration of the northwest Mediterranean margin, i.e., structural highs with reduced sedimentary cover alternate with tectonically depressed sectors with a thick sedimentary cover (Got et al., 1975). In the study area, the following configuration is mapped, from south to north: (1) a Miocene high off the Gavarres Massif, which extends southward; this zone is cut by the Canyon de Blanes initially incised prior to the Pliocene (G. Serra-Raventos, pers. comm. and thesis, in prep.); (2) the foundered Ampurdan sector with the La Escala Canyon cut in the Pliocene; (3) the Pyrenean high formed by the Paleozoic crystalline units; (4) the depressed Roussillon margin that extends northward toward the Gulf of Lion; the Lacaze-Duthiers Canyon in this sector is a good example of a valley formed in the Pliocene and Quaternary. In summary, late Pliocene events predominate while late Miocene erosive phases affected those sectors that were structurally high. The importance of these and Quaternary events are closely related to the geologically recent evolution of the northwest Mediterranean margin.

Discussion

The sedimentary sequences on the Catalonian margin, as revealed at several drill sites on land and offshore, includes Neogene and Quaternary units that lie upon a Paleozoic basement of granitic and metamorphic rocks. The available network of shallow to intermediate penetration seismic lines in this region serves to detail the distribution and configuration of Pliocene and Quaternary series whose combined thickness ranges from 100 to 1500 ms (100 to 1500 m). In general, sediment thickness increases away from the shelf, where a maximum of 500 ms (500 m) is recorded, seaward to the base of the slope (1.5 seconds, or 1500 m); thicknesses on the slope are highly variable due to growth faults affecting the Pliocene units and an irregular distribution of slump blocks of Pliocene and Quaternary sediment.

A remarkable variation in sediment thickness is also observed laterally on the different parts of the shelf proper. These differences reflect local fluvial input and also the marked regional differences in rates of vertical subsidence. The margin surface has served as an efficient sediment trap in those regions where subsidence rates are greatest. As an example, the Quaternary sequence on the mid-Ampurdan shelf is about 400 ms (400 m), or about twice as thick as on the adjacent Pyrenean shelf.

The evolution and subdivision of the different parts of the Catalonian shelf are the result of differential movements along a network of E–W trending Hercynian faults; this reactivation of old fault trends occurred in Miocene and post-Miocene time, particularly during the Pliocene. Seismic profiles and cores show that some movement has occurred as recently as the late Quaternary.

The local readjustment along the E–W trending faults, which has given rise to the irregular morphology of the Catalonian shelf, is closely associated with much larger displacements along the major N–S trending faults in the Pliocene and Quaternary. The geologically recent formation of the Catalonian slope and the major subsidence of the Balearic Basin are closely related to movement along these N–S faults. The displacement along these major fault trends has given rise to growth-faults and associated slump movements; the importance of these phenomena has diminished somewhat during the Quaternary.

The continued deposition of terrigenous sediments has (1) resulted in the accumulation of a

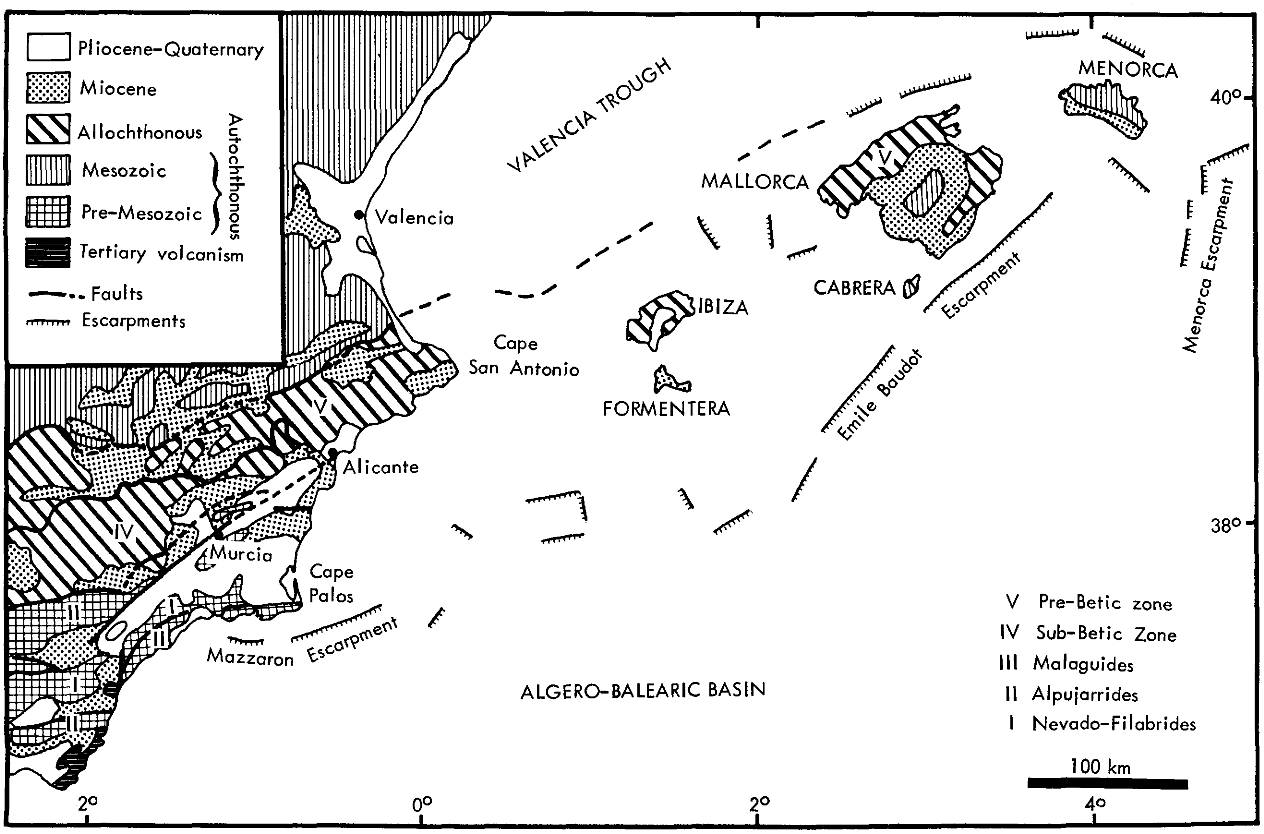


FIGURE 21.—Simplified geological map of southeastern Spain and the Balearic region showing major tectono-stratigraphic series and structural trends. (Modified after maps compiled by Biju-Duval and co-authors, 1974, Julivert et al., 1972, and Bousquet and Montenat, 1974.)

considerable thickness of Quaternary sequences that have partially buried the irregular underlying Pliocene and older structures and (2) has produced the smooth, convex-up configuration of the seafloor. We term this configuration of the Catalonian shelf and slope a *progressive* structural margin. It represents one type of margin associated with continental flexuring and regular subsidence of the western Mediterranean Basin.

Eastern Betic Margin

Geological Framework

The easternmost extremity of the Betic range in southeastern Spain and the Balearic islands, discussed in the following chapter, form a geological entity as demonstrated by the overall stratigraphic similarities and consistent structural style in the two regions. The major NE–SW trend of tectonic-stratigraphic units is apparent on the simplified map in Figure 21 compiled from several sources (primarily Biju-Duval, 1974, and Julivert et al., 1972). Studies that treat the relationship between the Betic chain and the Balearic islands have been published by Fallot (1923), Hollister (1934), Stille (1942), Carey (1958), Freeman and Simancas (1971), and Vogt et al. (1971). Among the many field studies conducted in the eastern Betics during the past decade are those by Azema (1966), Paquet (1969), Bourgeois et al. (1970), Egeler and Simon (1970), Bizon et al. (1973), and Montenat (1973). The geology of the Balearic islands has been summarized recently by Colom (1957, 1967), Bourrouilh and Magne (1963), Bourrouilh and Colom (1967), Cuerda et al. (1969), Rangheard (1969, 1970), Colom et al. (1970), Obrador (1970), Obrador et al. (1971), and Bourrouilh (1972, 1973).

The principal units depicted on Figure 21 include (1) the older (pre-Miocene) tectonically emplaced series, depicted as "autochthonous," which comprise pre-Mesozoic (including Nevado-Filabrides, Alpujarides, and Malaguides) and Mesozoic units; (2) the "allochthonous" series emplaced during the Neogene (including the sub-Betic and pre-Betic zones); and (3) the "post-tectonic" or "post-orogenic" units, primarily Neogene formations, which have been subjected to structural deformation from the Miocene to the present.

The major fold and fault trends in the eastern Betics are oriented NE–SW, including the important Murcia fault mapped by Bousquet and Montenat (1974, figs. 1, 2) and an E–W Cartagena–Cape Palos trend. Smaller N–S transverse fractures have offset the major NE–SW faults. Detailed studies (Montenat, 1970; Bousquet and Montenat, 1974) indicate that significant lateral displacement occurred along older (pre-Miocene) structures during the Pliocene and Quaternary, and that some faults in this region are still active.

The stratigraphic and structural configuration of units forming the islands of Ibiza-Formentera (Rangheard, 1970), Mallorca (Bourrouilh, 1972) and Menorca (Hollister, 1934; Obrador et al., 1971) are comparable in many respects to those of the NE Betic chain. Here the predominant structural trend is NE–SW of post-Langhian and older age (also in Menorca according to Freeman and Obrador, 1971), as well as NW–SE; these are in general accordance with the major Betic trend. The importance of reactivation and offset of NW–SE Hercynian faults during the Tertiary has been emphasized by Bourrouilh (1972); this movement may have contributed to the dislocation of the Balearic Platform into separate blocks. Important vertical displacements of Miocene age are recognized on the Balearic islands by Rangheard (1970) and Obrador et al. (1971); these movements continued until the end of the Miocene (Messinian) according to Bizon et al. (1973). More recent displacement of geologic units on the islands are cited by Mauffret et al. (1972).

Offshore surveys suggest that the predominant submarine trends east of the Betics in the vicinity of the Balearic Block are also oriented NW–SE (possibly related to major Oligocene-Miocene rotational movements associated with the origin of the western Mediterranean Basin) and NE–SW. This latter trend is interpreted as a more recent (Miocene to Quaternary) pattern related to major movements of the African plate relative to the European plate (Mauffret et al., 1972; Auzende et al., 1973). These geophysicists have attributed the present physiography and subbottom configuration of the margins to these geologically recent, largely post-Miocene, movements.

Physiography

The eastern Betic (or Cape San Antonio-Cape Palos) margin off southeastern Spain includes the region extending from the Rio Júcar south of the Gulf of Valencia to the town of Vera (Figure 22). The shelf in this region is relatively wide by Mediterranean standards. Its width off Villajoyosa is 44 km; it is 37 km off Gandía and 26 km off Cape San Antonio, the major promontory trending ENE toward the Balearic islands. The shelf is reduced to 9 km south of Cape Palos and the Mar Menor lagoon. The sharply defined E–W trending outer shelf and slope in this region delineates the Mazzaron Escarpment.

North of Cape San Antonio, the gentle submarine slope trends toward the northeast, i.e., parallel to the axis of the Valencia Trough, the major depression between NE Spain and the Balearic Platform. The margin between Gandía and Cape Palos extends eastward toward the Balearic Platform. Bathymetric profiles between Cape San Antonio and Ibiza show the margin sloping gently (2° to 3°) eastward to a depth of about 900 m. It is separated from the westward sloping Ibiza-Formentera margin by a narrow, N–S trending depression. The slope southeast of Cape San Antonio is cut by three large SE trending canyons that apparently do not head onto the shelf. Fans developed at the mouth of these canyons merge with the flat Algéro-Balearic Basin plain lying at a depth exceeding 2700 m.

The steep (>12°), narrow E–W trending slope, south and southeast of Cape Palos, called the Mazzaron Escarpment (Ryan et al., 1970), is about 90 km long and less than 20 km wide. The slope and rise becomes progressively wider (40 km) and more gentle west of Cartagena.

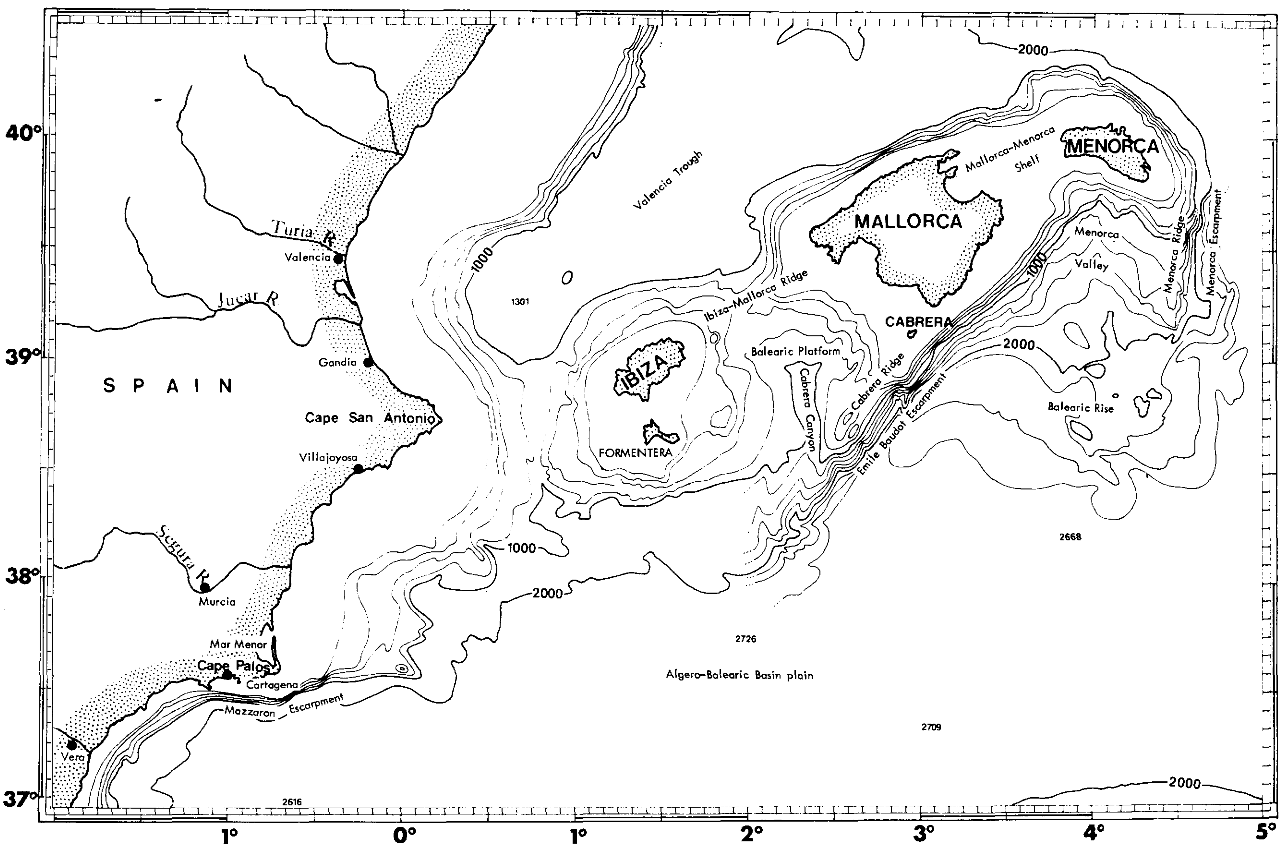


Figure 22.—Physiographic chart of the southeastern Spain–eastern Betic margin and Balearic region. (Based on Defense Mapping Agency Hydrographic Center Chart N.O. 310 (in Stanley, 1972); contours in region of Balearic Rise based on *LYNCH-I* cruise data; depth in meters.)

Stratigraphic Interpretation

The stratigraphic sequence defined in seismic profiles (Figure 23) can be traced in the various sectors of the study area. The following acoustic units are recognized between the base and the sea-floor surface:

1. A discontinuous acoustic zone, locally forming domes and piercement structures, is defined as basement; it represents consolidated sequences of variable age and lithology. Ultramafic rocks (peridotite and olivinic pyroxenite) have been dredged off Alicante; the overlying sequence may include lower Miocene calcarenites (Borsetti et al., 1974).

2. This is followed locally by a zone of poor to moderately defined acoustic reflectors, which may include Reflector N of upper Miocene age (Ryan et al., 1973b). The total thickness of this sequence above the basement is unknown, and appears to vary regionally.

3. The acoustically transparent layer ("couche fluante"), representing evaporite of Miocene age (Ryan et al., 1973b), was not identified with certainty except in the region of the Balearic Basin plain.

4. A bundle of well-defined reflectors, termed M reflectors (also K reflector by French geophysicists), has been dated as uppermost Miocene (Messinian) and consists of evaporite sequences (Ryan et al., 1973b); it also includes discontinuity surfaces. Its thickness is about 50 ms (90 m). This sequence, prominent on all profiles in this region, appears on sparker records (Figure 24A) as a series of subparallel reflectors that lie above hyperbolae (Leenhardt et al., 1969, 1970). On air gun profiles, at least six phases appear to make up the sequence.

5. The sequence immediately above the sharply defined M reflectors is poorly defined acoustically and appears as a transparent layer. This is attributed a Pliocene age (Alla et al., 1972; Ryan et al.,

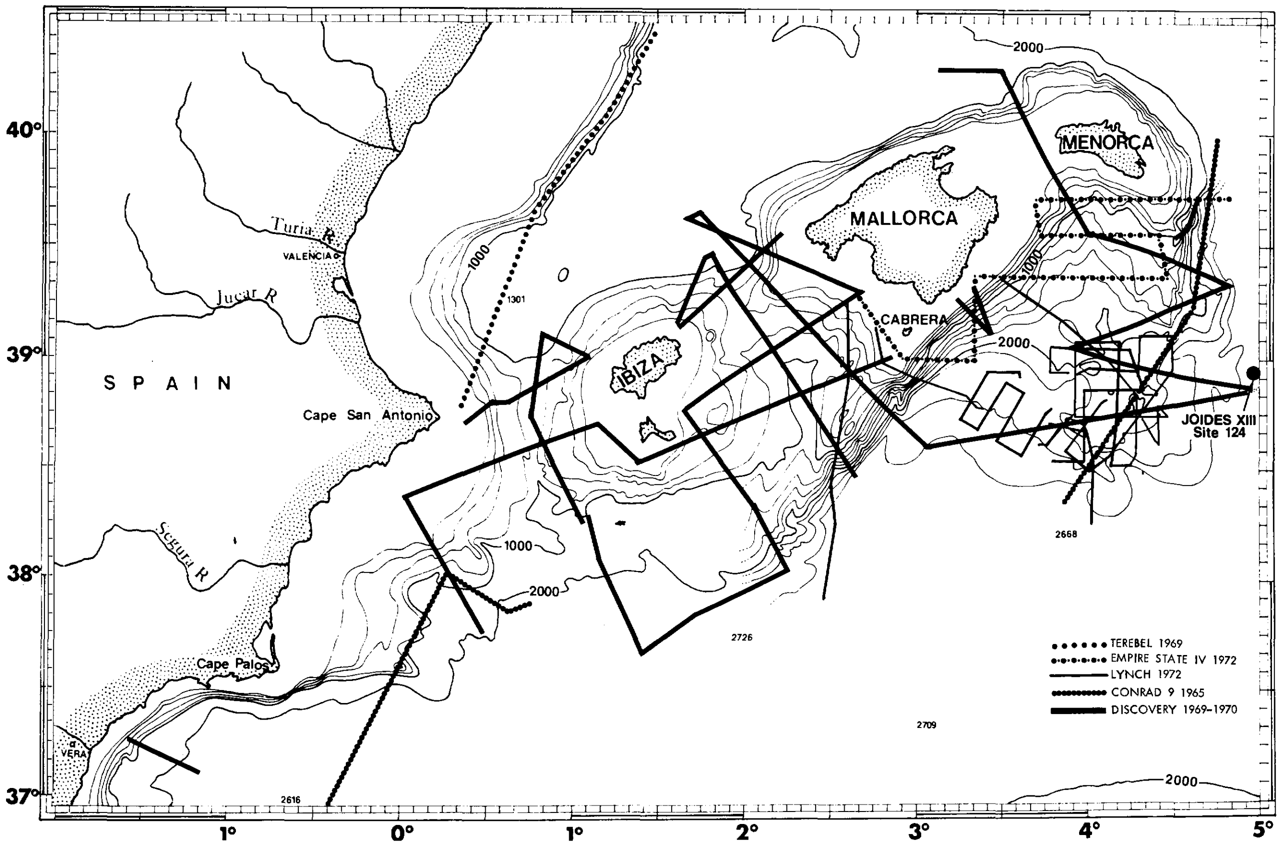


Figure 23.—Chart showing position of seismic track lines used in this survey. (Systems used on each cruise detailed in Methodology section; D/V *Glomar Challenger* leg 13 drill site 124 is shown east of the Balearic Rise.)

1973b). Along selected profiles, this acoustically transparent zone laterally becomes well stratified on the upper slope and shelf, as also was observed on the Catalonian margin (cf. Figure 24 with Figure 14). Throughout the study area, the transparent sequence becomes progressively layered toward the top. This upper unit consisting of parallel and subparallel reflectors is assigned a Quaternary age. It is not possible, however, to define the Pliocene-Quaternary boundary on the basis of our seismic profiles, nor is the Pliocene-Quaternary boundary observed on the shelf where it probably is represented by an unconformity, as in the Catalonian region (cf., Figure 7A). The thickness of the Pliocene-Quaternary unit varies considerably. The maximum thicknesses (in two-way travel time) are 800 ms (800 m) near the base of the slope in the Valencia Trough, 700 ms (700 m) on the shelf off Cape Antonio, 600 ms (600 m) on the slope west of the Mazzaron Escarpment, 400 ms (400 m) on the slope southeast of Cape San Antonio, and 500 ms (500 m) between Cape San Antonio and Ibiza. A 300 ms (300 m) sequence of flat, stratified sediment is observed in the narrow, deep depression between Cape San Antonio and Ibiza (Figure 24B).

Structural Configuration

The structural configuration of the eastern Betic margin is discussed from north to south. The stratigraphy and tectonics of this region have received little attention to date.

The seismic section extending NNE from Cape San Antonio (Figure 24A) shows a gentle, nondeformed, convex-up profile underlain by Pliocene and Quaternary sediments. These subparallel layers lie above a faulted sequence that includes the M reflectors (shown as K on some profiles) at the base of the slope and other displaced layers farther upslope and on the outer platform. These vertical offsets have affected the transparent layer but deformation becomes attenuated in the upper layered (Quaternary) sequence. It thus appears that the age of deformation occurred between the late Miocene and early Quaternary. The K (or M) reflectors and overlying sequences are near-horizontal and undeformed at the base of the Cape San Antonio slope in the Valencia Trough (Figure 24A).

The region east of Cape San Antonio is traversed by two parallel ENE–WSW profiles, 35 km apart, both of which show a relatively thick M reflectors-Pliocene-Quaternary series sloping eastward. The M reflectors are folded and offset by small faults (Figure 24B); these fractures also have affected the lower Pliocene transparent layer (see arrow). Deformation decreases in the upper layered sequence (Quaternary). Thus the displacement is dated as post-M, i.e., largely Pliocene. On the margin west of the Ibiza-Formentera shelf the thickness of the Pliocene-Quaternary cover is reduced and faulting considerably more extensive. Here, some major vertical offset and piercement of the M reflectors and younger sequences by basement (B) materials, possibly volcanic in origin (Figure 24C), are observed.

A seismic profile trending southeast of Cape San Antonio (Figure 24E) shows the margin to be broken by a series of large tilted block faults, which produce the highly irregular steplike physiography of the slope. The relief of each vertical offset, which affects the M reflectors and upper sequences, is of the order of 300 m (resulting in a total of about 1800 m vertical offset over a distance of 66 km). The geologically young age (post-Miocene) of these displacements is demonstrated by the faults that cut the uppermost stratified layers (see arrow). The M reflectors can be traced from block to block between the base and the uppermost slope. The acoustic basement, possibly consisting of volcanic material, forms domelike highs, which rise to the sediment-water interface in two areas.

A NE–SW air gun profile east of Cape Palos (Figure 24D) cuts across the heads of two large canyons (possibly tilted blocks as in Figure 24E) partially filled by sediment respectively 300 ms (300 m) and 500 ms (500 m) in thickness. The walls of one canyon, formed of basement material, are free of sediment; the sediment distribution in the second canyon is asymmetric, i.e., sediment covers the northeastern wall but is reduced on the southwest wall. This profile traverses the E–W trending Mazzaron Escarpment revealing its marked relief (approximately 2300 m) and steepness and the reduced sediment cover. The contact between the near-horizontal basin plain surface, locally pierced by salt domes, and the base of the escarpment is abrupt.

The southernmost seismic profile, west of the

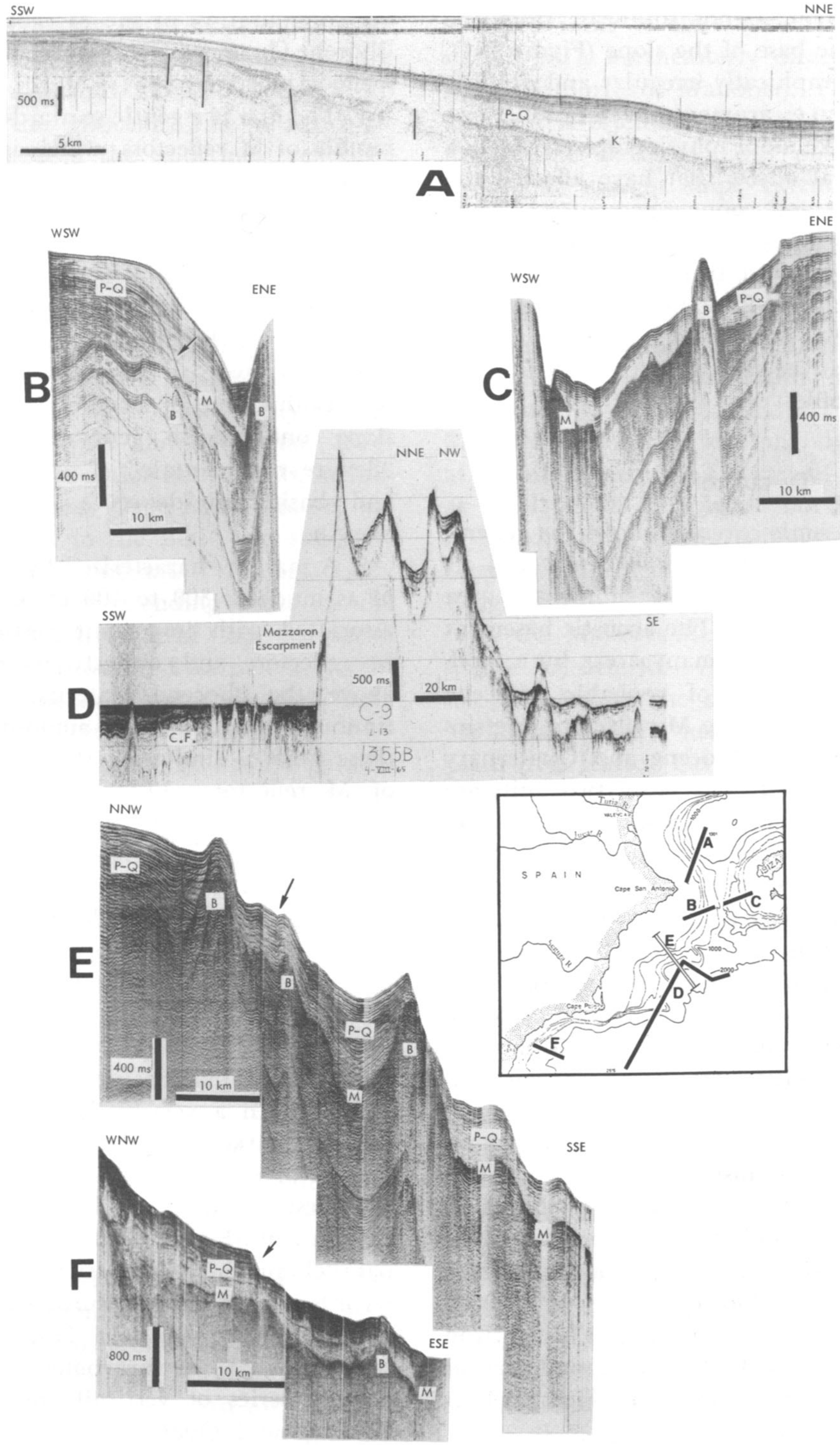


FIGURE 24.—Selected seismic profiles in area off southeastern Spain and the eastern Betic showing different types of margins: A, *progressive margin* (9000 J sparker); B, *progressive margin* (air gun); C, E, F, *intermediate*, or *steplike margin* (air gun); D, *abrupt margin* (air gun). (Symbols for this and following figures: B = basement, C. F. = "couche fluante" (salt), M = M reflectors (also K Reflector), P = Pliocene, Q = Quaternary; arrows denote selected faults.)

Mazzaron Escarpment, trends southeast from the town of Vera to the base of the slope (Figure 24F). The slope is topographically irregular and displays one prominent steep escarpment of 220 m relief (see arrow). The steplike slope physiography reflects a sequence of vertical offsets that have affected the M (or K) reflectors and younger sequences. Particularly noteworthy are the well-stratified (mostly Quaternary) units that are truncated at the escarpment, indicating a post-Pliocene vertical displacement. The bundle of M reflectors, offset by a series of young faults, can be traced at least to midslope depths in this profile.

Discussion

The available seismic coverage shows the general consistency in the stratigraphic sequence and its lateral extent over much of the submerged area off the eastern Betic Chain. The acoustic basement (age unknown), covered in many areas by a moderately stratified sequence of probable Miocene age, is in turn capped by the M reflectors (Messinian) and thick series of Pliocene and Quaternary unconsolidated sediment. The latter two units are ubiquitous, but vary in thicknesses from zero (on the Mazzaron Escarpment for example) to about 400 to 800 ms (400 to 800 m). The particularly thick Pliocene-Quaternary cover on the shelf between the Cape San Antonio and the Cape Palos area is due, on the other hand, to large sediment input (Rio Segura fluvial system) and also to the continued subsidence of this margin (Montenat, 1970), which enabled it to serve as an efficient sediment trap.

The regional variation of the Pliocene-Quaternary thickness in most instances reflects displacement during and after sedimentation as shown by profiles E and F (Figure 24). The bundle of M reflectors beneath these sediments can be traced between upper and midslope depths ($\cong < 1000$ m) and the Algéro-Balearic Basin plain. This horizon is almost always offset by faults, and a total vertical relief of at least 1800 m (profile E, Figure 24) is measured in this region.

The vertical displacement which accompanied the foundering of the Algéro-Balearic Basin and Valencia Trough in this region differs markedly from place to place. We observe three major styles of margin tectonics that can be distinguished on the configuration of the M reflectors and younger Pliocene-Quaternary sequences and on the related seafloor morphology:

1. The first is a gentle seaward-sloping, convex-up bundle of M reflectors, which is only slightly tectonically offset, covered by a sequence of laterally continuous, subparallel Pliocene and Quaternary sediments (Figure 24A,B). Only the basal (Pliocene) sequence appears broken by the same faults affecting the underlying M reflectors; this deformation decreases in the upper (Quaternary) units; the smooth, convex-up physiography of the seafloor reflects this type of structure. We term this shelf-slope configuration, generally associated with the "flexure continentale" (Bourcart, 1960a, b, 1963) and basin subsidence a *progressive* structural margin.

2. A margin characterized by small to large steps of as much as 300 to 400 m of relief is generally associated with important vertical offsets of the M reflectors and underlying series. Unlike the above, the Pliocene-Quaternary units are discontinuous seaward, and the amount of offset affecting these units is similar to that affecting the bundle of M reflectors. Tilting often accompanies the vertical displacement of blocks and is reflected in the sea-floor topography; the M reflectors and Pliocene-Quaternary units display equal amounts of tilting. The series of downthrown blocks can be traced in steplike fashion between the shelf margin and upper slope to the base of the slope. This structural configuration is herein termed an *intermediate* (or *step*) structural margin.

3. A steep margin (slope to 12°) showing high relief within a very narrow range (10 km wide) without marked steplike configuration and discontinuity of strata is attributed to major faulting. The best example in this region is the Mazzaron Escarpment (Figure 24D) whose trend appears to parallel an E–W fault system. Although seismic records suggest that the surface topography of such an escarpment defines a fault plane, it is more probable that the escarpment surface is actually a tight series of vertically displaced units. The Pliocene and Quaternary sequences on this type of margin appear reduced in thickness and may be locally absent, unlike the intermediate margin. This configuration defines an *abrupt* structural margin (cf. Mauffret et al., 1973).

Regardless of the particular structural style involved, profiles across the different margins show that both M reflectors and overlying sequences have been tectonically displaced in post-M time, i.e., since the end of the Miocene. The presence of faults that displace even the uppermost reflectors indicates the very recent and large-scale nature of some of these movements offshore. These important vertical displacements in Pliocene and Quaternary time, which have shaped the slopes, escarpments, and canyons in this eastern Betic region, can be related to major phases of Pliocene-Quaternary movement on land (cf. specific examples of recent tectonics of the eastern Betic chain described by Montenat, 1970; Bousquet and Montenat, 1974; and other workers). The major fault trends, including a large fracture near Cape San Antonio, are parallel or subparallel to the Betic and sub-Betic chain (Bousquet and Montenat, 1974, figs. 1, 2). Another important E–W trending fault in the vicinity of Cartagena and south of Cape Palos-Mar Menor parallels the Mazzaron Escarpment; recent movement of significant magnitude has been measured on land adjacent to this area.

It is noteworthy that the margin, when parallel or near-parallel to major Pliocene and Quaternary fault trends, is of the abrupt type; the Mazzaron Escarpment is an excellent example. In contrast, where oriented normal to major fault trends the margin is of the progressive type (e.g., the region north and east of Cape San Antonio).

Balearic Margins

Physiography

The Balearic Platform is a shallow topographic feature, elongate NE–SW and approximately 440 km long, which extends from Cape San Antonio and the southeastern Spanish Betic margin to the region east of the island of Menorca. It consists of two shallow (< 100 m) near-horizontal shelves: a smaller (55 by 80 km) western shelf on which rest the islands of Ibiza and Formentera and a larger one (80 by 185 km) to the east on which lie the islands of Mallorca and Menorca (Figure 22). The shallow Ibiza-Formentera shelf is separated from the Spanish mainland by a deep (900 m) narrow depression, and from the Mallorca-Menorca shelf by a broader N–S depression. The northern margin of the Balearic Platform, forming the southern limit of the Valencia Trough, becomes steeper in a northeasterly direction (2° north of Ibiza; 8° north of Mallorca). The margin east of Menorca is oriented NW–SE with a slope of 10° toward the Balearic Basin plain. A remarkably steep and straight slope extends from the shelf edge south of Mallorca-Menorca in a southwesterly direction to the region southeast of the Formentera-Ibiza shelf. This feature is called the Emile Baudot Escarpment and has a gradient of 15° or more between the abrupt shelf platform and the base of slope (about 1500 m) south of Menorca. The escarpment between 4°E, 39°45′N and 2°E, 37°55′N is about 275 km long, dying out westward at a point about 220 km east of the Spanish coast at the latitude of Murcia. To the east (southeast of Menorca) the Emile Baudot Escarpment is truncated by a linear morphologic feature, the Menorca Ridge, which trends N–S and extends southward from the Mallorca-Menorca shelf.

The Balearic Rise is a large semicircular feature located between the slope south of Menorca and Mallorca, and the near-flat Algero-Balearic Basin plain (this feature has also been termed the "seuil sud-minorquais"). The Rise covers an area of about 15,000 km^2 and ranges in depth between 1600 and 2600 m. On small-scale charts the Rise resembles a large fan at the base of the eastern Balearic Block; however, the relief and surface configuration distinguish it from most typical subsea cones. The Rise surface is very irregular and comprises a group of small seamounts and depressions; in one area, a mean relief of about 400 m is encountered along a distance of 3 km (i.e., a gradient of about 7°30′).

One of the main features encountered on the Balearic Rise is a submarine valley extending southward from a point near the Menorca Ridge between Menorca and Mallorca (at about 4°E, 39°45′N). Near the center of the Rise (4°10′E, 38°55′N) this depression trends toward the southwest. This Menorca submarine valley is about 150 km long between its head at the Mallorca-Menorca shelf platform and its mouth on the lower Rise, where it meets the Algéro-Balearic Basin plain at a depth of 2600 m.

The Menorca Valley is V-shaped and 3 to 4 km wide at its head; it has a flat floor (U-shaped) and widens to 25 km at its lower extremity on the Rise. The valley walls (the eastern side is generally higher in the upper reaches, and the western side is higher on the Rise proper) have slopes to about 5° (Figure 32), whereas the average overall downslope axis gradient is 1:60 (or about 55′). Gradients of axial sections vary between 1:30 (or about 2°04′) in the upper valley section and 1:150 (or about 23′) in the lower section near the Basin Plain.

Three groups of Balearic Rise seamounts comprising one to three separate topographic highs are prominently displayed on both sides of the Menorca Valley. Seamount slopes vary in gradient between 5° and 15° and their rounded crests are generally quite narrow (area 3 to 5 km^2, cf. Figure 22).

The margin south of Ibiza-Formentera trends E–W with a more gentle slope of 3°. The westernmost sector of this margin is cut by three large submarine canyons trending NW–SE off the Spanish coast (see discussion of the eastern Betic margin southeast of Cape San Antonio, p. 30).

Bathymetric and seismic transects were available for all sectors although coverage north of the Balearic Block bounding the Valencia Trough is less extensive (Figure 23).

Stratigraphic Interpretation

Interpretation of the stratigraphic sequences recorded on seismic profiles in the Balearic region is based mainly on correlation with drilling logs and description of cores and seismic profiles retrieved by the D/V *Glomar Challenger* at site 124 of leg 13 (Ryan et al., 1973a). Site 124 is located east of the Balearic Rise (38°52.38′N, 04°59.69′E) at a depth of 2726 m; some of our seismic lines (Figure 23) traverse this area, thus allowing regional correlation.

Five distinct units can be identified on the sparker and air gun profiles. Locally, where there is particularly good resolution of the reflectors, one or two of these five sequences can be allocated to subunits. These are as follows, from older to younger:

1. The acoustic basement (B) is most frequently recorded on traverses across the Balearic Platform, particularly in the region between the shallow island shelves (Figure 25) and also on steep escarpments forming the Platform margin. On the Balearic Rise, the basement pierces the overlying series and may represent volcanic (V?) extrusives (Gonnard et al., 1975) or older rock units (Figure 28c,d).

2. A series of moderately defined reflectors, usually 3 to 5 in number, locally lies adjacent to the basement (Figures 25, 26); this series may include the N Reflector. The lithology and age of this unit are unknown, but it probably comprises consolidated or semiconsolidated sequences of Tertiary (probably post-Oligocene) age (Hsü et al., 1975). It is observed at the base of the slope and on the Basin plain, on the Balearic Rise, and on the Balearic Platform. It is particularly prominent in the depression between Mallorca and Ibiza (Figure 25b,c).

3. An almost acoustically transparent series is commonly observed on the seismic profiles, sometimes displaying a faint, very narrow bundle of reflectors. The contact between the transparent layer and overlying unit is usually nonconformable; this probably results from postdepositional displacement of the overlying sediment above the series forming the transparent layer.

A group of medium-strength reflectors occurs near the base of this sequence. These reflectors (N Reflector of Ryan et al., 1973b) commonly occur below the limit of penetration of the seismic systems we have used, but in a few places they can be identified at depths of 600 to 800 m below the sea floor (Figure 28). The transparent layer, termed "couche fluante" by French workers, is present in the Basin plain and in the western sector of the Balearic Rise. Workers during the last decade interpreted this sequence (Ryan et al., 1970; Montadert et al., 1970; and others) as a salt series in light of the diapirs and other "plastic tectonics" observed. This hypothesis was confirmed by the *Glomar Challenger* leg 13 drilling in 1970, although halite was not cored at site 124. The thickness in those areas where no structural or diapiric disturbances are apparent varies between 100 and 400 m. At some localities this unit is missing altogether and elsewhere it is completely contorted into chaotic masses, where the original thickness is difficult to assess (Figure 28e, f).

4. A sequence consisting of a prominent bundle of reflectors, usually six to nine in number, is laterally extensive; it is interpreted as the M reflectors sequence (Ryan et al., 1973a). The thickness of this unit usually ranges from 100 to 300 m, and it is affected in places by intense tectonics

of diapiric origin (Figure 27F). There seems to be no correlation between thickness and present-day topography. In some locations, it crops out at the sea floor due to absence of the overlying sequences but elsewhere it is missing altogether either because of later erosion or because the unit has been incorporated in the diapiric, plastic material which has forced its way through it from below.

Drilling at JOIDES site 124 indicates that this unit is composed mainly of gypsum and anhydrite alternating with some carbonates (dolomites) and marls of Messinian age (Ryan et al., 1973a). The contact of this formation with the overlying Pliocene sediment is probably an unconformable one; a sharp change in lithology and compaction, and hence in reflecting properties, gives rise to a very prominent seismic signal, which makes it a most useful stratigraphic marker. This seismic reflector, however, is not necessarily of the exact same age throughout the study area (Messinian to lowermost Pliocene, Biscaye et al., 1972).

5. The uppermost sediment unit is characterized by 10 to 20 reflectors of moderate intensity, which fade out downward to an underlying transparent layer. This section, commonly about 200 m in thickness, attains a maximum thickness of 700 m; locally it is missing altogether. The thickness of this sequence varies with morphology, i.e., the thickest sections tend to occur in depressions. Noteworthy is the tongue of sediment in the lower section of the Menorca Valley, from about 2195 to 2375 m (Figure 22). In most of the area of the lower Menorca Valley on the Rise, the sediment thickness ranges to 700 ms (700 m), while at the head of the Menorca Valley and on the slope near the Emile Baudot Escarpment the thickness of this unit decreases to less than 100 ms (100 m). Measured core sections at JOIDES leg 13, site 124, provide additional information on the thickness and lithology of this unit (Ryan et al., 1973a).

The formation consists mainly of lutites of both turbiditic and hemipelagic origin, with variable amounts of turbiditic arenites. The cores penetrating the surficial sediment section are discussed elsewhere (Kelling, Maldonado, and Stanley, in preparation). The relative proportion of arenitic turbidites ranges from about one fifth of the recovered section in the upper part of the Balearic Rise to about one hundredth of the lithologic column at the margins of the Rise and in the Algéro-Balearic Basin plain.

The contemporaneous and genetically related sediment bodies of the Rise and the deeper Basin plain to the east and south display differences both in thickness and lithofacies. It is probable that the rate of sedimentation in the Algéro-Balearic Basin (Leclaire, 1972a,b; Rupke and Stanley, 1974) is higher than that on the Balearic Rise; coring also suggests that much of the sub-Recent and Pleistocene sand transported from the Balearic Platform is presently resting on the Rise surface and has not yet reached the Basin plain (Horn et al., 1972; Rupke and Stanley, 1974; Stanley et al., 1974b; Kelling, Maldonado, and Stanley, in preparation). Within this sequence, a few reflectors are better developed than others. These may be related to the P_α and P_β markers of Ryan et al. (1973a) but such a correlation is speculative at present.

The age of the transparent and overlying reflector-rich zone is Pliocene and Quaternary (Ryan et al., 1973b). It should be noted that the lower layer of Pliocene age is transparent in the basin plain and on the Balearic Rise but displays reflectors on the Balearic Platform. As in the region off southeastern Spain, it is not possible to distinguish the boundary between the Pliocene and Quaternary sequences on the available seismic profiles.

Structural Configuration

In the following discussion we treat successively the predominant structural characteristics of the Pliocene-Quaternary and underlying series on the Balearic Platform, its margins north and south (including the Emile Baudot Escarpment), the Balearic Rise, and the Menorca Valley. Selected subbottom profiles from the various regions illustrate specific points discussed here. The profiles used are oriented, wherever possible, either parallel or normal to each other (Figures 23, 25) and, in some instances, perpendicular to major structural trends of the region (Figure 21).

Balearic Platform

The platform east of the Spanish margin and west of the shallow Ibiza-Formentera shelf, unlike

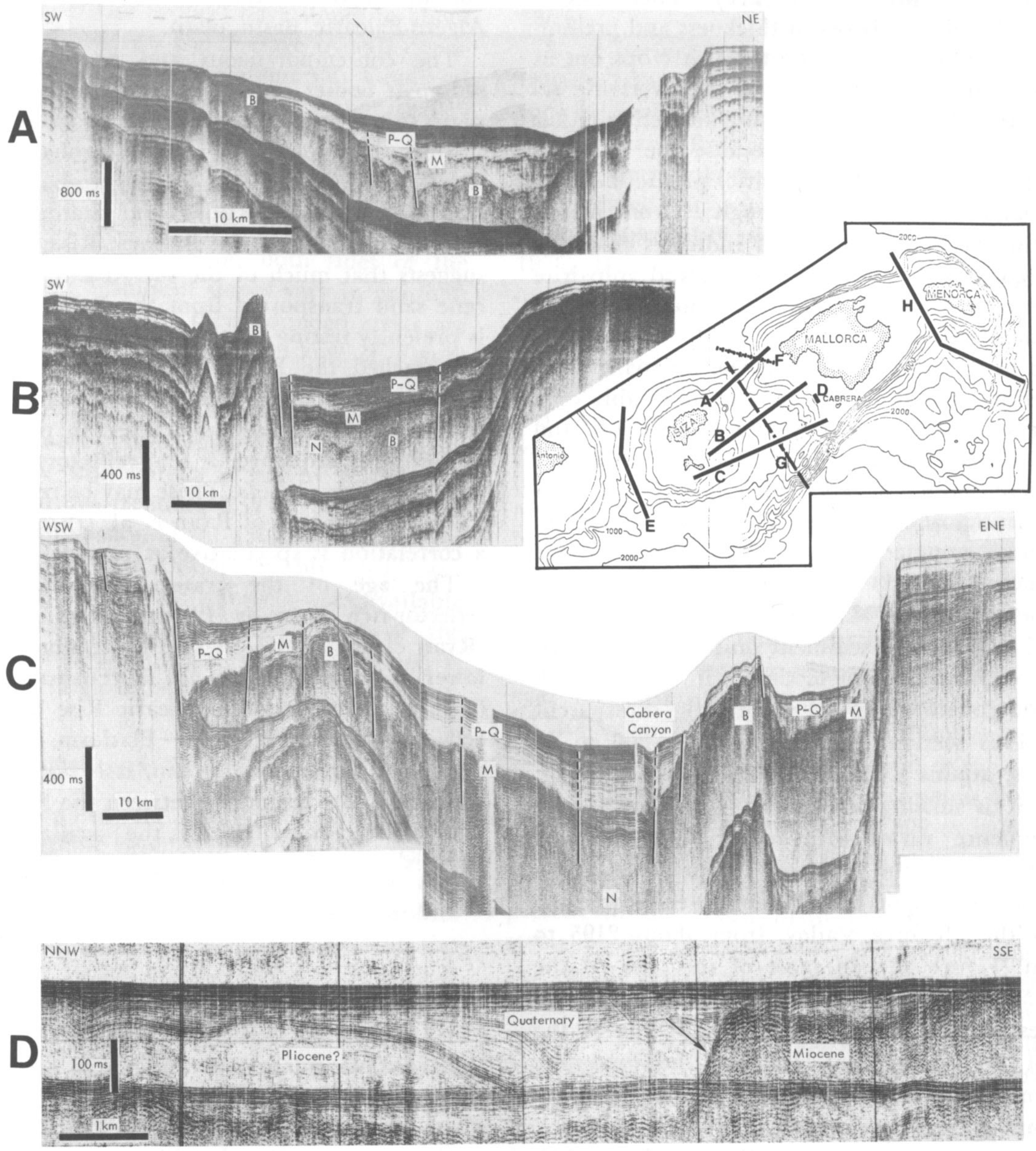
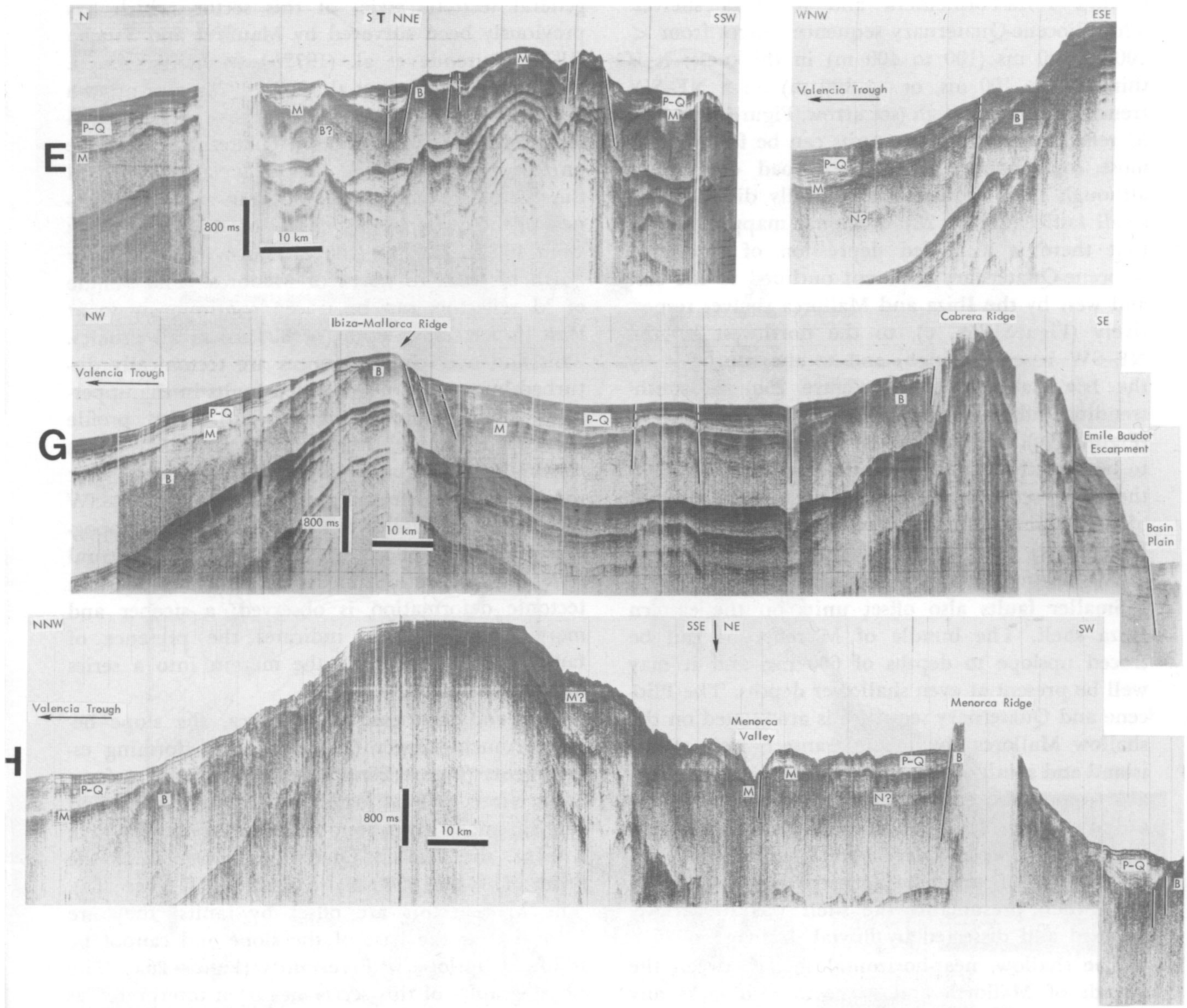


FIGURE 25.—Selected seismic profiles on the Balearic Platform: A–C, sections (air gun) between Ibiza-Formentera and Mallorca; D, detail of Mallorca shelf (8000 J sparker) showing erosional surface (arrows) filled by Pliocene-Quaternary sediments; E, section (air gun) between Ibiza-Formentera and Mallorca-Cabrera shelves; F, section (air gun) extending NW from the Mallorca shelf to the Valencia Trough; G, profile (air gun) across Balearic Platform between Valencia Trough and Emile Baudot Escarpment; H, section (air gun) extending from Valencia Trough, between Mallorca and Menorca and across Menorca Valley and Menorca Ridge. (N = N Reflector; symbols explained in Figure 24.)



the Cape San Antonio margin bounding the eastern Betics (see previous chapter and Figure 24c), displays an irregular topography and a much reduced Pliocene-Quaternary cover (about 100 to 250 ms, or 100 to 250 m). Thicknesses are reduced on topographic highs; these highs commonly denote the presence of the acoustic basement, which locally has pierced the M reflectors and underlying sequences (Figure 25E). A number of faults are observed, which have divided the entire region into a series of large tilted blocks 5 to 10 kms in length. Vertical displacement of the M reflectors approximates 200 ms (≅ 200 m), and movement along these faults appears to have affected the Pliocene and in some instances Quaternary sequences. The bundle of M reflectors can be traced upslope onto this sector of the platform to depths of about 800 ms (≅ 800 m). The thickness of Pliocene and Quaternary sequences is even more reduced on the Ibiza-Formentera shelf (< 100 m).

A broad depression characterized by more subdued topography occupies the sector between the shallow Ibiza-Formentera and Mallorca shelves. The Pliocene-Quaternary sequence ranges from < 100 to 400 ms (100 to 400 m) in thickness; it is thinnest (< 100 ms, or < 100 m) on a NE–SW trending basement high (see arrow, Figure 25G). The M reflectors and younger units can be followed almost continuously across the broad depressions although these sequences are locally displaced by small faults (Figure 25). Regional mapping shows that there is a buried depression of thickened Pliocene-Quaternary sediment outlined to the east and west by the Ibiza and Mallorca shelves respectively (Figure 25B, C), to the northwest by the NE–SW basement high, and to the southeast by the Isla Cabrera Ridge (Figure 25G). A south-trending submarine valley, the Cabrera Canyon (Figure 25C), cuts this basinal sequence and appears to be directly related to faults that have displaced the M reflectors and overlying units. The margins of this sediment-filled depression are delineated by large faults that vertically displace the basement and overlying units by as much as 400 ms (400 m).

Smaller faults also offset units on the eastern Ibiza shelf. The bundle of M reflectors can be traced upslope to depths of 600 ms, and it may well be present at even shallower depths. The Pliocene and Quaternary sequence is attenuated on the shallow Mallorca shelf. One transect, west of the island and south of Palma de Mallorca, shows probable upper Miocene sedimentary units covered by only a very thin veneer of unconsolidated sediments; the rock unit presents an erosional surface reflecting truncations of probable Quaternary age (Figure 25D) when presumably the shelf was subaerially exposed and dissected by fluvial drainage.

The shallow, near-horizontal shelf between the islands of Mallorca and Menorca also lacks any significant Quaternary cover (Figure 25H). The bundle of M reflectors is observed at a depth of about 600 m. The seismic systems used to profile across the shallow Mallorca-Menorca shelf do not enable us to distinguish fault patterns within the consolidated and upper sedimentary sequences forming the shelf.

NORTHERN AND EASTERN MARGINS OF THE BALEARIC BLOCK.—The limited number of subbottom traverses northwest and north of the Balearic Platform, which forms the southern limit of Valencia Trough, do not enable us to detail this margin. They nevertheless provide further indication of the general tectonic styles of this sector, which has previously been surveyed by Mauffret and Sancho (1970), Auzende et al. (1972*b*), Montadert et al. (1970), and Mauffret et al. (1972, 1973). Our profiles oriented NW–SE show a progressive reduction in the thickness of the Pliocene-Quaternary sequence on this margin between the Valencia Trough and the Balearic Platform (Figure 25F–H). The thickness of these younger sequences on the slope ranges from 400 to 500 ms (400 to 500 m) in the sector north of Ibiza to north of Menorca. The bundle of M reflectors can be traced continuously to at least upper slope depth (≅ 800 m) in all profiles. This and overlying sequences are tectonically disturbed by a series of small step faults in the uppermost slope regions (Figure 25H). The profile between Ibiza and Mallorca (Figure 25G) shows continuity with only minor displacements near the upper platform margin (i.e., near the NE–SW trending Ibiza-Mallorca Ridge). The slope topography closely reflects the underlying structural style: where gentle and smooth, little subbottom tectonic deformation is observed; a steeper and more irregular slope indicates the presence of faults that have broken the margin into a series of steplike blocks.

East and southeast of Menorca, the slope becomes much steeper (> 10°), locally forming escarpments (Figure 26A). Steep escarpment surfaces appear free, at least locally, of sediment cover and the basement crops out in some sectors. Where present, the Pliocene-Quaternary cover is of the order of 200 ms (200 m) in thickness (Figure 26B). The M reflectors are offset by faults; they are truncated at the base of the slope and cannot be followed upslope with certainty (Figure 26A). The physiography of this sector has been interpreted as a series of faults by Belderson et al. (1970) and Biju-Divual (1974).

The Menorca Escarpment facing the Balearic Basin plain forms the eastern edge of the Balearic Platform. Toward the south the relief of this feature is progressively reduced, its slope is less steep (4°), and the Pliocene-Quaternary cover reappears (Figure 26B). The topographic high extending south of the Menorca shelf is herein termed the Menorca Ridge; its crest, with a reduced sedimentary cover, appears to be underlain by acoustic basement. The western side of the Ridge also shows considerable relief (1600 ms, 2200 m), re-

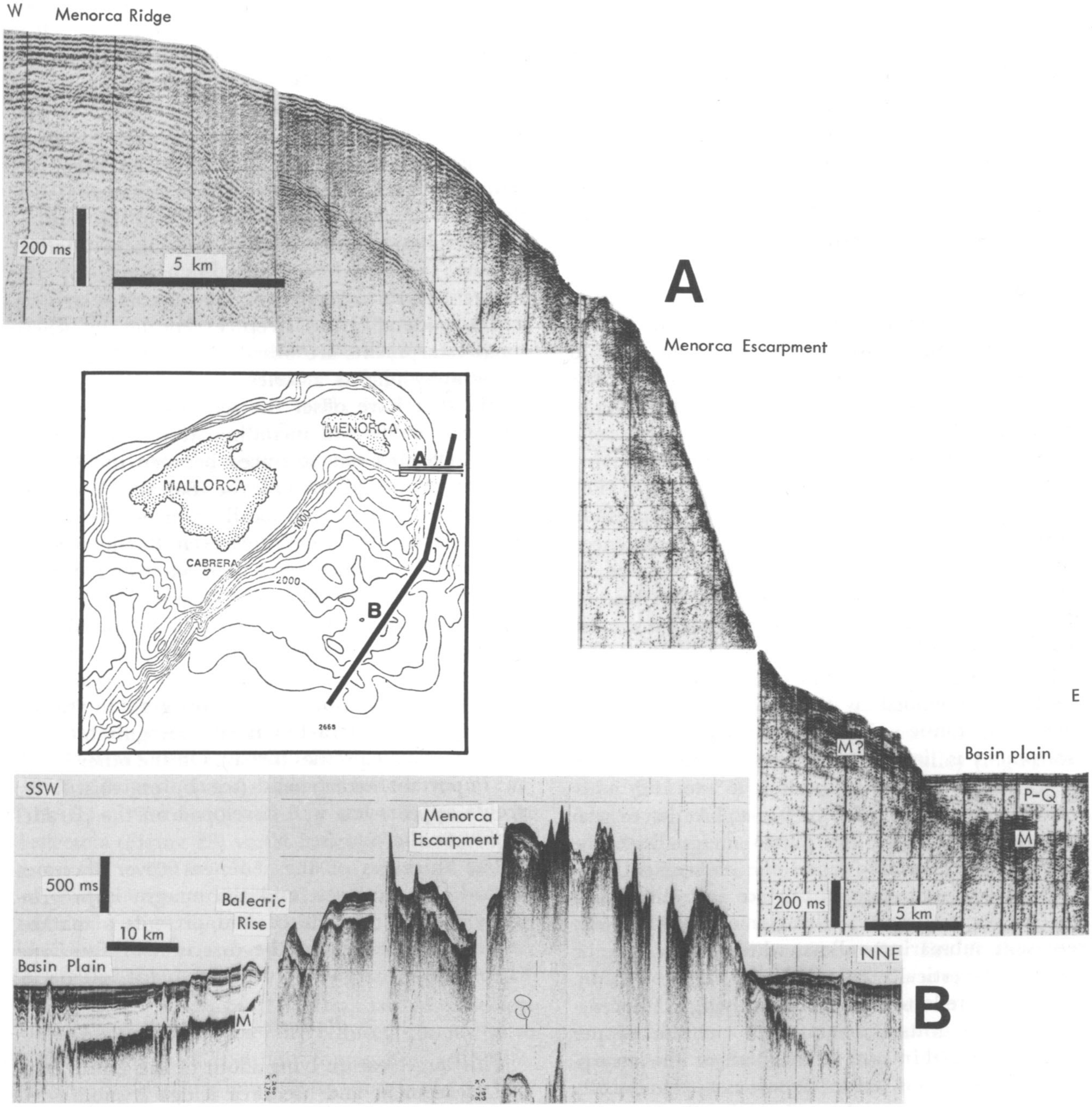


FIGURE 26.—Seismic profiles traversing the Menorca Escarpment: A, 8000 J sparker; B, Conrad-9 air gun. (Note vertical displacement of M reflectors and Pliocene-Quaternary sequences on Balearic Rise, and the sharp contact between the Rise and Algéro-Balearic Basin plain.)

sulting from probable vertical fault offset (Figure 25H).

SOUTHERN MARGIN OF THE BALEARIC BLOCK.—The southern margin of the Mallorca-Menorca shelf edge forms a V-shaped aperture (angle of about 120°) opening southward. This configuration results from the meeting of two steep margins: the NNW–SSE slope parallel to the crest of the Menorca Ridge, and the SW–NE trending Emile Baudot Escarpment. A submarine canyon, the Menorca Valley, lies at the junction of these two trends and extends southward toward the Balearic Rise. This region is covered by the Pliocene and Quaternary units ranging from 250 to 300 ms (250 to 300 m) in thickness. The bundle of M reflectors can be traced reasonably well upslope to a depth of about 500 m south of Menorca. The combined thickness of the M reflectors and overlying units remains fairly constant along the slope. The topography within the narrow V-shaped depression on the upper slope is very irregular; it is influenced to some degree by small fault offsets as noted by displacement of the M reflectors (Figure 33A, B). The topography and underlying structure are more gentle on the mid to lower slopes.

The Balearic Block south of Mallorca and Formentera is bounded by the prominent southwest-trending Emile Baudot Escarpment. The escarpment is limited to the east by the Menorca Valley (Figure 27A) and its slope (5° to 10°) is toward the southeast (Figure 27B–E). At its eastern end, the base of the escarpment merges with the Balearic Rise. In this sector the escarpment presents an irregular, steplike surface including some small V-shaped irregularities (some of which may represent submarine valleys, while others may be tilted and vertically offset blocks, Figure 27C, D). The M reflectors and overlying Pliocene-Quaternary units encountered on the upper Balearic Rise thin out at the base of the escarpment. Nevertheless, these sequences appear locally on the slope proper, where they are tilted.

The escarpment is steepest and has greatest relief south and southwest of the island of Cabrera along a 100-km-long sector (Figures 25G, 27F). The upper sequences forming the irregular Balearic Rise topography and, to the west, near-horizonal Algéro-Balearic plain sequences abut sharply against the base of the escarpment (relief of about 2500 m) south of this small island (Figure 27F). Deformation of the acoustically transparent layer, including salt domes and other forms of salt tectonics, is evident on the basin plain just beyond the base of the escarpment (Figure 27F,G). Our profile systems did not reveal any notable sedimentary cover on the escarpment in this steepest region. Studies by others in this area (Mauffret et al., 1972) also show this reduced Pliocene-Quaternary cover associated with the NE–SW trending faults which form this feature.

The physiography of the escarpment changes toward the west. Southeast and south of the Formentera-Ibiza shelf the slope becomes steplike and considerably less steep, except locally where small escarpments are observed (Figure 27H). This topography reflects a series of vertically displaced blocks that have offset the sedimentary sequences (900 ms, or 900 m), including M reflectors; these latter reflectors can be traced between the Algéro-Balearic Basin plain and the Balearic Platform. The acoustic basement locally pierces the overlying units on the slope, and even the uppermost Quaternary sequences have been offset by faults.

Some faults can be traced laterally, as demonstrated by an analysis of two parallel profiles 80 km apart (Figure 27H,I). The Emile Baudot Escarpment, which diminishes in relief toward the west (see a), disappears as a topographic feature south of Formentera but is still recognizable as a fault on seismic profiles (see a′). On the other hand, an important escarpment (see b) on this latter profile appears less well developed on the parallel profile to the east (see b′).

The thickness of the sediment cover increases toward the southwest and the margin is progressively more block faulted and presents a marked steplike topography in the direction of the Cape San Antonio margin (Figure 24E).

Balearic Rise

This large feature lying south of the Emile Baudot Escarpment and Menorca Ridge is subdivided into several tectonic zones on the basis of the dense network of sparker and air-gun profiles available in this region. By far the largest zone is the one broken into a series of large ($\cong$ 10 km wide) horsts and grabens. The offset sedimentary sequence includes the Pliocene-Quaternary cover, the M reflectors, the underlying transparent layer ("couche fluante"), and in some instances the N reflector (Figure 28). This series appears similar to that mapped on the adjacent basin plain. The Pliocene-Quaternary units vary in thickness, but they are not necessarily thinner on topographic highs. The overall structural configuration of this region appears to be of recent origin. This is particularly well illustrated by displacement of the M reflectors and both overlying and underlying horizons (see arrow, Figure 28H).

Seismic transects across the somewhat deeper and topographically subdued southwest sector of the Rise (at a depth of 2300 to 2600 m), south of Mallorca, cross a zone of salt domes, many of which reach the surface (Figure 28E). These domes are similar to those observed in the adjacent Algéro-Balearic Basin plain (Watson and Johnson, 1969; Wong et al., 1970; Alinat et al., 1970; Leenhardt, 1970; Stanley et al., 1974b). Salt dome structures are absent from the region immediately east of the Rise and just west of *Glomar Challenger* site 124 (Figure 28F).

The contact between the southern margin of the Balearic Rise and the Algéro-Balearic Basin plain is a sharp one as observed on several profiles (Figures 28G, I, J). Step faults generally separate the Rise from the Basin plain.

The density of seismic profiles enables us to determine variations in regional stratigraphy and to correlate these sequences with those mapped at the JOIDES leg 13, drill site 124 (Ryan et al., 1973a). Isopach maps show the following:

1. The Pliocene-Quaternary cover above the M reflectors (Figure 29) varies irregularly in thickness, from 100 to 700 ms (100 to 700 m). Isolated wedges of Pliocene-Quaternary units trend in two predominant directions: NW–SE and NE–SW; these thickened wedges are sometimes bounded by faults of similar trend.

2. The thickness of the Messinian M reflectors unit (Figure 30) is generally reduced about 100 to 150 ms (150 to 220 m) in comparison with that on the Basin plain immediately south of the Rise and of the Emile Baudot Escarpment (at least 200 ms). The thickness of the M reflectors is quite variable across the Rise, and there does not seem to be a close correlation with the thickness of the overlying Pliocene-Quaternary units.

3. The transparent layer ("couche fluante") underlying the M reflectors has not been contoured due to the structural complexities (Figure 31). Profiles show that this unit is present across much of the Rise and its thickness varies from about 0 to 400 ms (0 to 700 m). This unit tends to thicken slightly southward toward the Basin plain, and pinches out at the base of the Emile Baudot Escarpment. W. B. F. Ryan (pers. comm.), who has examined these records, ascribes the transparent layer to infrasalt deposits. The thickness of the transparent layer on the southernmost Rise, however, is comparable with that on the adjacent Basin plain, where salt tectonics are observed (see Figure 28I,J).

The sum of observations indicates that the Balearic Rise is an area broken by a complex network of faults. Vertical displacements have affected the upper unconsolidated sedimentary sequences as well as underlying basement, indicating the post-Miocene to late Quaternary origin of these features. The highly irregular topography of the Rise attests to this recent structural evolution.

Menorca Valley

A series of seismic profiles was made across the Menorca Valley between its upper reaches and its mouth on the lower Balearic Rise. The valley first trends to the south, and upon reaching the Rise veers to the southwest. Its cross-sectional character changes downslope from a narrow V-shaped profile to a broad, flat-floored U-shaped valley (Figure 32). The thickness of the unconsolidated fill is negligible at its head and tends to increase downslope to about 400 ms (400 m). On several cross-canyon profiles on the upper slope (Figure 33B) the M reflectors appear offset, suggesting that the head of canyon was cut along a fault. This is not unexpected inasmuch as the valley lies at the sharp juncture of the Emile Baudot Escarpment and the Menorca Ridge. Somewhat smaller valleys, adjacent to the Menorca Valley and observed on the upper slopes also display similar NNW–SSE trends; some of these are canyon tributaries. In the two shallowest profiles made just south of the Menorca Shelf, the V-shaped canyon cuts into the Pliocene-Quaternary as well as the underlying bundle of M reflectors. In all cross-canyon profiles obtained farther to the south, the valley is cut well into the Pliocene-Quaternary sequences, but the M reflectors can be traced beneath the valley (Figure 33C–F) and do not show evidence of earlier (pre-Pliocene) erosion or truncation by canyon cutting.

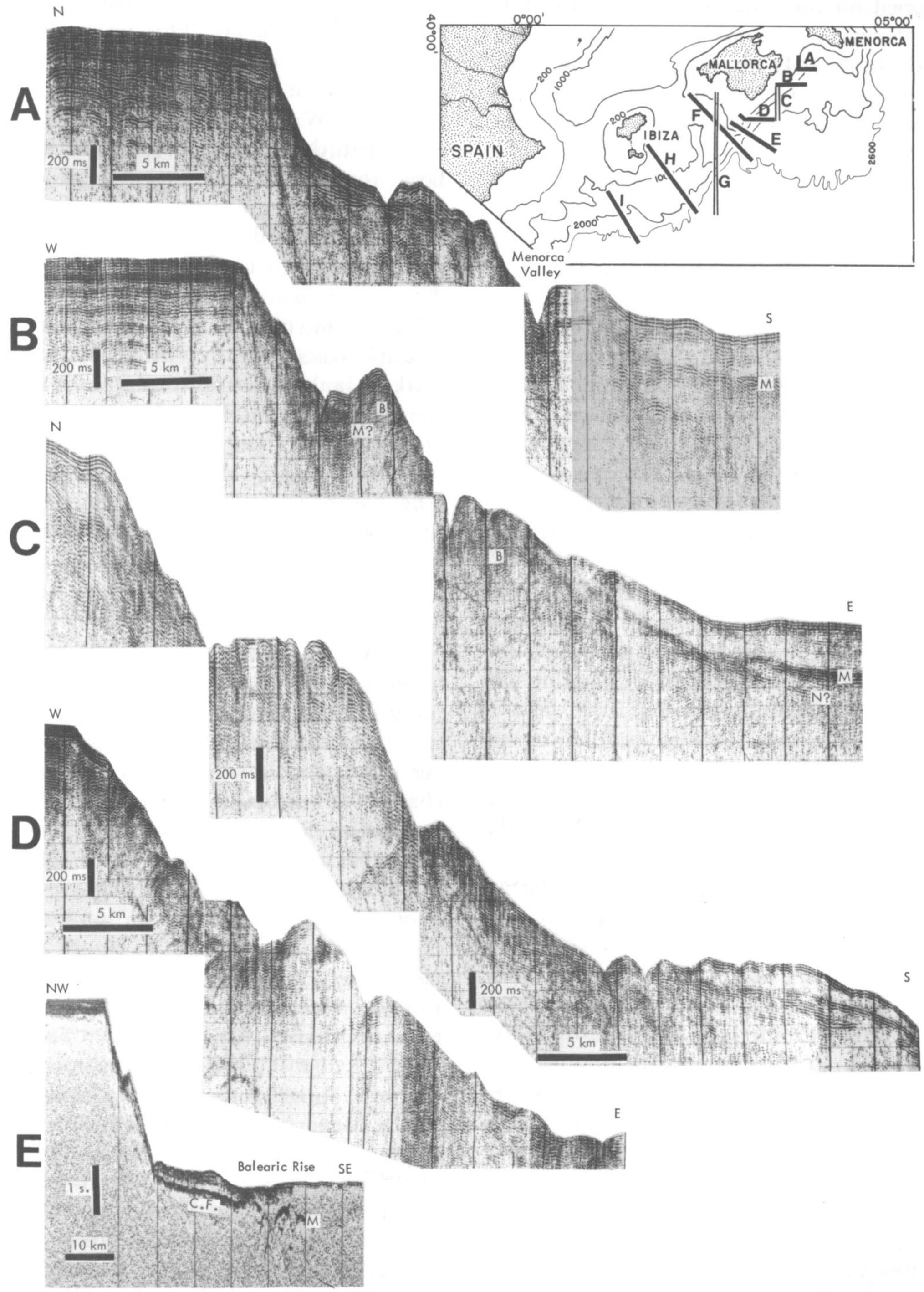
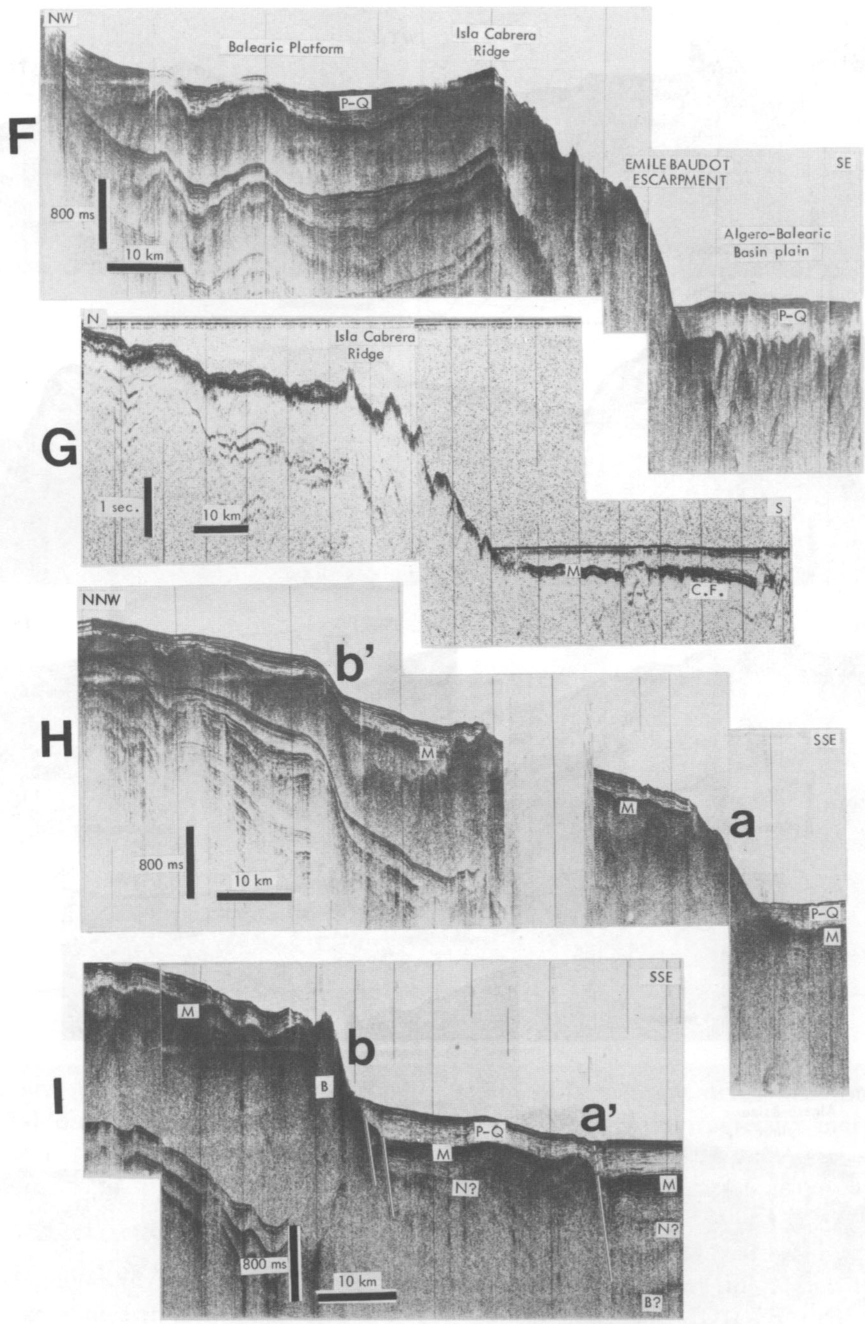


FIGURE 27.—Series of seismic profiles across the Emile Baudot Escarpment from southwest of Menorca to southwest of Formentera; A–D, 8000 J sparker; E, G, 30,000 J sparker; F, H, I, air gun. (Profiles A–E extend from the Mallorca shelf to the Balearic Rise; F–I extend to the Algéro-Balearic Basin plain. Note lateral changes of structure and physiography between profiles G, H, I. The large escarpment becomes a series of steps (a, on H) which subsequently die out toward the southwest (a′, on I).)



These observations indicate (1) that the origin and orientation of the upper reaches of the Menorca Valley were tectonically controlled, (2) that the phase of canyon cutting is probably younger than the M reflectors (i.e., post-Messinian) and in part may even be Quaternary in age; and (3) that the character and trend of the lower reaches of the Menorca Valley are to a large degree sedimentologically controlled: its migratory pattern on the lower Balearic Rise, well-developed natural levees (N.L., Figure 33C–F), and near-flat valley axis attest to its importance as a byway for sediment between the

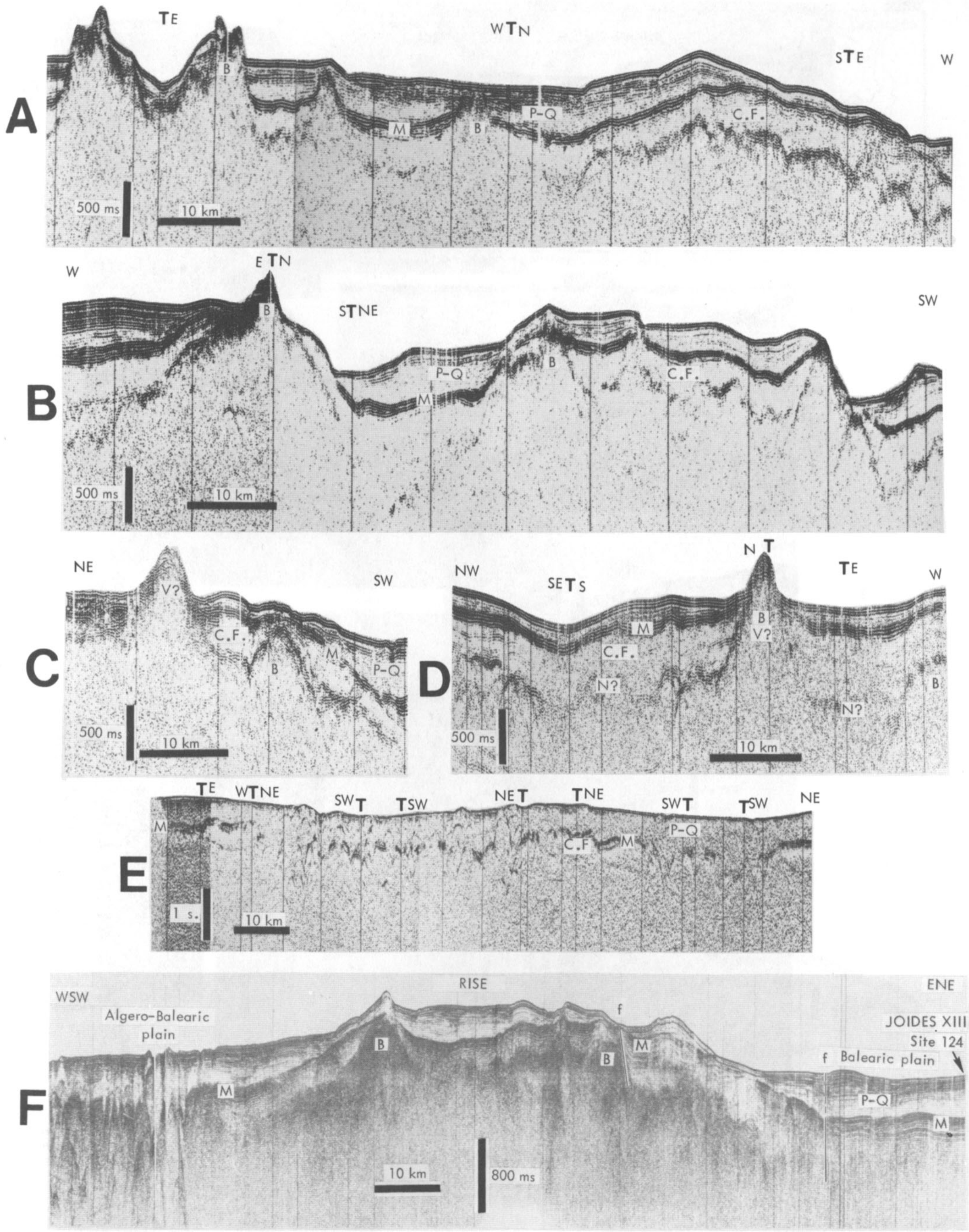
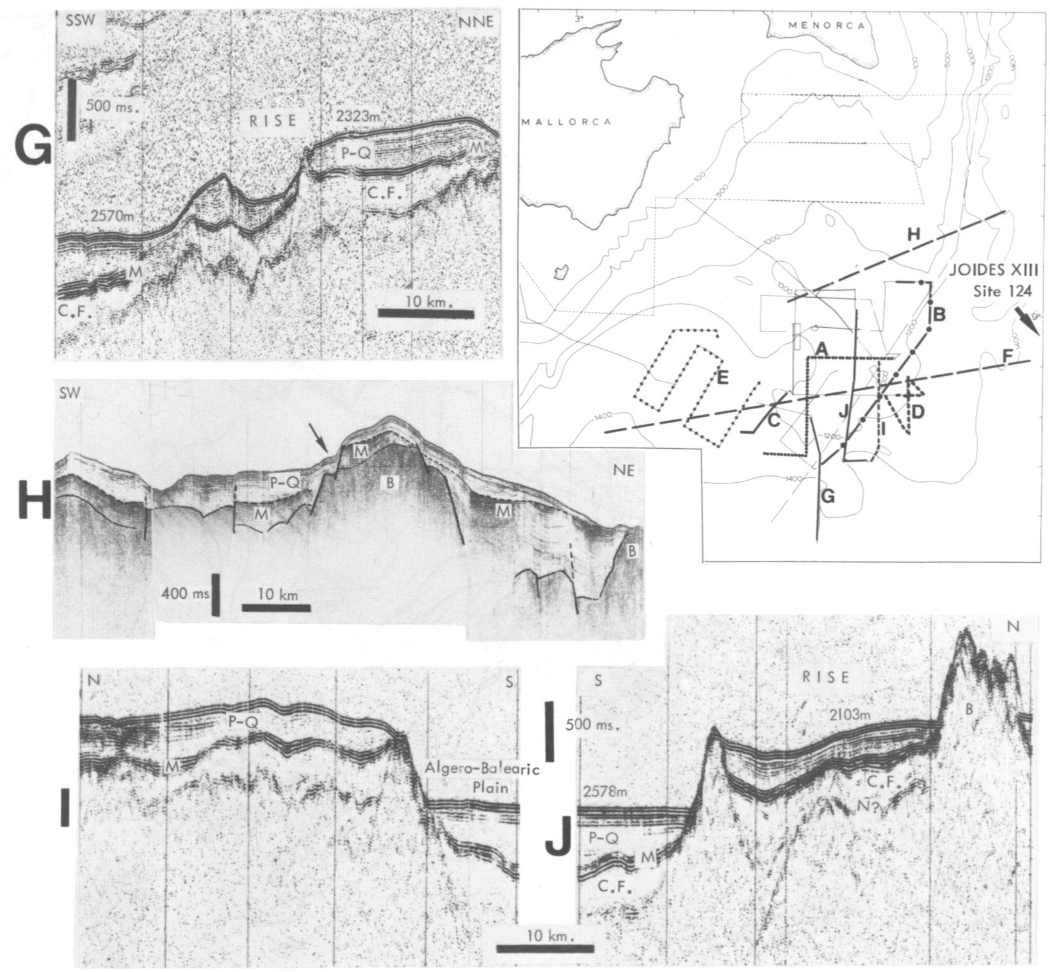


FIGURE 28.—Seismic profiles across the Balearic Rise showing the horst and graben structure of this feature: A, B, profiles show the vertical displacement of sedimentary sequences, including the Quaternary, which gives rise to the irregular topography; C, D, the acoustic basement (possibly volcanic, V?) locally pierces sedimentary sequences and forms seamounts (also in profiles A, B and J); F, profile across southern sector of the Rise from the Balearic Basin (near *Glomar Challenger* site 124) to the Algéro-Balearic plain; salt domes are noted on the southwestern part of Rise (also on profile E); G, I, J, profiles show fault contact between the Rise and basin plain; H, profile indicates marked vertical offset of the M reflectors and overlying series (arrow). (All profiles are 30,000 J sparker except F and H, which are air gun).



Balearic Platform and deep base-of-slope environments (Kelling, Maldonado and Stanley, in preparation).

Discussion

The seismic survey demonstrated that the present physiography of the Balearic Platform and adjacent regions is a result of extensive structural displacement that has occurred, for the most part, since the end of Miocene (i.e., post-M reflectors) time, or a period of at least five million years (Drooger, 1973). Not all of the movements need have occurred simultaneously nor have all the displacements been of equal importance during this period. For instance, it would appear that the steep sediment-free escarpments are younger than some of the more gentle progressive margins where faults that displaced the M reflectors and transparent Pliocene series became attenuated within the Quaternary series.

The bundle of M reflectors which are present almost everywhere in this region can be correlated with that of the JOIDES drill site 124 a few kilometers east of the Balearic Rise proper, where it was recovered as dolomitic marl with interbedded diatomites beneath nodular anhydrite of an upper Miocene (Messinian) evaporite series; here it contains brackish to marine shallow-water faunas (Ryan et al., 1973a). The M reflectors can be traced across both the gently sloping and the step-faulted portions of the Balearic Rise and also

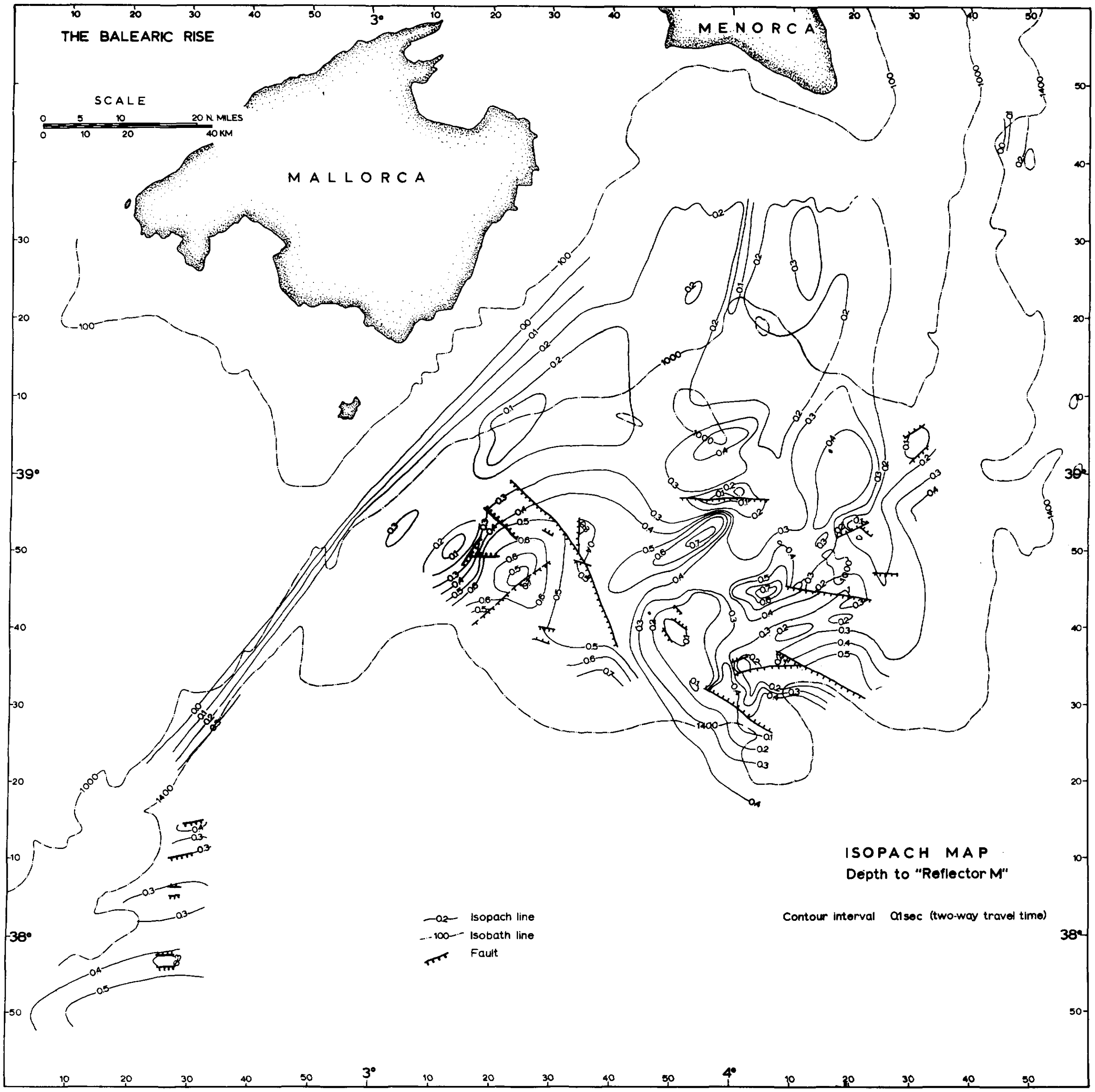


FIGURE. 29.—Isopach map showing the combined Pliocene and Quaternary sediment thickness and predominant fault patterns affecting these units on the Balearic Rise.

across the Balearic Platform proper, where it is observed at a depth of about 500 m. It probably occurs at shallower depths, but the seismic systems we used do not permit definition of this unit on the Ibiza-Formentera and Mallorca-Menorca shelves. Although the M reflectors are not necessarily synchronous throughout the area, it appears that some marine sequences of uppermost Miocene age occur discontinuously between the islands and the Balearic Basin plain some 2800 m below.

The Pliocene-Quaternary section is well developed in a tectonic depression on the Balearic

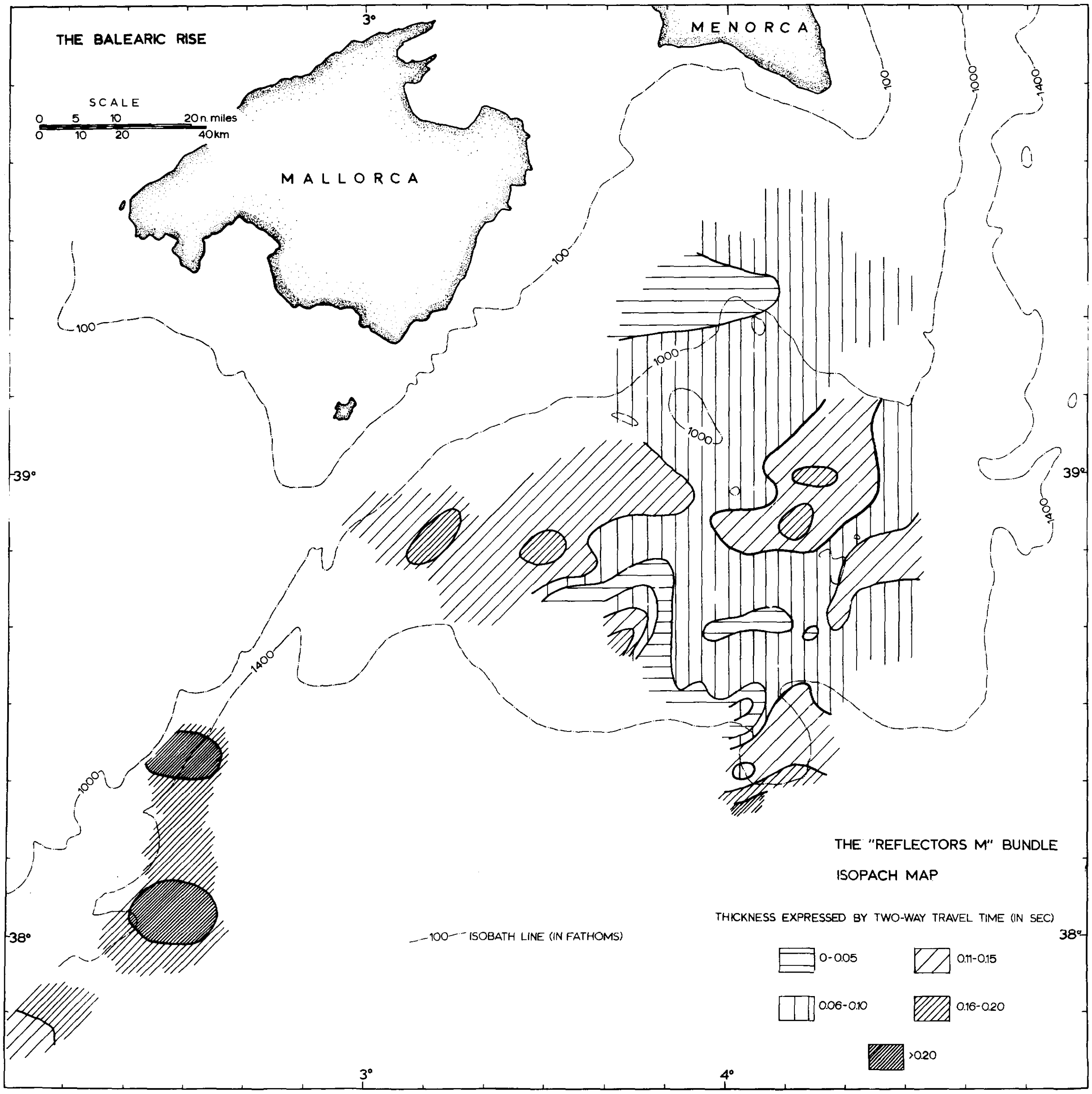


FIGURE 30.—Simplified isopach map showing the approximate thickness of the bundle of M reflectors (= Messinian age) on the Balearic Rise and adjacent Algéro-Balearic Basin plain.

Platform between Ibiza and Mallorca; it thins considerably on the shallow island shelves and adjacent steep margins and is possibly absent on some steeper escarpments. It is well developed on the Balearic Rise and Algéro-Balearic Basin plain, where piston cores show that the uppermost sequences consist of alternating hemipelagic mud and turbidite sand and mud; rates of sedimentation exceed 20 cm per 1000 years (Rupke and Stanley, 1974).

All of the units mapped, from acoustic basement to upper Quaternary, are almost everywhere struc-

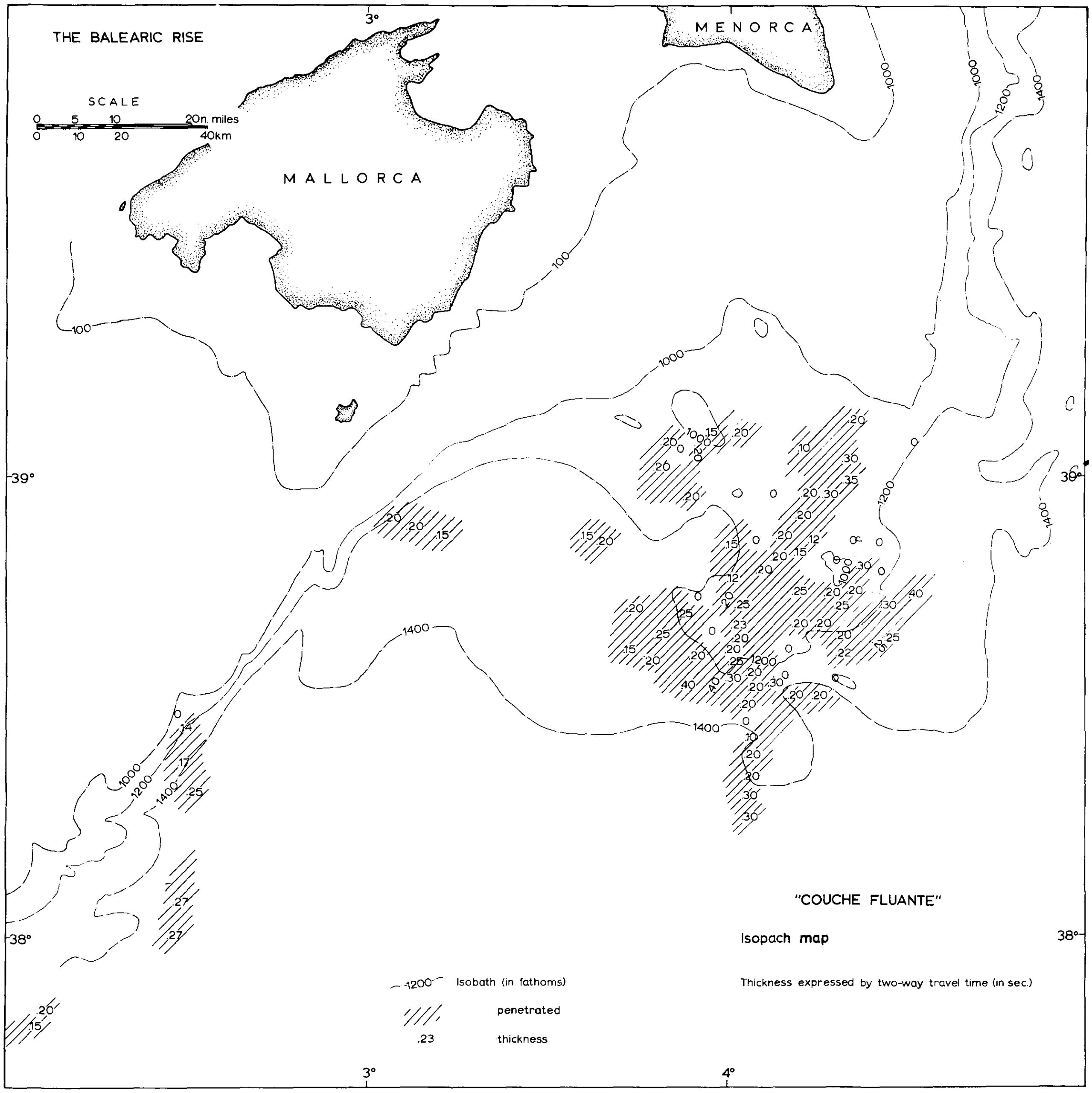


FIGURE 31.—Simplified isopach map depicting distribution and approximate thickness of the transparent "couche fluante" (upper Miocene salt) layer on the Balearic Rise.

turally deformed by folds and faults. However, the nature of this deformation and related sea-floor topography vary considerably regionally:

1. The slope north and west of the Ibiza Shelf is gentle, relatively undeformed, and physiographically presents a concave-up profile. Seismic profiles show that the Pliocene and Quaternary sequences that dip gently toward the Valencia Trough lie above slightly displaced M reflectors. This configuration is not unlike that observed north and east of Cape San Antonio and defined as a *progressive* margin.

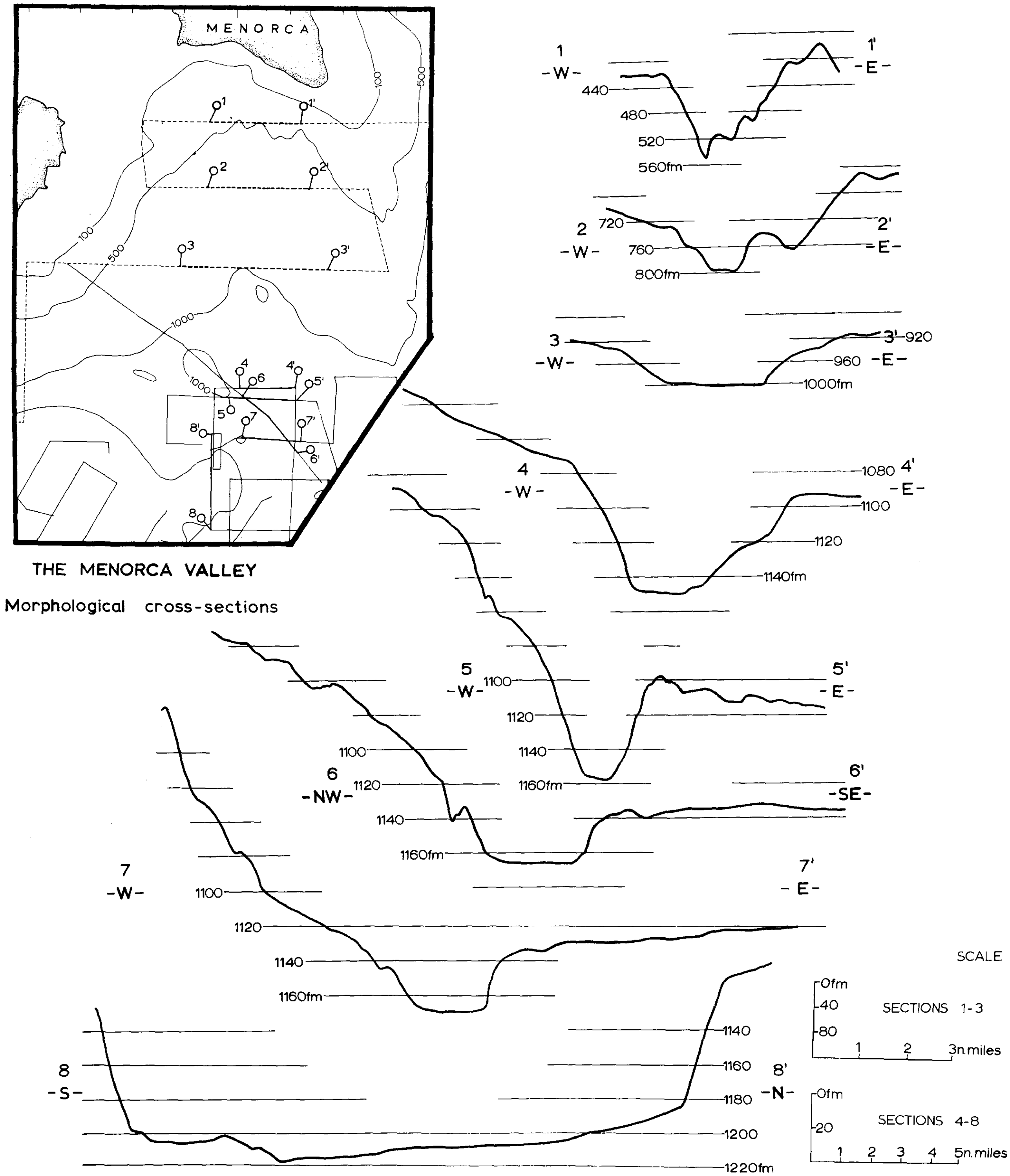


FIGURE 32.—Menorca Valley cross sections showing the transition from V- to the U-shaped configuration of the axis (see also Figure 33).

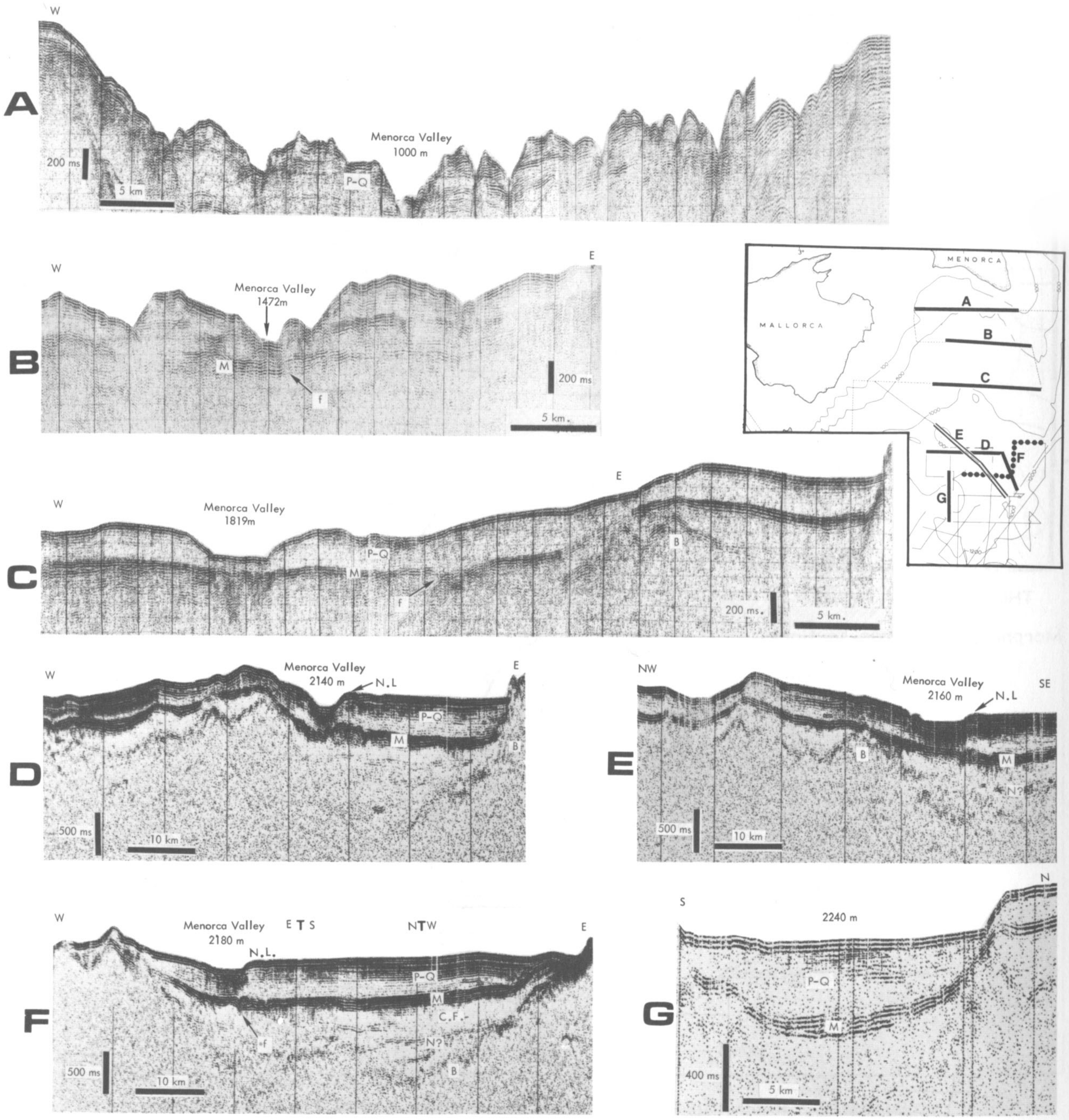


FIGURE 33.—Seismic profiles across the Menorca Valley: A–C, profiles on slope, 8000 J sparker; D–G, profiles on Balearic Rise, 30,000 J sparker. (Note possible structural displacement in sequences below canyon (arrow on B) and continuation of the M reflectors beneath the canyon on all profiles. See also Figures 25H and 27A. N.L. = natural levee.)

2. The slope north and northeast of the Mallorca-Menorca shelf is steeper and considerably more irregular than (1); it presents a steplike configuration. This margin is deformed by large-scale faulting, which has resulted in the vertical displacement of a series of large blocks between the shelf and the Valencia Trough. Pliocene-Quaternary thicknesses here are less important than those on the margin described in (1). A similar configuration also occurs on the margin south and southwest of Formentera. The Balearic Rise, lying between about 1600 m and the Algéro-Balearic plain at about 2700 m, is also broken into a series of large horsts and grabens. All margins described here are defined as the *intermediate* (or step) type.

3. The Menorca Escarpment east of Menorca and the Emile Baudot Escarpment south and southwest of Mallorca represent an *abrupt* structural margin. This type is characterized by a large relief (about 2000 m) formed by a series of tight faults with large vertical throw within a narrow (13–15 km wide) zone. In the two regions cited, this type of margin separates near-horizontal sequences of two quite different structural zones (i.e., shelf and basin plain). Furthermore, these abrupt margins appear devoid of any significant sedimentary cover. Two other observations should be noted: (a) near-horizontal basin plain strata abut directly against the steep escarpment base, and (b) there is an absence of allochthonous slump masses at the base of the slope. These observations indicate that the escarpments have not been covered by a Pliocene-Quaternary sediment cover of a thickness comparable to that on the Platform and Basin plain. Nondeposition may be due to erosion by contour currents (cf. Mauffret, 1969). More likely, the absence of sediment, including pelagic and hemipelagic cover, indicates a geologically recent formation of this type of margin.

4. The series of parallel transects across the Emile Baudot Escarpment and its western extension reveal a decrease in surface relief and slope toward the southwest. The faults producing the escarpment no longer have a significant surface expression, although one can trace the Emile Baudot structure westward as an important subsurface fault (see a′, Figure 27I). Moreover, faults that are poorly defined topographically southeast of Ibiza-Formentera form pronounced escarpments south of Formentera (see b, Figure 27I). These observations demonstrate a transition from an abrupt type margin to an intermediate (or step) structural type over a relatively short distance (less than 80 km). In those sectors where two major fault trends merge or are superimposed, one encounters an intermediate structural margin (i.e., the margin north and east of the Mallorca-Menorca shelf and the slope south and southwest of Formentera). Of particular interest in this respect is the Balearic Rise, which is interpreted as a large margin block presently undergoing subsidence by vertical displacement. This foundering is the result of displacement along two major fault trends, NNW–SSE (Menorca Ridge) and NE–SW (Emile Baudot Escarpment); the former may represent displacement along an older (?Oligocene) fault trend (Mauffret et al., 1972, 1973). The geologically rapid lowering of the Rise block is reflected by the broken horst and graben configuration of this feature, where even upper Quaternary sequences have been displaced. The Menorca Valley extending onto the Balearic Rise has a structural origin that probably postdates the Miocene, and its incision into Pliocene sediments suggests that it may be as young as Pleistocene. Thus both the canyon configuration and the particular tectonic style of the slope into which it is cut reflect this geologically recent foundering of the Balearic Rise, whose origin is closely related to the subsidence of the Algéro-Balearic Basin.

Regional Continuity of Neogene Sequences

A synthesis of the seismic surveys of the Catalonian, Betic, and Bealearic margins reveals some rather significant points common to the three areas, particularly with regard to the nature and distribution of the uppermost Miocene to Recent sediment sequences. Our observations of the underlying series, including the upper Miocene salt layer (transparent "couche fluante"), N Reflector, and acoustic basement, also supplement the data collected by geophysicists using deeper penetration systems in the western Mediterranean Basin [cf., Mauffret (1969), Alla (1970), Montadert et al (1970), Mauffret et al. (1972, 1973), Alla et al. (1972), Ryan et al. (1973b), and others].

The dense subbottom profile coverage provides good definition of the M reflectors and their regional extent. This is of considerable importance inasmuch as this stratigraphic sequence clearly is one of the keys to understanding the recent evolution of the margins and contiguous western Mediterranean Basin. This acoustically well-defined unit and the underlying upper Miocene salt can be traced across much of the Balearic Basin plain (Hsü, Cita and Ryan, 1973, fig. 3; Biju-Duval, 1974). The salt layer generally pinches out near the base of the margins, although it does extend marginward somewhat in areas such as the Gulf of Lion and the eastern part of the Valencia Trough (Mauffret et al., 1973, fig. 1), the Alboran Sea (Auzende et al., 1975), the Sardinian margin (Auzende et al., 1972a, 1974) and the Ligurian margin (Rehault et al., 1974). The data we present here show that the salt does in fact extend from the Balearic Basin plain to the base of the slope and occurs on some sectors of the Balearic Rise; the bundle of M reflectors, on the other hand, has a broader distribution and can be traced in all sectors from the basin plain well upslope to depths as shallow as 450 m. For instance, this unit is present almost everywhere on the Balearic Platform and southeastern Spanish margin. Furthermore, the M reflectors probably are continuous between the Catalonian margin and the Balearic region some 260 km to the south (cf., profiles extending across the Valencia Trough illustrated in Leenhardt et al., 1970, and in Mauffret and Sancho, 1970).

The M reflectors are traced with some reliability to shallower depths in the eastern Betic-Balearic region than in the Catalonian margin. This unit (or equivalent sequence), however, actually may be present at shallower depths on the Catalonian upper slope and shelf, although in different form than that observed on profiles at the base of the Catalonian slope. In this respect it is noteworthy that the M reflectors as such are not recorded in the Gulf of Lion region northeast of our study area; here they appear replaced by an unconformable surface interpreted as a Pontian ($\cong$ Messinian) erosional horizon by Bourcart (1963) and Glangeaud et al. (1966). Some authors (Burollet and Byramjee, 1974) have recently questioned the age of this unconformity and propose that it is not equivalent in age to the M reflectors but actually is older, i.e., upper Miocene, but of presalt age; others attribute to it a post-Messinian (lower Pliocene) age (Auzende et al., 1974).

In some areas there is evidence for the presence of Messinian sediments of this age at shallow depths. For example, on the islands of Mallorca and Menorca, Bizon and others (1973) have dated as Messinian calcarenites containing faunas indicative of open marine conditions (these same units, however, are dated as Tortonian and pre-Messinian by W. B. F. Ryan, pers. comm.). Thick evaporite sequences, possibly of equivalent age, are cited in the Almeria area of the eastern Betic range (Auzende et al., 1971, 1972b). Elsewhere, cores on the Provençal slope off southeastern France have recovered Messinian marine microfaunas at depths of 1750 m (Glaçon and Rehault, 1973). Thus in some sectors of our study area there is probable continuity of the M reflectors between the basin plain and shallow environments, while in other regions erosion of the Messinian unit has prevailed. Additional coring and drilling programs on the slope and outer margin sectors are needed to resolve this problem of lateral continuity of the M reflectors.

The seismic character of the Pliocene and Quaternary series is similar in the different areas examined. An upward transition from the lower transparent layer (Pliocene) to an upper acoustically stratified (Quaternary) unit is noted both on slopes and in the basin. The acoustically transparent Pliocene unit lying above the bundle of M reflectors can be traced upslope and onto the shelf, where it displays a stratified appearance. Some geophysicists attribute the transparent character of the sediment above the M reflectors to a purely acoustic phenomenon. The cores retrieved at the *Glomar Challenger* JOIDES leg 13, drill site 124 do, in fact, reveal relatively similar textural sequences (sand and mud) in both the transparent and reflector-rich horizons (Ryan et al., 1973a). However, other sediment properties (strength, water content, etc.) which might account for these acoustic variations cannot be ruled out.

The Pliocene-Quaternary boundary cannot be clearly defined in the basin plain and lower slope inasmuch as (1) the passage between the two units is gradual and (2) there is apparent conformity between them. Furthermore, as stated above, JOIDES drilling has shown that the lithology is not as markedly different as would be suggested by the differences recorded on seismic profiles. On the shelf, however, the distribution between the two units is marked by an unconformable surface (see Reflector G, Figures 7, 9).

The thickness of these Pliocene and Quaternary units is generally greater in the basin plain than on the slope and shelf. The lateral variations measured on the shelf and slope can be explained in terms of sediment input (i.e., proximity to major rivers and importance of fluvial supply), and of relative importance of structural mobility and vertical displacement of the platform receiving sediments. For instance, thick Pliocene-Quaternary units tend to occur in zones offset by active faults such as on the Balearic Rise (Figure 29) and on those sectors of shelves that subside rapidly. Examples of subsiding surfaces which act as efficient sediment traps include the Ampurdan margin (Figure 3), the eastern Betic margin near Cape San Antonio (Figure 24), and the large depression between Ibiza and Mallorca on the Balearic Platform (Figure 25). On those margins that display greater subsidence rates there has been relatively little modification of the shelf sediments by the repeated Pleistocene regressions and transgressions. This lack of modification is ascribed to the maintenance of such platforms below sea level even during eustatic low stands (Figure 13).

Structural Configuration of Margins in Study Area

Previous geophysical investigations, using deep penetration (particularly Flexotir and Flexichoc) systems, have shown that the margins of the western Mediterranean are not uniform in character. Two contrasting margin types have been defined (cf., Mauffret et al., 1973, fig. 17): (1) an abrupt structural margin where the continental slope is steep and localized within a very restricted area and where strata of the deep basin plain pinch out against a rise of the basement; the margin off the Provence region of France is one example; (2) a wide intermediate margin zone characterized by a shallower depth than the basin plain, a sedimentary basement of continental origin, discontinuous infrasalt strata on an irregular basement surface, absence of salt, and extensive erosion at the base of the Pliocene-Quaternary sequence; the margins north of the Balearic islands and north of Corsica are cited as type examples.

Our investigation confirms the presence of such tectonically controlled margins but, on the basis of higher resolution subbottom surveys, we find that the structural configuration of the western Mediterranean margins is more complex than envisioned above. A detailed evaluation of the post-salt layers (uppermost Miocene M reflectors and overlying Pliocene and Quaternary series) reveals three types of margin: progressive, intermediate (or steplike), and abrupt.

The first is characterized by a smooth, gently dipping, convex-up physiography of the sea floor, reflecting the regular lateral continuity of the Pliocene and Quaternary sediments and M reflectors. This latter unit is slightly offset by faults that are attenuated in the Pliocene series above it. Growth faults and slumping have modified the upper Pliocene and Quaternary sequences. Most of the Catalonian margin is of this type, as are the eastern Betic regions north and east of Cape San Antonio and the margin north of Ibiza.

The intermediate type presents a marked steplike physiography between the outer shelf and the base of the slope. The relief of each of the steps or escarpments may be as high as 300 to 400 m or more, and these reflect a series of important vertical offsets of the Pliocene-Quaternary series, M reflectors, and underlying series, all of which are discontinuous between the shelf edge and the base of the slope. The downthrown blocks are frequently tilted. This structural type defines the margins southeast of Cape San Antonio, north and northeast of the Mallorca-Menorca shelf, southeast and south of the Menorca shelf (including the Balearic Rise), and southwest of the Ibiza-Formentera shelf.

The third, or abrupt, type is the steepest and presents the greatest relief within a restricted zone; it defines the sharpest and most distinct boundary between the shelf platform sequences and those of the basin plain. The near-horizontal basin plain strata abut sharply against the base of the steep escarpment and the M reflectors cannot be traced upslope; the Pliocene-Quaternary sequences are reduced or absent. This type of margin defines three major sectors in the study areas: the Menorca, Emile Baudot, and Mazzaron escarpments.

Furthermore, our observations show the interrelation of these three types of structural margins. We have recorded the transition from abrupt to intermediate types in the region extending south of Mallorca to south of Formentera (Figure 27). The investigation of margins of the eastern Betic-Balearic Block reveals the lateral variation from progressive to intermediate types (in a northeastern direction between the Cape San Antonio-Ibiza-Mallorca margins north of the Balearic Platform) and a succession of intermediate to abrupt margins in the regions east and south of Menorca and extending toward the Cape Palos-Vera margin.

The canyons detailed in the study area are present on all three types of margins but are best developed on the progressive and intermediate types. On abrupt margins canyons are "perched," due to faulting subsequent to their formation. An example is the Cabrera Canyon, draining the Mallorca-Formentera basin on the Balearic Platform, which has a steep gradient on the Emile Baudot Escarpment. All canyons examined in detail reveal complex tectonic as well as sedimentary origins, i.e., they follow fault trends, and their subsequent development is largely structurally controlled, although canyon cutting and migration were modified to some extent by the Quaternary eustatic events that affected the shallow platforms and influenced sediment transport across the margins toward the basin plain.

Age of Margin Formation

The present configuration of the Mediterranean Basin has been attributed to the superposition of Mesozoic (Hsü, 1971), and Tertiary and post-Miocene structural events (Auzende et al., 1973). Our data in the three study areas provide further insight on the significance of geologically recent tectonic phases. Particularly significant in this respect is the regional configuration of the Messinian and younger series and the structural style of the margins bounding the deep Balearic Basin.

Compelling evidence for the recent origin of these margins is provided by the following observations:

1. The M reflectors and their lateral equivalents (including erosional surfaces), dated as uppermost Miocene, have a wide-ranging distribution and occur at highly variable depths in different physiographic and structural provinces. These series have been mapped at depths of 2220 m at the base of the Catalonian, Gulf of Lion, and other margins and can be traced upslope from the basin plain to the shallow margins (i.e., to depths of 450 m on the Balearic Platform for example) by means of seismic records and cores (Glaçon and Rehault, 1973). In addition, marine Messinian sediments have recently been recorded on Mallorca and Menorca, and evaporites occur on land in adjoining areas (Almeria basin, Murcia, Vera, Sorbas, etc. in the eastern Betics).

2. The Pliocene sequences also present an irregular and obviously displaced configuration on most margins. One example is the lower Pliocene sequence containing shallow marine microfaunas recovered at depths of 2000 m (Bellaiche, 1972; Bellaiche et al., 1974).

3. Seismic records in all areas show that the M and above units have been subjected to post-depositional vertical displacement of large amplitudes which occurred during the Pliocene and the Quaternary. Our seismic evidence enables the M reflectors to be traced from broken block to broken block and across vertical offsets between the shelf and basin plain. The M unit and lateral equivalents, when placed in their original configuration, outline a late Miocene bathymetry unlike that suggested by Hsü (1972), Hsü and Ryan (1972), Benson (1972), Ryan et al. (1973b), and others.

4. The formation of submarine canyons in the three areas provides additional support for the recent date of the major subsidence and locally accelerated foundering. The age of canyon cutting is variable along different margin sectors and also within the same valley. Canyons in areas that were structural highs in pre-Pliocene time were initially cut in the upper Miocene; evidence of this early erosional phase is recorded only on the continental shelf and upper slope. In contrast, the Pliocene-Quaternary phases of canyon cutting are well developed between the upper continental shelf and the base of slope. Progressive margins do not provide evidence of pre-Pliocene canyon incision; the first major phase of canyon incision is dated as Pliocene.

5. The presence of Pliocene and Quaternary volcanism in Catalonia and on the Balearic Rise(?), including domes which have penetrated thick sequences of the surficial sedimentary cover, may be related to the post-Miocene tectonics.

6. Further evidence of the youthful origin of the western Basin margins is indicated by the fact that the margins are incompletely covered by Quaternary deposits, although high sedimentation rates prevail throughout this land-enclosed area (more than 20 cm per 1000 years are recorded,

Gennesseaux and Thommeret, 1969; Labeyrie et al., 1968; Leclaire, 1972a; Rupke and Stanley, 1974).

Although the structural, physiographic, and sedimentary configuration of margins is generally youthful, a point of clarification is needed. The style and scale of recent structural displacement have varied from region to region, and the age of the movements was not necessarily synchronous throughout a particular region. For instance, the escarpments are characterized by a marked reduction of sediment cover and are bounded sharply at their base by the horizontal basin plain Pliocene-Quaternary sequences; these escarpments probably record the most recent major vertical movements. The lack of slump wedges at the base of the escarpments provides further evidence of the youthful nature of these slopes, which apparently are so young as not to have accumulated a sedimentary cover of hemipelagic mud. A somewhat older date for the inception of vertical displacement can be deduced for some progressive and intermediate margins, where faults are attenuated in the thick upper Pliocene and Quaternary sequences. It can be demonstrated, however, that even those margins displaying a slightly disturbed and thick Quaternary cover have recently subsided; this is best exemplified by the evolution of the Ampurdan sector of the Catalonian margin. Subsidence of the Ampurdan sector accelerated during the upper Quaternary and is probably continuing at present, while shelves immediately to the north and south have been relatively more stable since the middle Quaternary (Got et al., 1975). Thus evidence of both gentle subsidence and foundering are recorded in the same region.

It should also be noted that in the case of an abrupt or intermediate margin, there appears to be a progressive displacement of structural activity in a landward direction. A case in point is the Emile Baudot Escarpment south of the Balearic Platform, where a series of faults parallel the margin. Our seismic profiles in this sector show that the faults are progressively younger in a direction away from the basin plain, i.e., up the slope (cf. Figure 27H,I).

In this same region we find evidence of the geologically recent vertical displacement of the Balearic Rise, a large continental block dislocated from the Balearic Platform. Its recent age is demonstrated by the close association with the Emile Baudot Escarpment, the completely broken (horst and graben) configuration affecting the Quaternary sedimentary cover, and the fault contact between the outer Rise and adjacent Balearic Basin.

Margin Formation and Western Mediterranean Basin Evolution

Although the previous sections have emphasized the importance of geologically recent movement, it is recognized that the configuration of the present western Mediterranean Basin is closely related to older major structural trends that developed during the Tertiary (cf. structural models of Auzende et al., 1973 and Mauffret et al., 1973). These trends are related to large-scale geodynamic events that included (1) the rotation of the Corsican-Sardinian block in the Oligocene (Stanley and Mutti, 1968; Gennesseaux et al., 1974) and/or Miocene (Alvarez, 1972; de Jong et al., 1972) (this resulted in the formation of NW–SE fractures and foundered zones in the Gulf of Lion region) and (2) the relative displacement of the African and European plates in the Miocene (Mauffret et al., 1972; Auzende et al., 1973) (the NE–SW tectonic trends, as defined by such features as the Emile Baudot Escarpment, are related to these movements). The distinct configuration of margins as we know them today and the marked relief between the shelves and the Balearic Basin plain are attributed to continued structural activity in the Pliocene and the Quaternary. Thus, a Mediterranean margin formation model should take into account the importance of these recent displacements, for it is during this most recent geological phase that some margins became accentuated either by renewed movement along older trends or by subsidence along new directions with respect to the earlier fractures. In both instances, the foundered zones, in general, are closely related to major structural trends on land, regardless of age. For instance, movement has occurred along reactivated Tertiary faults (NW–SE and NE–SW) as well as along older Hercynian and Pyrenean (NNW–SSE and E–W) axes in the region off Catalonia.

The abrupt type margin occurs in sectors where the Tertiary margins tend to coincide with major structural trends on land, as in the case of the Emile Baudot Escarpment, which follows the important NE–SW axis cited earlier, and of the Mazzaron Escarpment, which parallels the E–W trend of the eastern Betic chain. Studies of other parts of the western Mediterranean such as off Provence (Glangeaud et al., 1965; Mauffret et al., 1973; Rehault et al., 1974), off North Africa (Auzende and Pautot, 1970; Auzende et al., 1973), and off the Tunisian-Sardinian sector (Auzende et al., 1972a, 1974) also provide good examples of abrupt margins. In these regions, the predominant land and continental borderland structural trend is parallel, or subparallel, to the edge of the basin. The major phases of margin subsidence and accentuation of basin relief are attributed an upper Pliocene as well as a Quaternary age.

A significant aspect of progressive and intermediate margins is the postion of the zone undergoing subsidence, which in time has migrated progressively in a landward direction. These margin types (the two are ascribed to the intermediate margin defined by Mauffret et al., 1973) are distinguished on the basis of sea-floor morphology and of the nature of the displaced configuration of the Pliocene-Quaternary cover. These differences reflect distinct structural and depositional origins of the two types of margins. The intermediate type as defined in the present study tends to occur in sectors where two major tectonic trends converge, such as in the region south of the Mallorca-Menorca shelf and southwest of Ibiza and Formentera where NE–SW and NW–SE fractures intersect (Mauffret et al., 1972). Intermediate margins in the Alboran Sea are also related to these same tectonic directions (Olivet et al., 1972, 1973; Auzende et al., 1975). The margin southwest of Sardinia is also of the intermediate type and its origin may be related to the interplay of the NE–SW ("fracture nord-tunisienne") and the NW–SE ("zone de fracture Baléares-Sardaigne, fracture d'Iglesiente") trends defined by Auzende et al. (1974). In the Ligurian Sea farther to the north, an abrupt type margin parallels the dominant NE–SW trend along the French and Italian Riviera (Fierro et al., 1973; Rehault et al., 1974). Here, the presence of NW–SE trends is recorded by the orientation of the major submarine canyons. These NW–SE fracture patterns are more pronounced on the opposite margin of the Ligurian Sea in the northwest sector of Corsica; the merging of this and NE–SW fault trends are associated with an intermediate type margin (Mauffret et al., 1973, fig. 13; Rehault et al., 1974, fig. 6). The majority of margins defined as intermediate in type display a series of fractures along which vertical movement has occurred during much of the Pliocene and the Quaternary.

The progressive margins tend to occur seaward of basins on land filled with thick Tertiary sequences, and subsidence of continental blocks result from movement taking place along several structural lines which may vary in orientation. Seaward, the Upper Miocene salt pinches out at the base of the slope; unlike the abrupt and intermediate margins, the M reflectors, which cannot be traced from the basin upslope to the shelf, are replaced laterally by an erosional surface. These progressive margin characteristics observed in our study area also are noted in the Gulf of Lion (Burollet and Byramjee, 1974) and in the Valencia Trough (Mauffret and Sancho, 1970).

Evidence of accelerated subsidence during the Pliocene is recorded by the configuration of the unconsolidated sedimentary cover; displacement resulted in a lowering of the sectors of the margin progressively closer to the coast relative to the more seaward position of the older Tertiary margin, which presently lies at greater depths and is buried by a thick sediment cover (Mauffret et al., 1973). The foundering phase in the Pliocene was followed by somewhat more subdued subsidence during the Quaternary, which resulted in the flexing (convex-up folding) of Pliocene and Quaternary series and in the large-scale slumping of the sedimentary cover on the slopes. Post-Miocene displacement along preexisting structural trends has, in some sectors, resulted in subdivision of margins into individual blocks, some of which have moved more rapidly than others (an example of this is the Ampurdan sector of the Catalonian margin).

The origin of submarine canyons can be interpreted in light of these events. Some canyons were cut during the Miocene, and the initial valley systems are related to the fluvial patterns and to the structural configuration of the margins then in existence; incision of the present canyon network in the study area developed primarily during the Pliocene and Quaternary. The importance of the Pliocene erosion is particularly well displayed in the seismic records collected along the middle and lower sectors of submarine valleys. The effects of Quaternary eustatic oscillations, which also have played a significant role in canyon formation, are recorded primarily in the heads and upper reaches of canyons.

Pliocene-Quaternary foundering has been important as well as widespread, but the mechanisms involved were varied, and the resulting structural and depositional configuration is by no means uniform (Stanley, 1976). Thus, the geologically recent movements in the western Mediterranean, related to older Tertiary events, have fashioned a remarkably varied but predictable series of margin types.

Conclusions

Evaluation of the data presented here is, in our view, only compatible with the concept that the form and depth of the present-day western Mediterranean Basin result largely from accelerated foundering of this area since the upper Miocene (i.e., the "révolution pliocène" of Bourcart, 1960b). This in no way minimizes the importance of Oligocene-Miocene or earlier movement, including subsidence, although we find no evidence to support a hypothesis of a large, deep ($>$ 2500 m) Mediterranean basin at the end of Miocene time as proposed by Hsü (1972), Cita (1973), Hsü et al. (1973), and Ryan et al. (1973b), or of a very shallow ($<$ 500 m) basin as proposed by Nesteroff (1972, 1973). *On the contrary, the data evaluated by us suggest a western basin of bathyal depths, locally in excess of 1000 m.*

The post-upper Miocene displacement emphasized here does not imply only one major episode of foundering, nor does it imply a uniformity in style or scale. The movement along the margin of the basin has occurred primarily along major structural trends, some of which are old (pre-Miocene), and these earlier trends, subsequently reactivated during the past five million years, are responsible for the major outline of the modern western Mediterranean Basin. A particular structural style, as illustrated in the previous sections, is determined by the orientation of the principal fault trends relative to land and the degree of interplay along the major fractures. Almost certainly the vertical relief of the modern Mediterranean Basin resulted not from a single structural event but from alternating phases of gentle subsidence (associated with the progressive margin type) and rapid foundering (abrupt margin type) within any one regional sector.

The origin of the Mediterranean is frequently discussed in terms of the formation of the Balearic Basin plain. Records obtained with deep penetration seismic systems tend to reveal the plain as a broad, flat surface extent, suggesting a structurally quiescent environment, where deposition has prevailed and where the unconsolidated sediment cover masks the underlying structure of the Miocene and older units. However, the more detailed high-resolution surveys of the different margins show that basin plain formation did not take place in uniform fashion and is by no means complete. The example of the Balearic Rise, the large subsiding continental block detached from the southern part of the Balearic Platform, is significant in this respect.

It is probable that a similar mode of block foundering has occurred along other sectors of the basin and that older blocks of this type are now buried under the thick wedges of turbidite and hemipelagic muds and sands provided by the Rhone, the Ebro, and by the myriad smaller fluvial systems bounding the basin, which presently continue to contribute a considerable volume of sediment (Stanley, 1976).

The large-scale block foundering of the Balearic Rise cited above, coupled with observations based on numerous deep penetration seismic profiles obtained across the Balearic Basin, indicate that the sub-Pliocene sea floor of the plain collapsed and subsided considerably during the Pliocene and Quaternary. The displacement of the M reflectors observed on the margin transects indicates a lowering by perhaps as much as 1500 to 2000 m of the large blocks presently underlying the basin plain. This amount of subsidence of the basin plain to present depths (in excess of 2700 m) is compatible with the findings of workers in various sectors of the western Mediterranean (Heezen et al., 1971; Finetti and Morelli, 1973; Storetvedt, 1973) and of the most recent JOIDES deep-sea drilling leg 42A, which suggest that basins possibly as shallow as 500 m, but more likely between 500 and 2500 m, existed before the deposition of the Messinian evaporites (Hsü, Montadert et al., 1975). An average rate of subsidence of less than 40 cm per 1000 years is suggested if the larger value of 2000 m of vertical offset is selected, and if lowering of this amount is assumed to have occurred since the beginning of the Pliocene. Larger rates of displacement are recorded in the eastern Mediterranean and other tectonically active ocean basins, as well as in many sectors of the contiguous land bounding the western Mediterranean Basin.

We should be able to see some record of such marked subsidence of the basin in geologically recent time and in this respect the disposition of marginal faults is significant. As emphasized earlier, some faults paralleling the basin margin appear younger in a landward direction, and this arrangement of fractures is similar to the fault patterns in a rift zone. Our observations tend to support the hypothesis of large-scale regional rifting, which has been suggested for the origin of the modern western Mediterranean (Bauer, 1974).

While we do not feel able to comment on the possible mechanisms (oceanization, sea floor spreading, or other) that produced large-scale foundering, we recognize that further detailing of continental margins is essential for interpreting the geologically recent evolution of the western Mediterranean Basin.

Summary

1. Relatively high-resolution, shallow penetration seismic surveys of the Catalonian, eastern Betic, and Balearic margins in the western Mediterranean detail the regional distribution and configuration of the upper Miocene units and the overlying, unconsolidated sedimentary sequences of Pliocene and Quaternary age. These sedimentary series, including the M reflectors (dated as Messinian) and lateral equivalents, have been displaced by post-Miocene vertical movements in all sectors examined.

2. Although large amounts of sediment, largely of fluvial origin, have been introduced in this quasienclosed sea during the Neogene and Quaternary, these deposits have not masked the marked fault-controlled configuration of the basin margin. Vertical displacement of Quaternary to Recent deposits reflects the geologically recent nature of margin subsidence.

3. The upper Miocene to Recent movements have not been synchronous, and significant differences both in terms of structural style and scale are recorded along the edges of the basin. Three essentially different types of margin configuration are defined: abrupt, intermediate (or steplike), and progressive. There is a direct relation between margin configuration and tectonic trends on land.

4. The present margin configuration results (1) from pre-Messinian subsidence along preexisting (Oligocene or earlier) structural trends and (2) from geologically recent (post-Miocene) movement along new as well as older structures.

5. Abrupt margins are characterized by continued vertical displacement within a relatively restricted structural zone; this type prevails in areas where the margin parallels the major tectonic trend on land (Emile Baudot and Mazzaron Escarpments are examples of this margin type).

6. Intermediate and progressive margins reflect a displacement of the margin in time and space. The former type is identified by subsidence in which the sedimentary cover has been offset in a steplike manner. The movements, which occurred throughout much of the Pliocene and Quaternary, are found in areas where two major structural trends merge (the margins southeast of Cape San Antonio and the Balearic Rise are examples; NE–SW and NW–SE fractures predominate).

7. Progressive margins are related to phases of foundering during the Pliocene, followed by more gentle subsidence occurring from the upper Pliocene to the present. This margin type, which displays a flexing of the Pliocene and Quaternary cover, occurs seaward of Tertiary basins where older (Hercynian to Miocene) tectonic trends have been reactivated (the Catalonian margin and the sector northeast of Cape San Antonio are examples).

8. It appears that a major phase of submarine canyon cutting on the different margins examined occurred in post-Miocene time. Canyon origin and configuration are closely related to the structural, paleogeographic, and sedimentary events that affected the western Mediterranean Basin during the Pliocene and Quaternary.

9. The Balearic Rise south of the Balearic Platform is a large, detached continental block which foundered in the post-Miocene and has not yet completely merged with the Balearic Basin plain. The large continental blocks beyond the base of slopes that are presently buried beneath thick sediment

sequences of the basin plain may have had an origin similar to that of the Balearic Rise.

10. Geologically recent foundering of large continental segments is directly related to the development of the western Mediterranean Basin, and there appears to be a similarity between the formation of the basin margins and the structural evolution of rift zones.

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