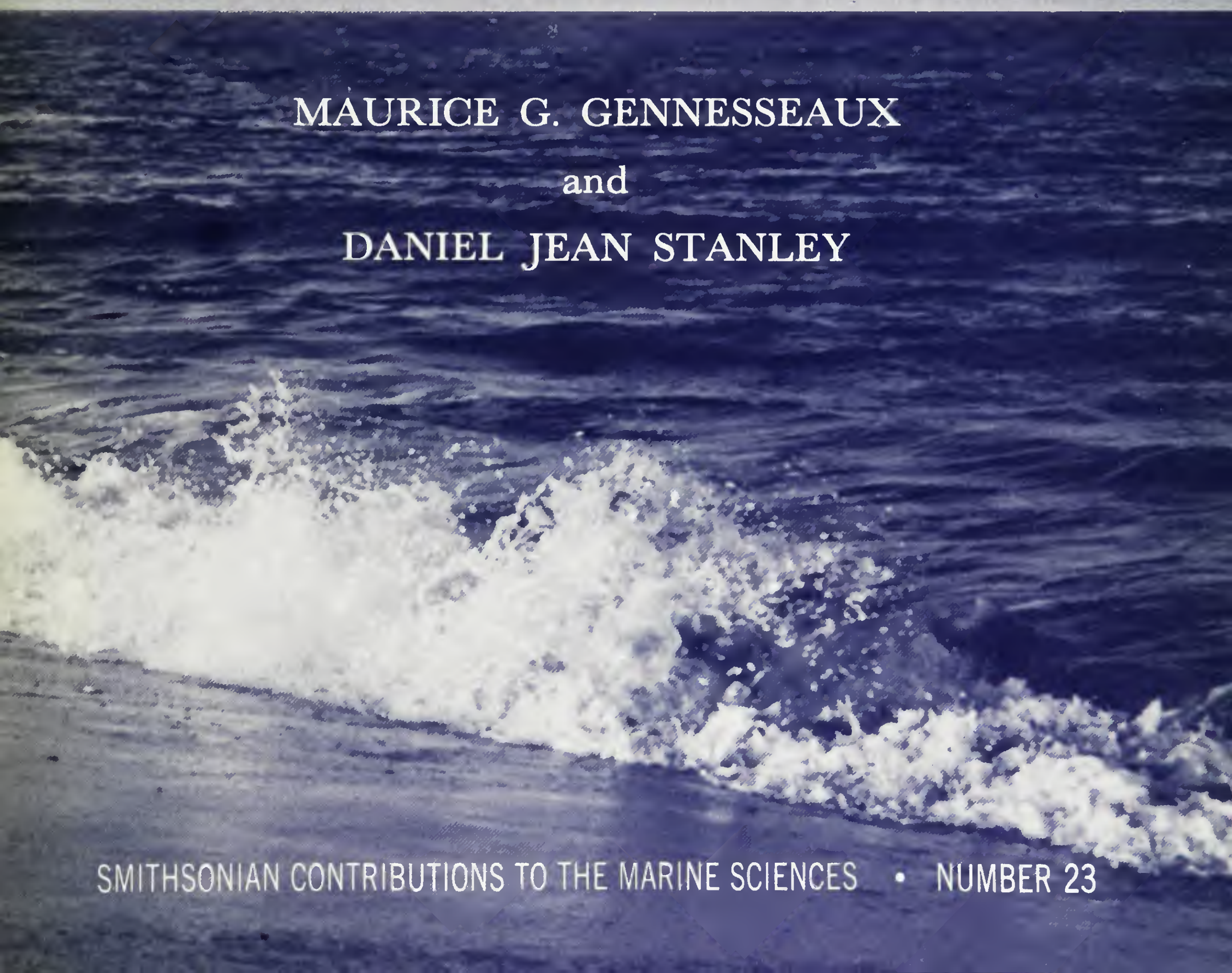
Neogene to Recent Displacement and Contact of Sardinian and Tunisian Margins, Central Mediterranean



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and

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SMITHSONIAN CONTRIBUTIONS TO THE MARINE SCIENCES • NUMBER 23

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Neogene to Recent Displacement and Contact of Sardinian and Tunisian Margins, Central Mediterranean

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ABSTRACT

Gennesseaux, Maurice G., and Daniel Jean Stanley. Neogene to Recent Displacement and Contact of Sardinian and Tunisian Margins, Central Mediterranean. *Smithsonian Contributions to the Marine Sciences*, number 23, 21 pages, 9 figures, 1983.—The seafloor between Sardinia, Tunisia, and Sicily occupies a key sector essential for understanding the geological evolution of the central Mediterranean. Although plate motion is generally considered as an explanation, this structurally complex region remains poorly defined. To interpret better the Neogene evolution, we prepared a detailed bathymetric chart and a map showing structural provinces and post-Miocene sediment patterns, which are constructed on the basis of seismic data (primarily a dense network of 30 KJ Sparker and 3.5 kHz profiles). The data suggest that the present-day configuration of the Tunisian and Sardinian margins results, in large part, from the contact of the southern part of the Corsican-Sardinian microplate with North Africa.

Several dominant structural-stratigraphic trends are recognized in this study area: (1) NNW-SSE and NW-SE trends in the northwestern part of the study area are most likely related to the formation of the Algéro-Balearic Basin since the late Oligocene. (2) Pronounced NNE-SSE trending structural axes (largely normal faults) are related to the near-parallel (N-S) tilted fault blocks in the Tyrrhenian Sea east of Sardinia. One of these tectonic structures on the margin east of Sardinia may possibly extend southward (190°–200°) onto, and across, the Tunisian margin. The largest, most obvious physiographic features south of Sardinia, including seamounts, ridges, and canyons, are associated with these trends. These features, for the most part of middle to upper Miocene age, are believed closely related to the opening and subsidence of the Tyrrhenian Sea. (3) Morphological, structural, and stratigraphic-sedimentary trends, particularly off Tunisia, suggest Pliocene-Quaternary compression (E-W trending tectonics and depositional axes), resulting from the northward movement of Africa. (4) Important NW-SE structural-depositional trends (many extensional, some strike-slip) of Miocene to Quaternary age dominate the Strait of Sicily area east of Tunisia and south of Sicily. These may be related to displacement along the Calabrian-Sicilian Arc and to a collisional regime between the arc, the Corsican-Sardinian block, and African margin.

We believe that the present configuration of the two margins resulted from plate contact and welding during several major Miocene events and also from subsidence, first, of the Algéro-Balearic Basin and, then, of the Tyrrhenian Sea. In theory, the Tunisian margin and adjacent land have been subjected to compression as a result of seafloor spreading and collision. The physiographic trends and subsurface structural-stratigraphic configuration we map, however, reveal a predominance of Neogene to Recent structures, primarily of extensional origin.

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Contents

Neogene to Recent Displacement and Contact of Sardinian and Tunisian Margins, Central Mediterranean

Maurice G. Gennesseaux and Daniel Jean Stanley

Introduction

The seafloor between Sardinia, Tunisia, and Sicily (Figure 1, inset) is physiographically one of the most complex regions in the central Mediterranean. Most regional syntheses indicate that this sector occupies an area of convergence between Europe, including the Corsican-Sardinian microplate, and the northern part of the African plate that includes Tunisia, the Pelagian Sea to the east, and southern Sicily. It should be pointed out, however, that the area between Tunisia and Sardinia remains poorly defined geologically. On the basis of earlier work on land and at sea, we would expect this Sardinian-Tunisian region to record the effects of the welding of two or more plate boundaries and of their subsequent tectonic deformation in the Neogene and Quaternary. In theory, it would be expected that structural trends and sedimentary patterns, as well as physiography, should display evidence of such plate contact and geologically recent (some Oligocene, and primarily Miocene to Quaternary) displacement (Stanley, 1977).

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In this study, the configuration of the seafloor, major structural features, and Miocene to Recent sediment series are detailed in the area between 8°30′E and 11°15′E longitude and 37°15′N and 39°00′N latitude. This is based on a close-grid 3.5 kHz and 30,000 Joules Sparker survey by the USNS *Kane* in September 1975. About 2000 km of continuous seismic profiles were collected along 17 parallel transects, for the most part oriented NW-SE, between northern Tunisia and southern Sardinia (Figure 1). Navigational control was accomplished by satellite positioning, Loran C, and radar in nearshore sectors; transects were made at a ship speed of about 10 knots. The study also incorporates earlier soundings and nautical charts, and available published (Auzende, 1969, 1971) and several unpublished seismic transects. A revised detailed chart of this region, based on these data, is presented.

The purpose of this study is to focus on and interpret the major physiographic, structural, and depositional traits mapped on the seafloor and in the subbottom. Moreover, this information may help unravel the series of events that led, in the Neogene, to the formation of the Algéro-Balearic Basin to the west, the Tyrrhenian Sea immediately to the northeast, and the Strait of Sicily-Pelagian Sea to the east and southeast of the study area.

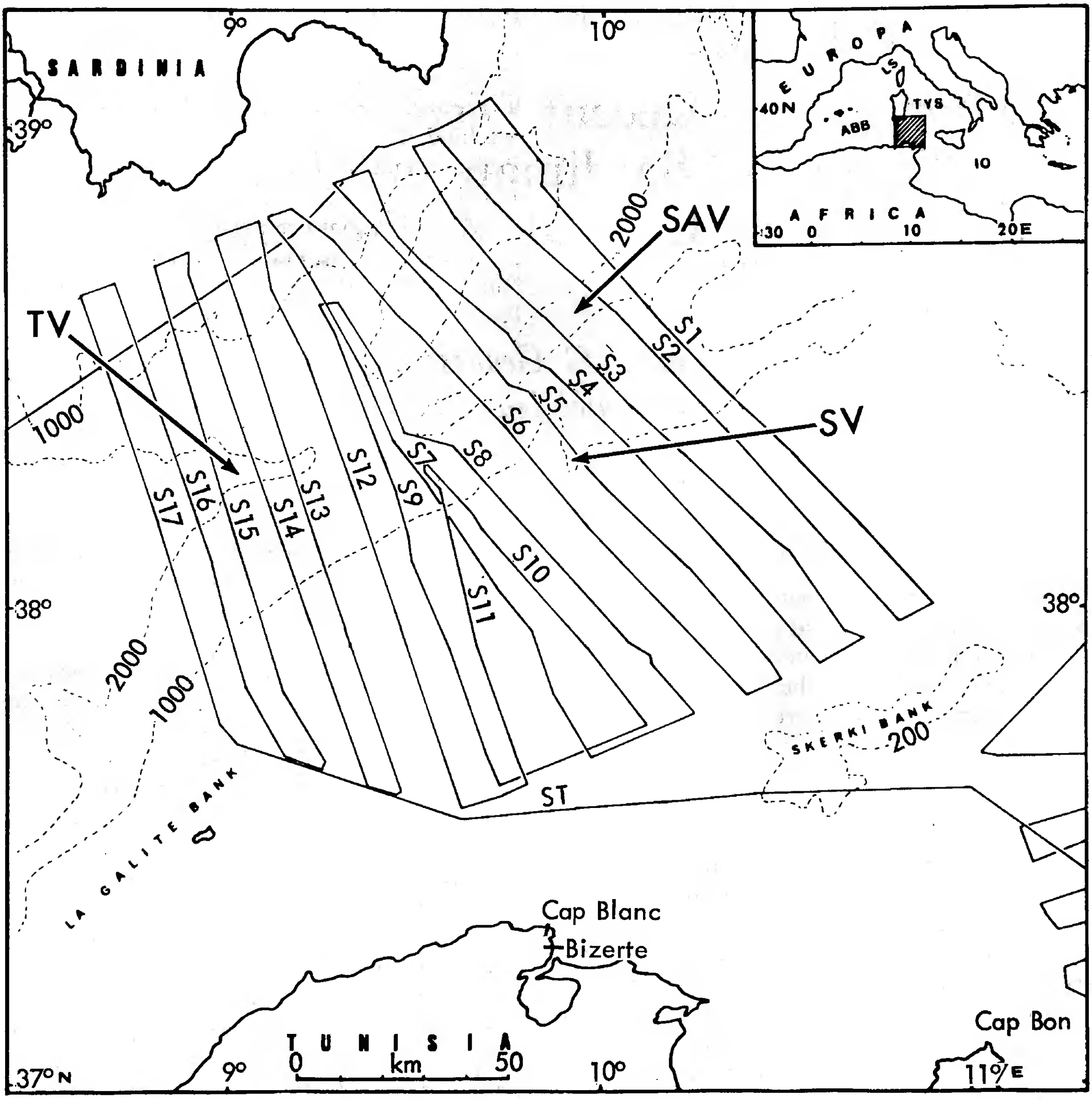


FIGURE 1.—Chart showing location of 3.5 kHZ and 30 KJ Sparker transects (S1 to S17) in the region between Sardinia, Tunisia, and Sicily (inset) obtained on the September 1975 cruise of the USNS *Kane.* Selected portions of Sparker transects are shown in Figures 5 and 6. Teulada Valley (TV), Sardinia Valley (SAV), and Sentinelle Valley (SV) are shown as reference points. In inset: ABB = Algéro-Balearic Basin; LS = Ligurian Sea; TYS = Tyrrhenian Sea; IO = Ionian Sea. Depth in meters.

ABBREVIATIONS.—The following abbreviations are used in the text and illustrations:

ABB	Algéro-Balearic Basin
BA	Balearic Islands
CA	Calabrian Arc
CC	Carbonara Canyon
CG	Campidano Graben
CO	Corsica
CV	Carbonara Valley
EB	Estafette Bank
GB	Galite Bank and Island
GC	Gulf of Cagliari
GK	Grande Kabylie
IO	Ionian Sea
IS	Ichnusa Seamount
LM	Lower Miocene
LS	Ligurian Sea
M	Miocene
MS	Messinian
N	Sedimentary nappe series
P	Pliocene
PA	probable Paleozoic basement
PG	Pantelleria Graben
PK	Petite Kabylie
PQ	Pliocene-Quaternary sediment series
Q	Quaternary
RB	Reagui Bank
SA	Sardinia
SAB	Sardinia Basin
SAV	Sardinia Valley
SB	Sentinelle Bank
SI	Sicily
SKB	Skerki Bank
SS	Sardinia Shelf
SSL	Sardinian Slope
STS	Strait of Sicily
SV	Sentinelle Valley
TP	Tunisian Plateau
TR	probable salt diapir
TS	Tunisian Shelf
TSL	Tunisian Slope
TU	Tunisia
TV	Teulada Valley
TYS	Tyrrhenian Sea
UM	Upper Miocene
UO	Upper Oligocene

ACKNOWLEDGMENTS—We thank the U.S. Navy (NAVOCEANO) for generously providing USNS *Kane* September 1975 cruise seismic data, including 3.5 kHz and Sparker profiles; we also express our appreciation to the Compagnie Française des Pétroles and ETAP-Tunis for releasing selected seismic transects (including Figure 8, this study). Prof. C. Morelli made available bathymetric plotting-sheet notations. The manuscript was reviewed by A. Fabbri, I. Finetti, and other colleagues who provided useful critique. This study was funded by the Mediterranean Basin (MEDIBA) Project (Smithsonian Scholarly Studies grants 1233S201 and 305), and by the Groups d'Etude de la Marge Continentale, Université Pierre et Marie Curie, Paris, France. This is Contribution Number 194 of the French Centre National de la Recherche Scientifique, ERA 605.

Geological Background

The transformation from the Tethys Ocean to the much restricted Mediterranean Sea as we know it today has resulted primarily in response to the convergence of Africa and Europe. Interpretations of this geological transformation have been summarized in numerous studies. Biju-Duval et al. (1977), for example, have shown, by means of a sequence of time-lapse reconstructions, the initiation and evolution of basins underlain by oceanic crust (Algéro-Provençal Basin, Ligurian Sea, and Tyrrhenian Sea) and the marked changes with time in the configuration of the contiguous land mass. Creation of oceanic crust related to the displacement of microplates has occurred since the Oligocene (Le Pichon et al., 1971) and, in certain areas, such as the Tyrrhenian Sea and Strait of Sicily, structural activity (including crustal motion and volcanism) has continued to the present. Moreover, regional geological surveys indicate that our study area in the central Mediterranean has experienced major change since the Mesozoic.

The highly simplified structural map of the western and central Mediterranean (Figure 2), a summary of many investigations, shows the interrelationship among rift-opening of basins, formation of oceanic crust, and development of major subduction-collision zones. As noted on the chart, basins probably did not form contemporaneously. Rather, opening and deepening of the basins have occurred during several stages, largely after the Oligocene. The major initial rifting phases of the Liguro-Provençal sector may be of

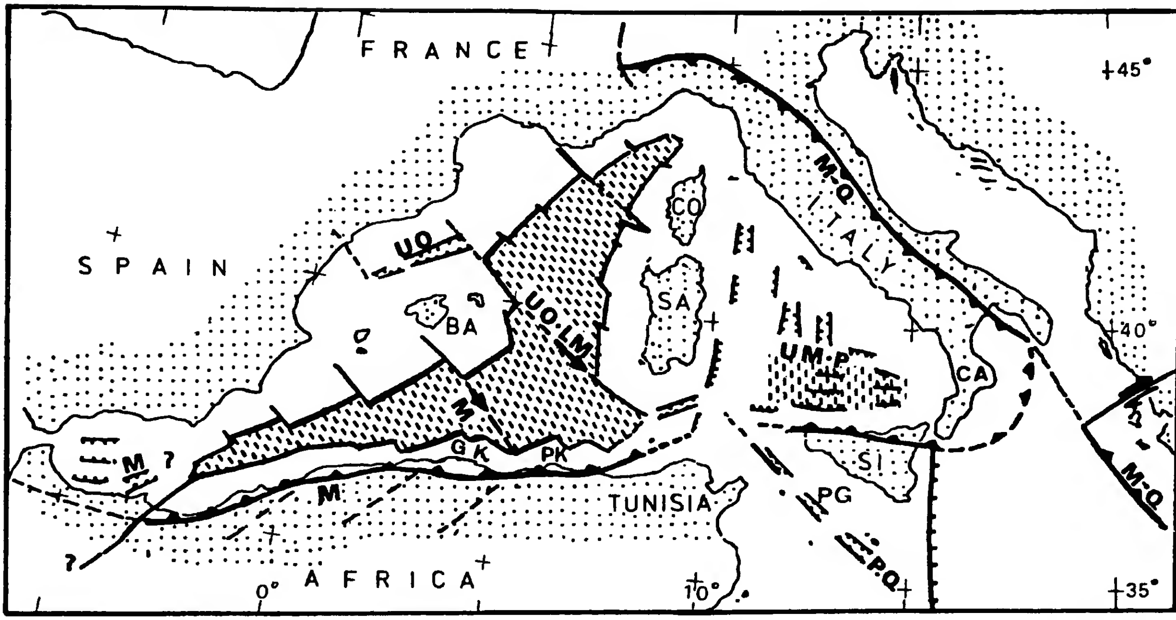


FIGURE 2.—Geological map, a synthesis from many published studies, showing in simplified fashion the evolution of the western and central Mediterranean since the Oligocene. BA = Balearic Islands; CA = Calabrian Arc; CO = Corsica; GK = Grande Kabylie (GK and PK probably once formed part of an island arc); LM = lower Miocene; M = Miocene; M-Q = Miocene to Quaternary; P = Pliocene; PG = Pantelleria Graben; PK = Petite Kabylie; Q = Quaternary; SA = Sardina; SI = Sicily; UM = upper Miocene; UO = upper Oligocene. Dashed-line pattern indicates area underlain by oceanic crust; lines with triangles indicate normal faults and axes of compression.

upper Oligocene to lower Miocene age (UO·LM) as indicated by Auzende et al. (1974) and Rehault (1981); this involved the counter-clockwise rotation of the Corsican-Sardinian block (for an updated summary, see Rehault, 1981). Rifting of the Algéro-Balearic Basin to the southwest is probably somewhat younger, i.e., the major rifting phase ended in the middle-upper Miocene (shown as M in Figure 2). The Tyrrhenian Sea is the youngest basin in the western Mediterranean, that is, upper Miocene to Pliocene (UM·P; cf. Malinverno et al., 1981); a major subsidence phase is documented during the Pliocene (cf. Selli and Fabbri, 1971). Attention has been called to the more recent development, largely by extension (Pliocene and Quaternary, P·Q), in the Strait of Sicily region (cf. Finetti and Morelli, 1972).

Generalized structural syntheses that more specifically discuss the study area between Sardinia and Tunisia are provided by Auzende et al. (1974), and Boccaletti and Manetti (1978). These studies, coupled with detailed mapping in northern Tunisia and its margin (Auzende, 1971; Caire, 1973; Rouvier, 1977), Sardinia and its margin (Cocozza et al., 1974; Fanucci et al., 1976), and Sicily and its margin (Wezel, 1974; Grandjacquet and Mascle, 1978) have revealed the close relationship between structural trends on land and those immediately offshore. Moreover, the complexity and diversity of structural trends in offshore sectors more distal from Tunisia, Sardinia, and Sicily land masses also have been shown. We show in Figure 2 that major structural features include N-S, NE-SW, and NW-SE trends, probably of different ages, and that these axes appear to converge in the study area.

To interpet these features better, the following three sections will focus on physiography, structural trends, and dominant stratigraphic-sedimentary patterns in this zone between the Tyrrhenian Sea, Algéro-Balearic Basin, and Strait of Sicily-Pelagian Sea.

Seafloor Configuration of Study Area

A revised and more detailed chart (Figure 3) has been compiled on the basis of 3.5 kHz profiles taken by the USNS *Kane* and older bathymetric data (C. Morelli, unpublished sounding data sheets, University of Trieste), the French research vessel *Jean Charcot* (cruises 1970–1972, 1978), Italian CNR *Bannock* (cruise 1975), data in Gennesseaux and Vanney (1979), and soundings on published French, Italian (Morelli, 1970), and U.S. (Carter et al., 1972) nautical charts of the Tunisian and Sardinian regions. The chart, prepared at a scale of 1:250,000, is contoured at 100 meter intervals (corrected depth values after Mathews, 1939). The major trends shown on our detailed chart also appear on the map recently published by the UNESCO Intergovernmental Oceanographic Commission (1981, sheets 2, 7, and 8).

A series of physiographic features and morphological provinces are recognized from south to north and these are identified on the simplified chart (Figure 4). Many of the geographic names adopted here are those shown on the chart published by Morelli et al. (1975, pl. 18).

1. The E–W trending Tunisian Shelf, north of Cap Blanc and off Bizerte, dips gently seaward for a distance of about 40 km from shore and to a depth of approximately 200 m (Figure 3).

2. The Tunisian Shelf is bordered seaward by a broad ENE–WSW borderland (to 100 km in width) that consists of a low relief surface ranging in depth from about 200 to 500 m. This province, termed Tunisian Plateau, comprises Galite Island and bank (GB), Skerki Bank (SKB), Sentinelle Bank (SB), and Reagui Bank (RB); the plateau is also cut by a large SSW to NNE trending submarine valley (herein named Sentinelle Valley, SV). This distinct valley is V-shaped and deeply incised (relief to as much as 600 m) on the outer plateau (Figure 5); it widens and becomes U-shaped northward, where its axis extends to depths in excess of 2500 m on the southwest Tyrrhenian Sea margin. Numerous small depressions of subrounded, elongate or irregular shape (from 1 to over 2 km in length, and with a relief of less than 100 m) are mapped on this plateau; these depressions (in black) and possibly related paleo-drainage systems are shown in Figure 4.

3. The Tunisian Slope (TSL) forms the northern limit of the Tunisian borderland. The slope (ranging from about 2° to 7°) dips northwestwardly, toward a large median valley (see 4 below) whose axis is deeper than 2000 m. The predominant strike of this slope is NE–SW. The slope is markedly offset at about 10°E longitude, i.e., where the Tunisian Slope is incised by the large Sentinelle Valley.

4. The most distinctive negative topographic relief feature in the study area is the deep, arcuate median valley that separates the Tunisian from the Sardinian physiographic provinces. Its flat bed is about 9 km wide at its narrowest and shallowest point (about 1950 m). This median valley is formed by two submarine canyons. The western canyon is called the Teulada Valley (TV); the northeastern one is the Sardinia Valley (SAV) (cf. Morelli et al., 1975). The Teulada Valley is generally V-shaped (Figure 6) and, from its shallowest point, trends westward toward the floor of the Algéro-Balearic Basin (2600 m) where it merges into a low, gentle deep-sea fan and the contiguous basin plain. From its shallowest point (at about 9°20′E longitude), the Sardinia Valley continues towards the NE and NNE (also to a depth of about 2500 m). On the lower Tyrrhenian margin, the valley merges on the rise without very pronounced fan development. The NE-trending Sardinia Valley branch is generally more U-shaped than the Teulada Valley. Moreover the axial trend of the former is highly irregular and displays several sharp bends, presumably the result of offset by recent faulting. The Sardinia Valley is separated from the Sentinelle Valley in the study area proper (Figure 4); to the northeast, however, the two valleys appear to merge

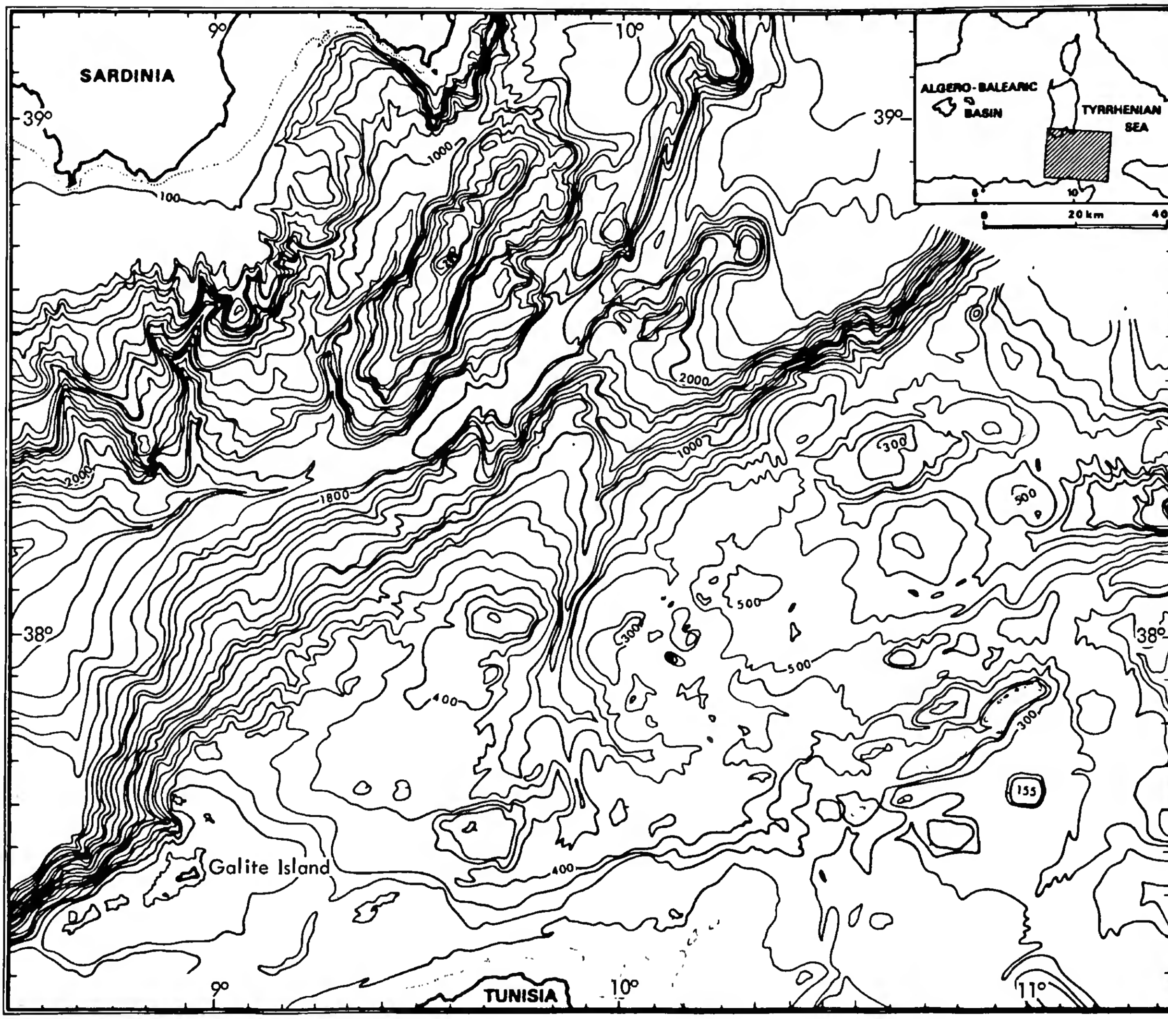


FIGURE 3.—Physiographic chart of study area, based on 3.5 kHZ data collected by the USNS *Kane* (see track lines S1 to S17 in Figure 1) and earlier soundings (p. 5), contoured at 100 m intervals. Specific morphological features and physiographic provinces are identified in Figure 4.

beyond the base of the slope in the SW Tyrrhenian Sea basin.

5. The Sardinia Slope (SSL) (2° to 4°) dips southward to the median valley described above. This province is about 50 km wide. The Ichnusa Seamount (IS), a large NE–SW trending high feature on the slope, is about 75 km long, 18 km wide, and has a relief of about 1800 m. The Sardinian Slope, in contrast to the Tunisian Slope, is highly dissected by numerous submarine valleys. West of 9°30′E longitude, these are oriented NNW–SSE. A very large valley, the Carbonara Canyon (CC), extends from the Gulf of Cagliari (GC) to the SE (to a depth of about 1000 m), then veers to the SW, paralleling (and bounded by) the Ichnusa Seamount, and then bends south where it merges with the Teulada Valley near its shallowest point, at about 2000 m.

6. The Sardinia Shelf (SS) is wide (about 25 km) south of Cape Teulada, but narrows mark-

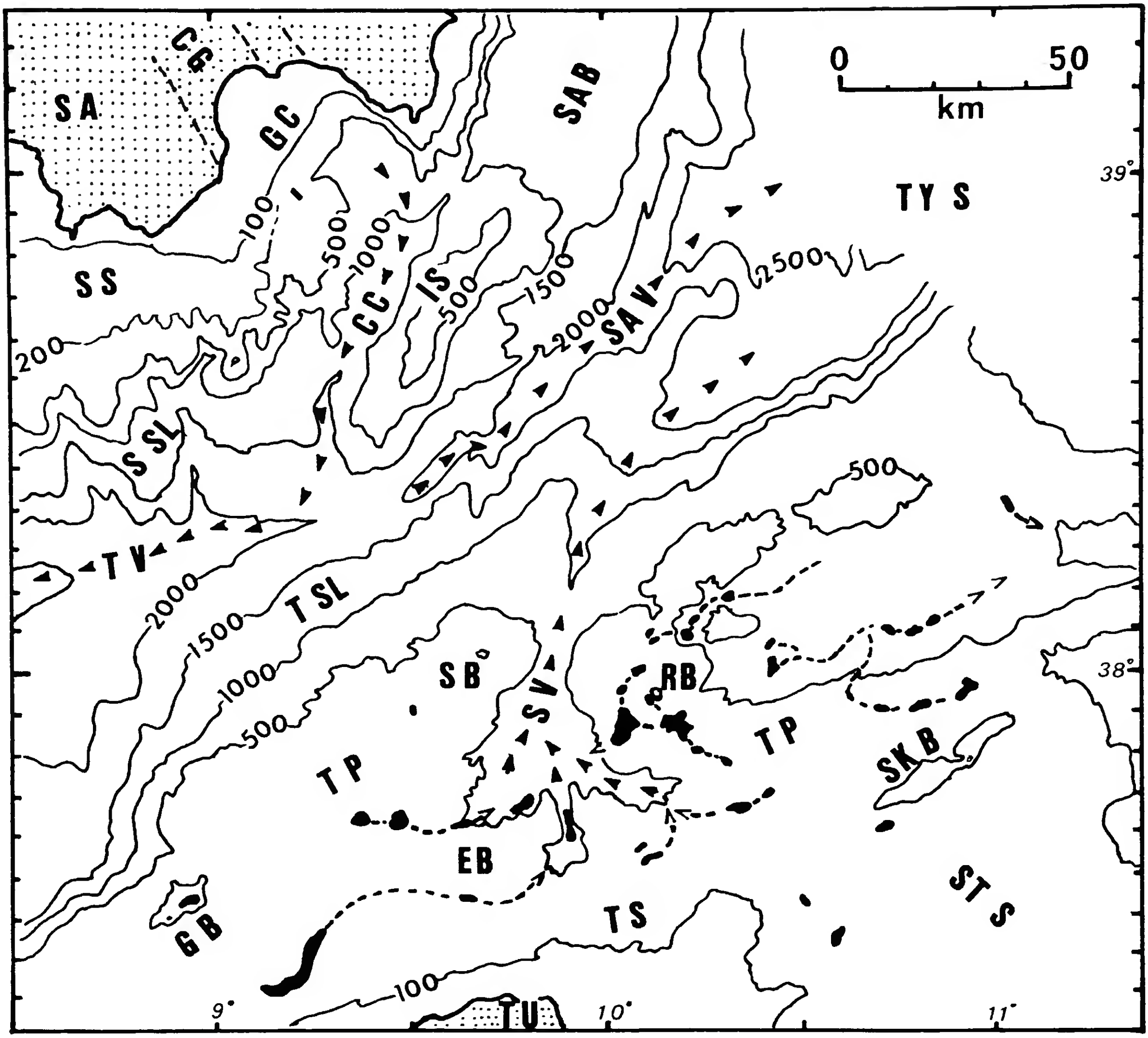


FIGURE 4.—Simplified chart (500 m intervals; modified from Figure 3) showing physiographic features discussed in text, including small depressions (in black), possible associated paleodrainage pattern (dashed lines and open arrows); and major valley axes (solid arrows). CC = Carbonara Canyon; CG = Campidano Graben; EB = Estafette Bank; GB = Galite Bank and Island; GC = Gulf of Cagliari; IS = Ichnusa Seamount; RB = Reagui Bank; SA = Sardinia; SAB = Sardinia Basin; SAV = Sardinia Valley; SB = Sentinelle Bank; SKB = Skerki Bank; SS = Sardinia Shelf; SSL = Sardinian Slope; STS = Strait of Sicily; SV = Sentinelle Valley; TP = Tunisian Plateau; TS = Tunisian Shelf; TSL = Tunisian Slope; TU = Tunisia; TV = Teulada Valley; TYS = Tyrrhenian Sea.

edly in the eastern Gulf of Cagliari, near Cape Carbonara. The sharp, angular (E → NE → SE → NNE) configuration of the shelf edge parallels the southeastern Sardinian coastline. The shape of the shelf is clearly related to the wide Campidano (Graben) Valley (GG) in southern Sardinia (shown on geological map in Cocozza et al., 1974), and also to the Ichnusa Seamount.

In summary, the new detailed chart highlights the physiographic complexity of both Tunisian and Sardinian margins that are in juxtaposition. The sharply defined (angular, youthful) nature of major submarine features is revealed by the contours, and many of these features are directly related with land forms on Sardinia and Tunisia. Moreover, seismic profiles reveal that the youthful appearance of the seafloor surface is a function of the plexus of geologically recent structures mapped in this region.

Structural Trends

The configuration of the region between Sardinia and Tunisia, as highlighted in the previous section, could suggest a zone of contact resulting from the collision of plate boundaries. Geophysical studies indicate the presence of continental crust in this region, which now separates the Algéro-Balearic Basin from the Tyrrhenian Sea (Figure 2); to date, there is no evidence indicating the presence of oceanic crust. Preliminary investigations also have attempted to reconstruct drift direction and define the boundary between microplates (cf. Auzende, 1971; Auzende et al. 1974). In these latter syntheses the predominant drift direction was shown to extend, in gently arcuate fashion, along a NE–SW (N40°E) trend for about 270–300 km between the eastern Algerian margin (near Cap Rose) and the SE part of the Sardinian margin (off Cape Carbonara). Subsequently, geophysical (gravimetric, magnetic) surveys (Morelli et al., 1975) have shown this NE–SW trend is not, as previously postulated, characterized by an alignment of extrusive volcanic bodies. Moreover, dredging indicates that the Ichnusa Seamount comprises Paleozoic lithologies comparable to the Sardinian basement (cf. Colantoni et al., 1981) locally covered by evaporitic limestone (Wezel et al., 1977), and is not a high relief feature formed by Tertiary extrusive volcanism (Morelli, 1970).

Our data tend to support these latter conclusions and brings to light a complex network of diverse tectonic trends, some superposed, which have evolved in space and time. Selected profiles revealing faults are shown in Figures 5 to 8. In Figure 9 we identify and interpret the following structures, proceeding from older to younger trends.

1. Probably the oldest structure constitutes a series of N–S trends (some NNW–SSE) on the slope south of Sardinia and extends onto the Sardinia Shelf (observed in air-gun profiles collected on the Bannock 1974 cruise (I. Finetti and C. Morelli, pers. comm., 1981) and onto Sardinia itself (Cherchi and Montadert, 1982). These structures, resulting from the rifting phase, could be as old as Upper Oligocene. The local NNW–SSE and NW–SE orientation of canyon axes may possibly be the result of subsequent displacement of the margin and associated sedimentary processes. To the east, the much larger reentry forming the Gulf of Cagliari is directly associated with the NW–SE Campidano Graben, the dominant structure in southern Sardinia. The Gulf of Cagliari and Campidano structure are superposed on faults that are originally of Oligocene age, but along which vertical displacement has continued, particularly during the Pliocene and Quaternary (Coccoza and Jacobacci, 1975; Fanucci et al., 1976). This land-to-offshore structural complex is associated with the major initial rifting phase that preceded and was associated with the opening of the Ligurian-Provençal Basin in the northern and eastern parts of the western Mediterranean. Studies in Sardinia (Cocozza et al., 1974) and of our offshore seismic transects reveal no clear evidence after this rifting phase of compressional movement (in the Miocene and Recent) related to the counter-clockwise rotation of the Corsican-Sardinian Block and its supposed contact with the African plate (Boccaletti and Guazzone, 1974a). We recall, however, that indication of compressive motion is difficult at best to demonstrate, even on multichannel records, and thus we cannot exclude some thrust motion.

2. The broad, NE–SW trending Tunisian Plateau comprises a series of parallel and subparallel structural axes, possibly including reversed faults, which likely are an extension of similarly oriented NE–SW structures in northern Tunisia and Algeria. A large portion of the Plateau comprises a

series of dislocated, imbricated series (Auzende, 1971): on land these are covered by the Numidian Nappe that includes sediments of Oligocene to lower Miocene age (Rouvier, 1977). This interpretation is based largely on surface morphology and shallow penetration seismic records. Clearly, better quality seismic coverage is required to accurately define deep structures and identify the presence of nappes. Well-cemented series, particularly sandstones and limestones, form positive relief features prominent on the Plateau (Sentinelle, Skerki, and other banks; cf. Dangeard, 1928). This region does not comprise extrusive volcanics or igneous basement series, except those mapped on Galite Island. The Tunisian Slope forming the external limit of this geological region is oriented N50°E, and is markedly offset at about 9°E and also at 10°E longitude. This NE–SW trending tectonic province, forming a large part of the Tunisian Plateau, is believed to have developed at the end of the major compressional phase when the northern African plate came into contact with a European island arc. This island arc, separated from Europe, was formed by crystalline basement which extended northeastward from the Petite (PK) and Grande Kabylie (GK) (Figure 2). It is conceivable that the granitic substrate of the Galite Bank on, and the slope at the outer edge of, the western part of the Tunisian Plateau may represent another remnant of this arc. As a result of convergence, the Numidian Nappe was dislocated and moved in a southward direction. The end of the major collision phase has been dated as Tortonian by Rouvier (1977).

We note that during lower Miocene time, sediments deposited in an elongate N–S trending basin on the slope off SE Sardinia (Sardinia Basin) were deformed by gentle, short-term compression before Tyrrhenian distensive phases as shown by seismic reflection profiles (unpublished, Compagnie Française des Pétroles, Paris). This is the only evidence, albeit indirect, of post-Oligocene compression recorded on the Sardinian margin. This convergence-compressional trend off Sardinia is poorly defined. It is almost certainly older than the above-cited major compressional phase on the plateau off Tunisia.

3. The gently arcuate trend of the major median depression (E–W Teulada Valley, and N50°E oriented Sardinia Valley) is well defined on physiographic charts (Figures 3, 4). This feature (illustrated in seismic profiles, Figures 5, 6) appears to have originated primarily as a result of extension rather than erosion. Deposits interpreted as Messinian evaporites in the upper reaches of Sardinia Valley, and non-evaporite sediment series of possible upper Miocene age exposed along both valleys, suggest that this median depression formed during the upper Miocene. This tensional phase, which occurred at about or shortly after the end of the collision-compressive events to the south, on the Tunisian margin, is probably related to large-scale subsidence of both Tyrrhenian and Algéro-Balearic basins in the Miocene and Pliocene. The steep valley walls (Figures 5, 6) are interpreted as step-fault surfaces, along which movement has continued during the Pliocene and Quaternary, primarily by extension. Shallow, high-resolution 3.5 kHz records suggest that motion has continued to the present.

4. Structural trends oriented NNE–SSW on the Sardinian margin control large features, such as the Carbonara Valley (oriented about N30°E) and the Ichnusa Seamount that borders it; roughly parallel to these is the Sentinelle Valley on the Tunisian Plateau (N20°E). The trend of both valleys extends to the north by the N–S strike of slopes off SE Sardinia (one slope lies at about 1000 m, and the other, parallel, at about 2000 m). These eastern Sardinia slopes, recording major faults related to the subsidence of the Tyrrhenian Sea, were very active in Plio-Quaternary time (Bacini Sedimentari, 1977). By analogy, we attribute a comparable age to the major formation of Carbonara (Fanucci et al., 1976) and Sentinelle valleys, and relate these features to vertical movements along the Tyrrhenian margin. The opening of the Sentinelle Valley and, more particularly, the northward change in direction of its axis (from NNE to NE) may be related to the contemporaneous evolution of the North Sicilian margin, also of Plio-Quaternary age. The dominant controlling factor is the sub-

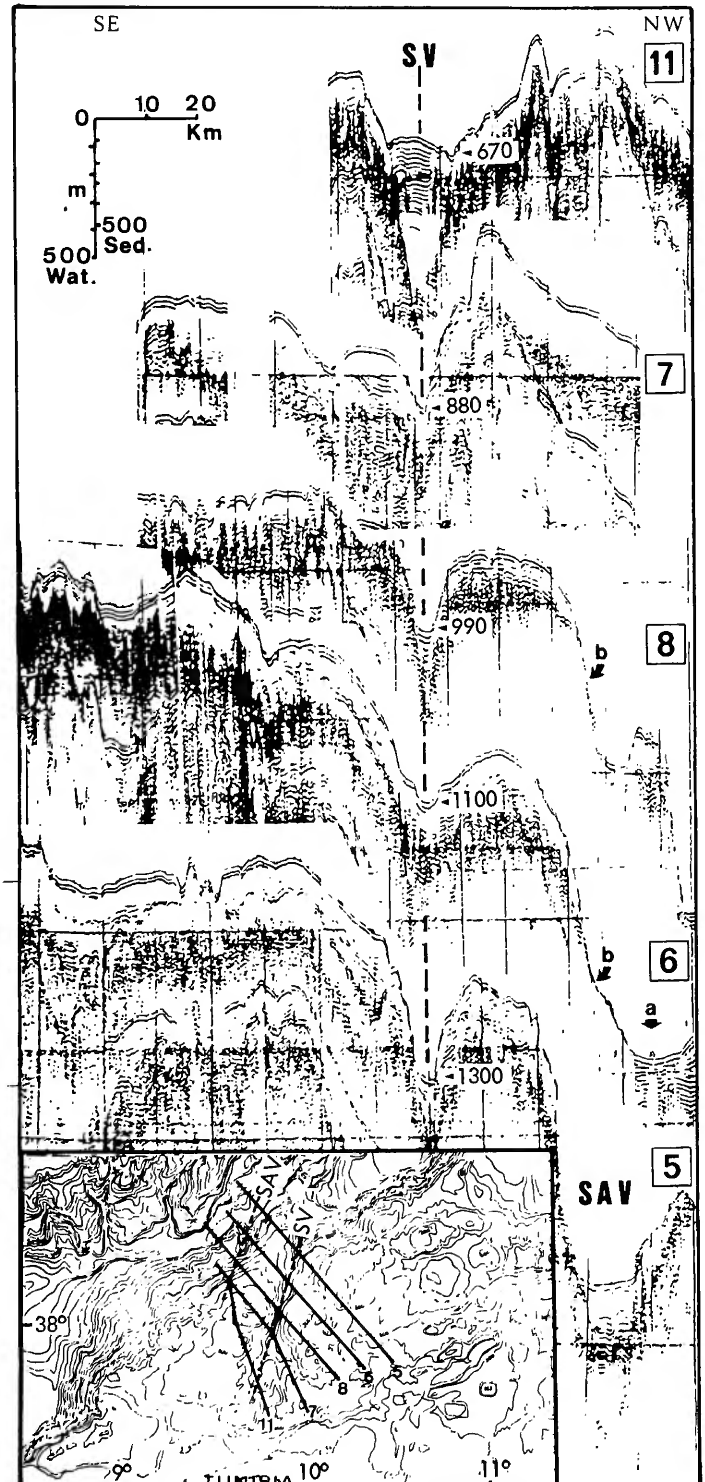
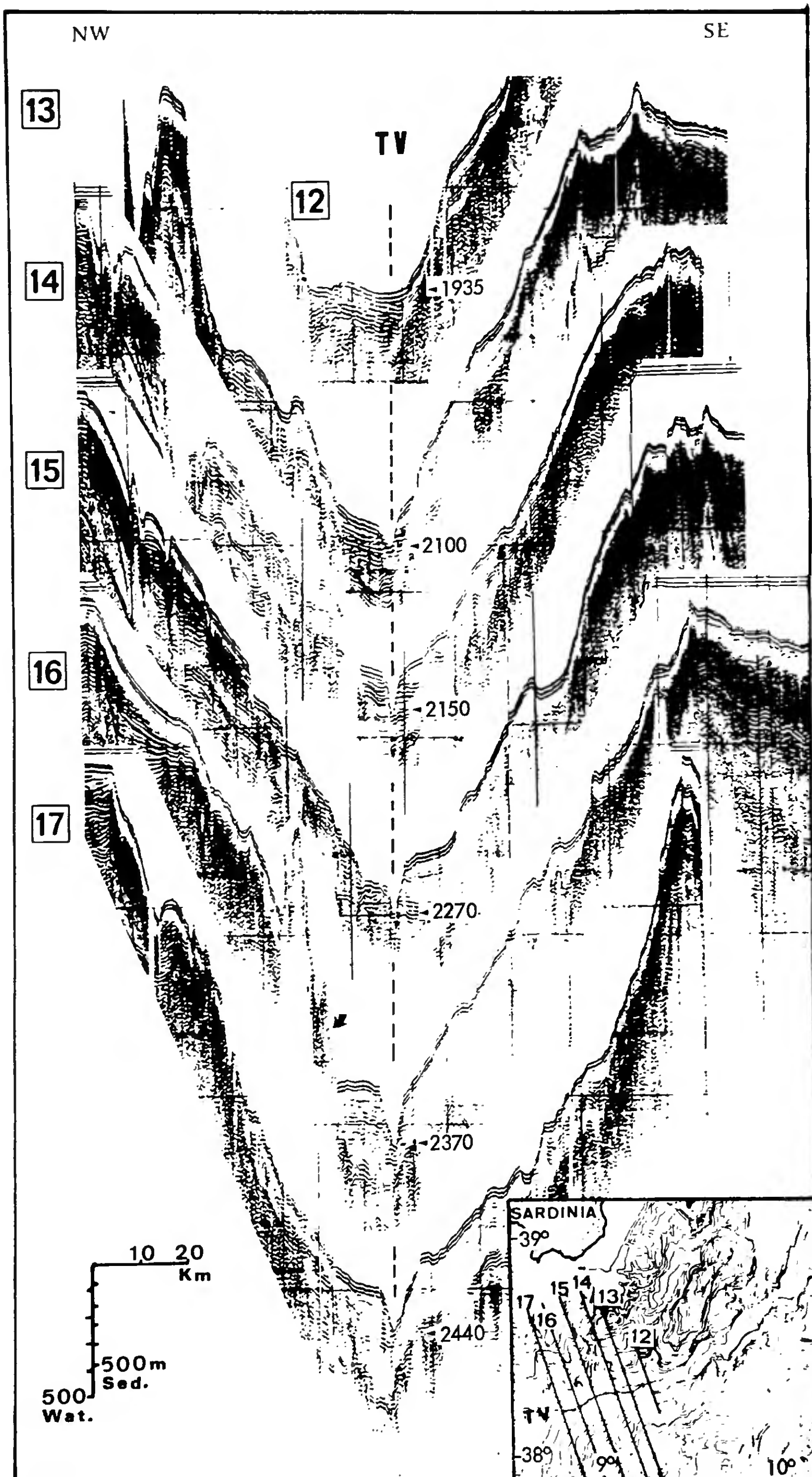


FIGURE 5 (*left*).—Selected Sparker profiles, oriented NW-SE (position shown in the inset; see also Figures 1 and 3). Sentinelle Valley (SV) and Sardinia Valley (SAV) are aligned. Transects (see Figure 4) cross Ichnusa Seamount, Carbonara Valley, and Sardinia Slope. Arrow *a* = Messinian evaporites underlying recent sediments; arrow *b* = crystalline basement. Note thick sediment fill at head of Sentinelle Valley (profiles 11 and 7). Depths of Sentinelle Valley axis in meters; Sed. = sediment thickness; Wat. = water column.

FIGURE 6 (*right*).—Selected Sparker profiles (12–17) across Teulada Valley (TV), oriented NW-SE (shown in the inset; see also Figures 1 and 3). Transects cross the Tunisian Plateau, Tunisian Shelf, and Sardinian Slope (see Figure 4). The incised part of the thick sediments in the Teulada Valley are aligned in the different profiles. Arrow shows crystalline basement outcropping on valley slope. Depths of Teulada Valley axis in meters; Sed. = sediment thickness; Wat. = water column.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500
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SARDINIA
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16
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TV
38°
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10°

sidence on the Tyrrhenian Basin (cf. Selli and Fabbri, 1971; Bacini Sedimentari, 1977).

5. Large NW-SE trending features in the study area include the Gulf of Cagliari and Campidano Valley south of Sardinia. These are of extensional origin, probably the direct result of movement during the Miocene to Recent (accelerated activity during the Plio-Quaternary), with subsidence taking place along reactivated Oligocene fractures on the Sardinia margin and adjacent Sardinian land mass. This fault-controlled topography is particularly apparent along the southwestern flank off Cape Carbonara. This trend is blocked to the SE by the Ichnusa Seamount.

To the south, in the Strait of Sicily, similarly oriented NW-SE trends are mapped, but these are of different origin and form topographically less obvious features than off Sardina. The NE-SW (Numidian Nappe) structure off Tunisia (pattern 2, Figure 9) is interrupted by a series of NW-SE normal faults, which are a northwest extension of the Pantelleria Graben and associated tensional features (normal faults, volcanoes). This normal faulting of upper Miocene Plio-Quaternary age in the Strait of Sicily (Maldonado and Stanley, 1976) and Pelagian Sea (Blanpied, 1978) is related to geologically recent movement in the Calabrian-Sicilian Arc (Dewey et al. 1973; Boccaletti and Guazzone, 1974b; Dubois, 1976). A NW-SE (and NNW-SSE) fault system (often dextral) is also well developed on the northern Sicilian margin to about 11°E; this system may dissect part of the Maghrebian chain in the study area (A. Fabbri, 1983, personal communication). We note that the northwestern geographic limit of this NW-SE trend is not at all obvious on the chart; subtle surface expression on the seafloor is, in part, due to masking by the sedimentary cover.

6. The E-W and NE-SW structural trends on the Tunisian Shelf and inner Tunisian Plateau, apparent in seismic profiles as folds (synclines and anticlines), have resulted from the northerly motion of Africa with respect to Europe, particularly important in the Miocene (Cohen et al., 1980). This same compressional trend has been mapped on land, where it is dated primarily as lower Quaternary (Rouvier, 1977). This compression, recording the continued motion of Africa northward (Auzende et al., 1972; Purcaru and Berckhemer, 1982), is superposed on the major Miocene deformation cited above. Displacement of the type leading to compression of structures in northern Tunisia and the adjacent margin is probably comparable to that presently affecting Algeria; evidence for the latter includes powerful earthquakes, such as the 1954 Orleansville and the 1980 El Asnam events (Lepvrier, 1981; King, 1981).

The E-W axes are somewhat oblique to those produced by the NE-SW Miocene trend and overthrust phases cited earlier (see section 2 above). Compressive movement along both trends during the Quarternary may have produced most of the small depressions mapped on the Tunisian Plateau (Figure 4). It is noted, however, that the Tunisian Plateau most likely subsided as a result of post-Miocene lowering of the Tyrrhenian Basin and extensional events in the Strait of Sicily. These extensional events also are related to the displacement of the Sicily-Calabrian Arc (Dubois, 1976). It is also possible, however, that the small depressions on the Tunisian Plateau are related to fluvial systems, or karst development, that prevailed on this surface during Messinian dessication events. Thus, we view surface relief on the Tunisian borderland as the consequence of a complex structural evolution, modified by the effects of major sea level oscillations.

Stratigraphic-Sedimentary Patterns as Related to Tectonics

The previous sections attempt to correlate the present seafloor configuration with the sequence of tectonic events that have modified this region. The effects of structural deformation, so clearly recorded by the relief features and sedimentary sequences, are not all of the same age. For example, the physiography suggests that vertical displacement during the Quaternary has been more active on the Sardinian (Campidano sector) than on the Tunisian margin; this is due to the proximity of the former to fault movement associated with the origin of the southwestern Tyrrhenian margin. Evidence of such neotectonic events is recorded by high-resolution Sparker (Figures 5, 6) and 3.5 kHz profiles, and also by deeper penetration acoustic records (Figures 7, 8).

At least two types of acoustic basement are identified on the basis of sampling on land and dredging on the seafloor, and from available seismic profiles. The first consists of Paleozoic crystalline rocks (igneous and metamorphic, Figure 7) of the type that crops out in southern Sardinia; these rocks underlie large areas of the Sardinian margin. A substantial part of the Ichnusa Seamount, for example, is believed to be formed by this type of Paleozoic basement (Colantoni et al., 1981). Crystalline basement also underlies much of the Tunisian Slope and parts of the Tunisian Plateau, particularly in the western part of the study area (example: Galite Bank). These lithological series may correlate with rock formations cropping out in the Kabylie coastal range of Algeria (Figure 2). Other areas where crystalline basement probably occur are shown in Figure 9.

A second type of acoustic basement underlies, and locally crops out on, the Tunisian Plateau and Shelf (Figure 9, pattern 6). This consists of allochthonous sedimentary rock series of Tertiary age (including Oligocene to lower Miocene formations) emplaced and offset during the Miocene (Figure 8A,B); these series have been displaced toward the southeast. Moreover, the physiography and examination of unpublished proprietary seismic records (CFP, ETAP, and others) indicate that the amount of deformation affecting these series decreases toward the northeast (i.e., on the Plateau north of Skerki Bank).

The autochthonous sedimentary cover, consisting of near-parallel acoustic reflectors on seismic profiles, is highly variable in thickness throughout the study area (Figures 5–8). The high vertical exaggeration (to × 40) of Sparker profiles (Figures 5, 6) distorts acoustic reflectors. The limited quality of some records is such that it is not possible to precisely map the unconsolidated (post-nappe emplacement) sedimentary thicknesses and accurately plot isopach charts. On the basis of seismic profiling data, however, we can identify areas covered by about or greater than 300 m of sediment and those covered by less than 300 m (Figure 9). Locally, such as off northeast Tunisia (Cap Blanc), this sedimentary cover exceeds 1500 m in some tectonic depressions (Figure 8). The

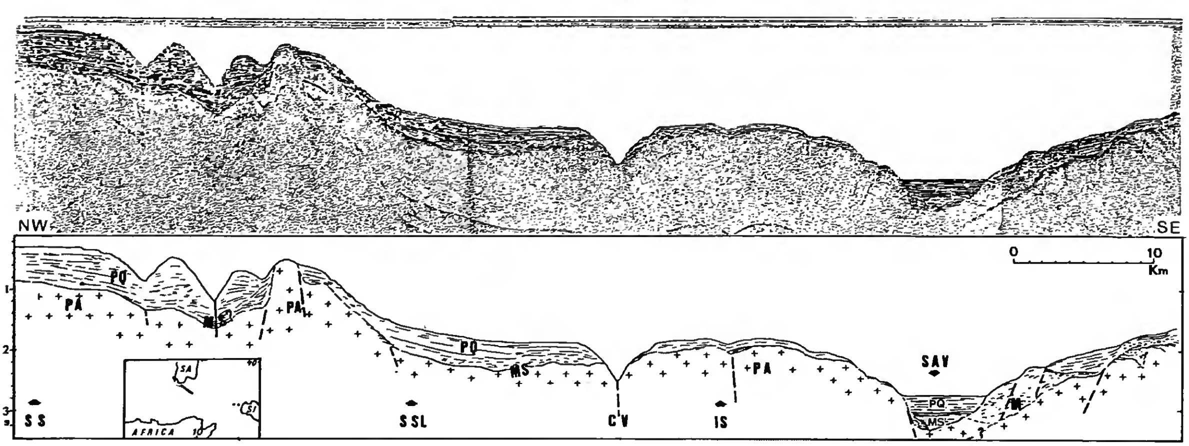
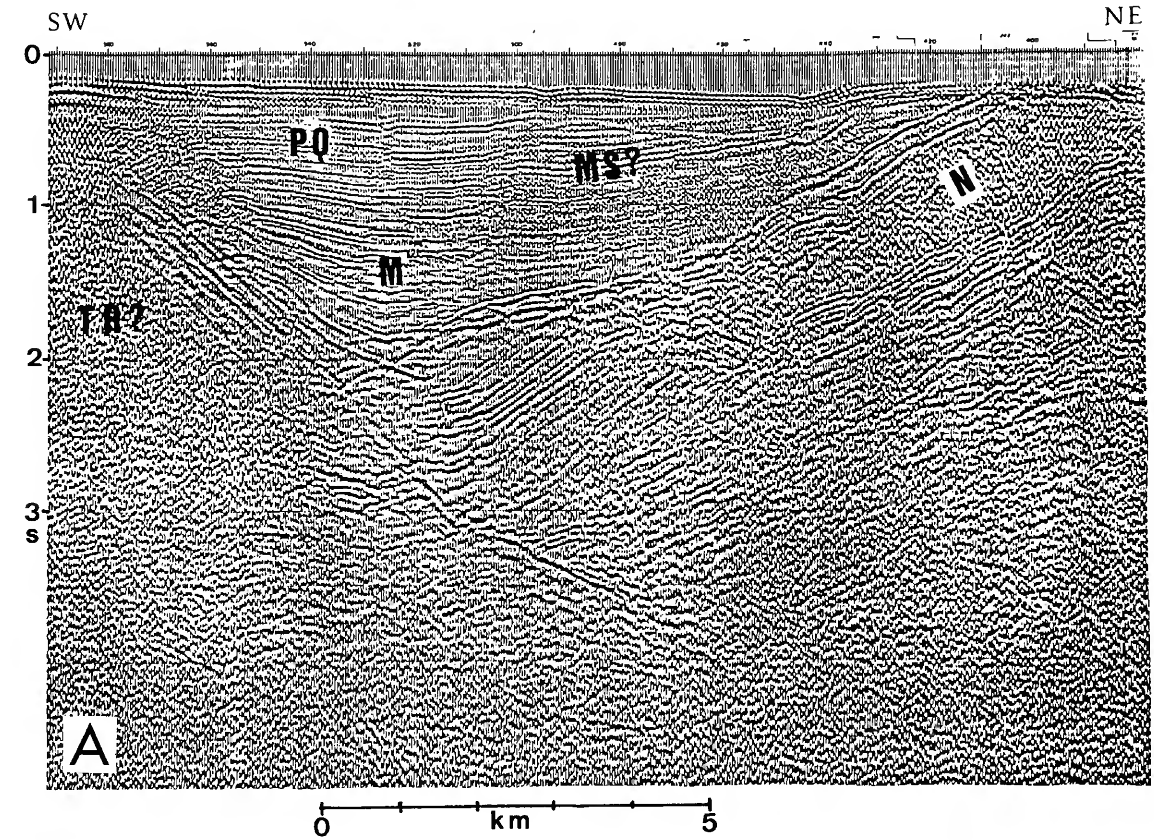


FIGURE 7.—Deeper-penetration Sparker profile: oriented NW–SE, and interpreted record, crossing Sardinian Shelf (SS) and slope (SSL), Carbonara Valley (CV), and Ichnusa Seamount (IS). PA = probable Paleozoic basement; M = Miocene (possibly upper Miocene) sediment series; MS = Messinian surface; PQ = Pliocene-Quaternary sediment series. SAV = Sardinia Valley; SA = Sardinia; SI = Sicily. Horizontal scale in km; vertical scale in seconds.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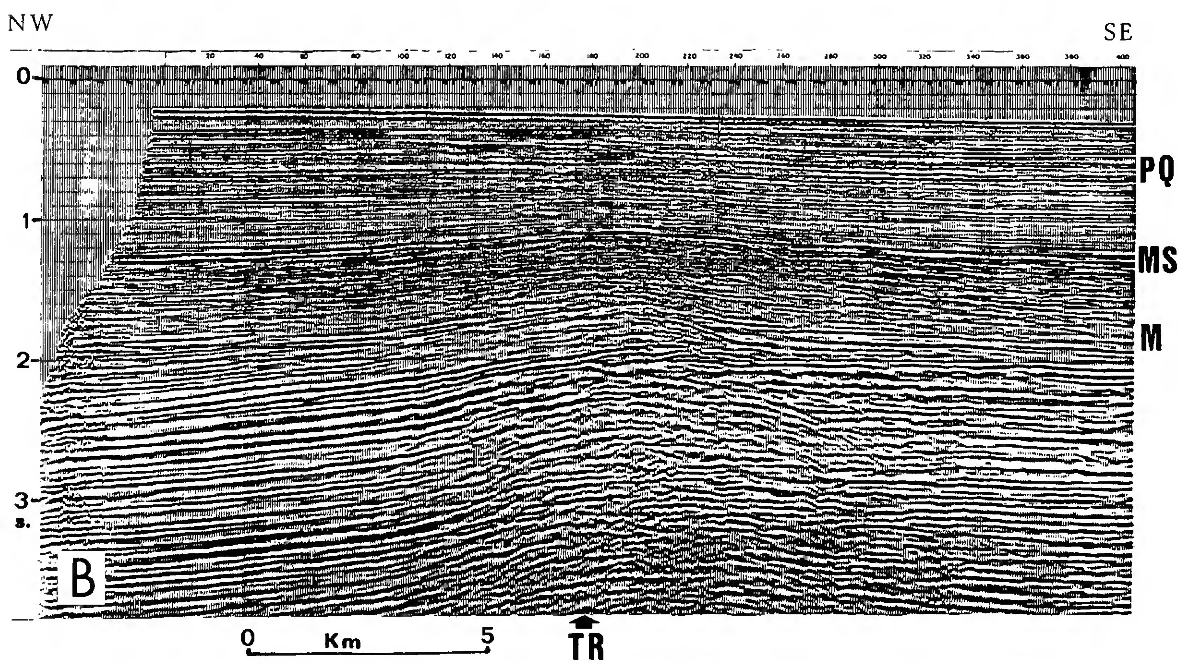
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relative thicknesses of these deposits, which presumably range in age from Miocene to Quaternary, are not correlatable with seafloor depth, that is, thicker sediment sequences do not necessarily occur in deeper or low-lying areas. In many parts of the study area, however, there is a moderate to good correlation between sediment thickness and the dominant morphostructural trends. Furthermore, there is good evidence of an early Quaternary to Recent structural overprint on depositional thickness and deformation of the upper sedimentary series throughout the study area (Figure 5: profiles 7 and 11, Figure 8A).

Tunisian Margin

On the Tunisian Shelf and adjacent inner plateau, a series of E–W and NE–SW depositional trends are apparent. As noted on some NW–SE oriented profiles in the Gulf of Tunis (Figure 8B), thick wedges (>3 seconds, or to about 4000 m) of upper Miocene to recent sediment has filled subsiding depressions which, locally are presently undergoing compression. These are comparable to thick basin-filled synclines mapped by Rouvier (1977) on the adjacent Tunisian land mass.

In the vicinity of Skerki Bank (east of 11°E long; 38°N lat.; Figure 5: profiles 7 and 11), the sector west of Sicily, and in the Strait of Sicily proper, there is also a thick (locally >500 m) accumulation of Plio-Quaternary deposits. The depocenters appear structurally controlled by the network of presently still-active NW–SE trending normal faults.

FIGURE 8.—Selected deep-penetration air-gun profiles on the Tunisian margin east of Cap Blanc. A, NE–SW oriented transect across the Tunisian Shelf north of Cap Bon, showing post-Miocene tectonic displacement of the basement (sedimentary nappe series, N) which crops out at surface; reflectors interpreted as Messinian (MS?) deposits and overlying prograding and deformed Pliocene-Quaternary (PQ) sediments also are identified. TR? = probable salt diapir. B, NW–SE transect in the Gulf of Tunis region showing a thick (>4000 m) accumulation of Neogene sediments. Movement of evaporite diapir (TR) appears to have stopped by the end of the Pleistocene. Abbreviations as in A; horizontal scale in km; vertical scale in seconds.

In other parts of the Tunisian Plateau and on the slope (both affected by post-Miocene subsidence), the Plio-Quaternary cover generally exceeds 100 m. Generally, there is a reduced depositional cover on high relief features (Figure 6: profiles 13–15) and on the slope, where the failure and downslope redeposition of sediment exposes older rock units. The borderland has undergone somewhat less movement than the Tunisian Shelf and inner plateau, presumably affected by compression. Indirect evidence of the minor subsidence affecting the plateau is indicated by the small depressions (Figure 4), some of which also may have resulted from gentle synclinal deformation and fault-displacement of the substrate, and/or dissolution of underlying Triassic salt piercement features. The thin sediment fill in these depressions is due partly to the structural high of this region and to some of the depressions that are of geologically recent tectonic origin (see also p. 9).

The main supply of sediments on the submerged Tunisian margin is land-derived, primarily from rivers (oueds such as the Majardah) in northern Tunisia. These rivers transported much more material seaward during wetter climatic phases and eustatic lowstands in the Quaternary than at present. These fluvial sediments, and those derived from coastal and sea-floor erosion, have been displaced and redeposited by the Intermediate Water mass, which is presently flowing northwestwardly through the Strait of Sicily and then diverges westward over the Plateau and northward (toward the Tyrrhenian Sea) in the study area (Wüst, 1961; Miller, 1972). Moreover, the less saline surface Atlantic Water mass, flowing generally eastwardly (Lacombe and Tchernia, 1972), also transports sediment into this region. The southern (headward) sector of the Sentinelle Valley has trapped large volumes of sediment (Figure 5: profiles 11, 7, 8), in part from water masses flowing across the inner Tunisian Plateau. Sediments in this region have been trapped in structurally deformed depressions; this tectonic effect has precluded the transport of sediment along the Sentinelle Valley axes further

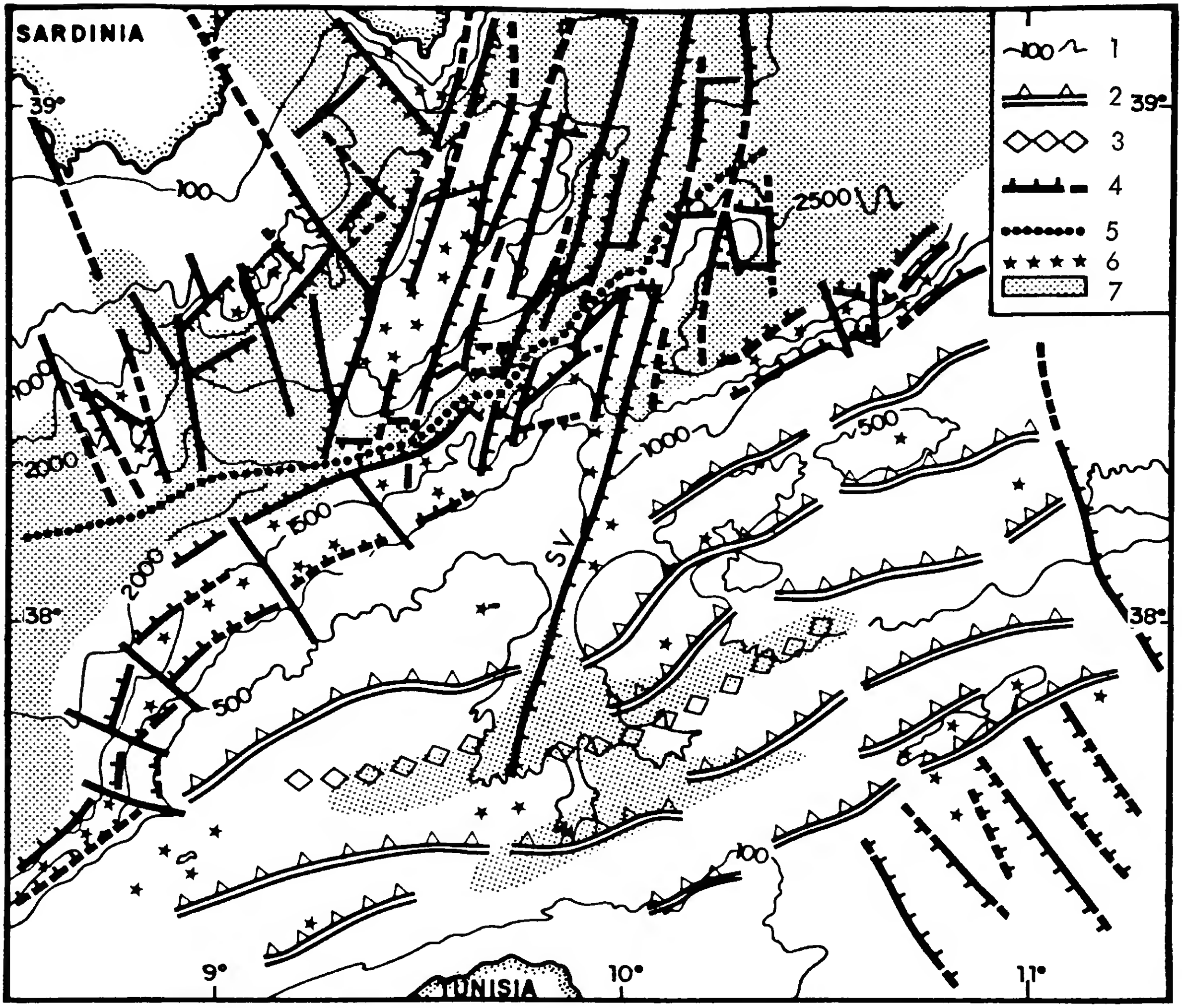

FIGURE 9.—Major structural trends and sedimentary patterns of study area. 1 = Contours of present seafloor surface, in meters. 2 = Overthrust symbols depicting recent direction of movement of Africa toward the north, resulting in compression off Tunisia. 3 = Low surface relief features, indicating structural axes, probably result from lower Miocene compression. 4 = Effect of extension as recorded by NW–SE grabens in and near the Strait of Sicily, by normal faults, oriented NNE–SSW, on the Sardinian margin and also forming the Sentinelle Valley (SV), by normal faults (step-faults) on the Tunisian and Sardinian slopes, and by the Campidano Graben. 5 = The trend of the Teulada and Sardinia Valley axes, denoting the major boundary at the present seafloor surface between the Tunisian and Sardinian margins. 6 = Acoustic basement, which includes Paleozoic crystalline rocks sampled on the island of Sardinia and, locally, on the two margins, and allochthonous (Nappe) units. 7 = Pliocene-Quaternary sediment series are shown as thin (<300 m; in white) or thick (>300 m; stippling pattern) accumulations. Thick, well-layered acoustic series consisting largely of mud turbidites, prevail in both the Tyrrhenian and Algéro-Balearic basins.

to the north across the Plateau (Figure 5: profile 5).

Sardinian Margin

In contrast to the Tunisian Plateau, the Sardinian margin is characterized by a generally thicker (>500 m) series of sediment that covers a substantially larger surface area (Figure 9). The most extensive amount of sediment is mapped on the slope south of Sardinia and is particularly important in the Gulf of Cagliari-Carbonara Canyon complex (Fanucci et al., 1976). This thick series is related to the presence of the Ichnusa Seamount, which serves as a tectonic dam behind which sediments have been trapped. Tectonic damming resulting in thick sediment accumulation also occurs in the Sardinia Basin southeast of Sardinia (Bacini Sedimentari, 1977); moreover, this phenomenon of sediment entrapment in slope basins has been recorded along many sectors of the Tyrrhenian margin (Selli, 1974).

The generally thick sedimentary cover on the Sardinian margin records the direct dispersal from the southern Sardinia land mass onto and across the smaller surface area of the contiguous Sardinia margin. Furthermore, the north-to-south flow of the Intermediate Water mass along the eastern margin of Sardinia, and then to the west (out of the Tyrrhenian Sea and off southern Sardinia as indicated by Allen et al., 1972, and Miller, 1972) probably has also played an important role in sediment deposition on the highly dissected margin. Sediment series are generally much thinner and locally absent on high relief features, such as the Ichnusa Seamount (Figure 7), as a result of seafloor erosion by flowing water masses and of spill-over and downslope redepositional processes (cf. Maldonado and Stanley, 1976).

Teulada-Sardinia Valley Complex

Sediment series are generally thick (in excess of 500 m) in the lower reaches of the Teulada-Sardinia Valley complex that serves as the major physiographic boundary between the Tunisian and Sardinian margins. Reflectors on the high-resolution 3.5 kHz profiles suggest that a large portion of these deposits are of gravitative (turbidite, slump) origin. We recall that in the Sardinia Valley, sediments as old as Messinian, and some perhaps older, are observed (Figure 5: respectively arrow *a* in profile 6 and arrows *b* in profiles 6 and 8).

It is of note that the sediment fill in the Teulada Valley (Figure 6) is incised. This V-shaped cut is at least 1 km wide, and has a relief of at least 100 to 300 m (Figure 6). We suggest here that the origin of this feature is in part due to bottom scour by gravity transport, such as turbidity currents (cf. Wezel et al., 1979).

It is also possible that the incision in the Teulada Valley axis records the combined effects of synsedimentary tectonic displacement (normal faulting related to a recent tensional phase) and erosion by bottom currents. The currents may result from a flow of Deep Mediterranean Water by way of the median valley, from the Tyrrhenian Basin westward toward the Algéro-Balearic Basin. It is also possible that scour was accelerated during lowered eustatic sea-level stands in the late Pleistocene. The nature of this flow remains poorly defined (Lacombe and Tchernia, 1972). These latter hypotheses need to be tested.

A similar V-shaped incision is observed in the Carbonara Valley. This submarine canyon has served as a major by-way for the long-term downslope transport of sediment of Sardinian origin from the Campidano Graben Valley on land seaward to the Teulada Valley. Seismic profiles that cross the axis of the Sardinia Valley do not show a comparable incision (Figure 5: profiles 5, 6).

Conclusions

The configuration of the present Mediterranean is largely a result of convergence between Africa and Europe, one which has involved a progressively greater amount of closure as one proceeds toward the east in the Mediterranean (Biju-Duval et al., 1977). In theory, the Sardinian-Tunisian study area occupies a setting that primarily has undergone compression during much of the period since the Upper Jurassic. In more recent time we envision that the study area occupies a key position involving the merging of the Tunisian and Sardinian margins. This likely resulted from the counter-clockwise rotation of the Corsican-Sardinian block in the Oligocene and Miocene, and the continued northward movement of Africa relative to the European plate; this latter also has induced displacement along the Calabrian Arc. Seismic profiles we examined tend to give some additional precision on this geologically recent evolution.

The effects of Quaternary (and probably continuing) compression in northern Tunisia is believed to extend seaward on the contiguous Tunisian Shelf and inner plateau. Evidence for continuing lithospheric plate motion is provided by the E-W seismicity trend, including the destructive Orleansville and El Asnam earthquakes in Algeria in 1954 and 1980. Further evidence for a northward-directed compression is indicated by seismic reflection profiles on the Algerian margin (Auzende et al., 1974). This E–W compressive axis appears interrupted in the southeastern part of the study area and adjacent Strait of Sicily, but reappears further to the east, in Sicily, as overthrusts that have continued to be displaced as recently as the Quaternary. Some workers envision that the Maghrebian chain is continuous from North Africa to Sicily and that the sector between these two regions is dissected and displaced by the NW-SE (and NNW-SSE) dextral fault systems (A. Fabbri, personal communication, 1983).

Although the Sardinian-Tunisian seafloor is believed to represent a welded plate boundary and occupies a sector that has undergone compression during much of the Neogene, our investigation indicates a predominance of structural features of extensional origin. We propose here that many of these features are related to the subsidence of the Tyrrhenian Sea involving much vertical movement from the Miocene to the Recent. It is tempting, for example, to place the geological limit between the original Sardinian microplate and North Africa along the Teulada and Sardinia valleys which so obviously defines the present physiographic boundary between the Tunisian and Sardinian margins. Caution, however, is needed in this respect, since the superposed major structural trends and associated sedimentary patterns, in themselves, do not prove that this median depression necessarily closely conforms to and overlies directly above a deep-lying crustal plate boundary. We do recognize that the two valleys result primarily from tensional motion related to geologically more recent subsidence of the Tyrrhenian Sea and Algéro-Balearic Basin. Moreover, extensional motion in the southeastern part of this area, recorded by the dominant NW-SE trend of normal faults, is related to horst and graben formation in the Strait of Sicily. This extensional trend, in turn, is probably associated with the eastward displacement along the Calabrian-Sicilian Arc and subduction in the Ionian Sea.

The dominant NNE-SSW orientation of tectonic axes in the Sardinian-Tunisian region is shown by seafloor relief, structural trends, and depositional patterns (Figure 9). This orientation (about N20°E to N30°E) clearly projects to the south the major structural trends mapped east of Sardinia in the Tyrrhenian Sea (Bacini Sedimentari, 1977; Fabbri et al., 1981). Among the more obvious features are the Ichnusa Seamount and Carbonara Canyon on the south Sardinia margin, and the Sentinelle Valley on the Tunisian borderland. Some workers interpret the NNE-SSW trending Sentinelle Valley as a reactivation, during the Plio-Quaternary, of an older fault (probably transcurrent) on the African margin (A. Fabbri, personal communication, 1983). In our view, however, the Sentinelle Valley, which cuts across most of the Tunisian Plateau, provides evidence of the southward extent of Tyrrhenian-related margin features, which have been active from the upper Miocene to the present. On the North African margin, this NNE-SSW trend is superposed on the older Miocene NE-SW compressional trend previously delineated by Auzende (1969, 1971).

The E-W normal fault axes on the North Sicilian margin, in the Tyrrhenian Sea (Figure 2), do not appear to extend westward into and across the study area. The extent to which these still-active Sicilian East-West trending extensional structures have played a role in the Plio-Quaternary evolution of this region is not determined here with available data.

In summary, the central Mediterranean region highlights the southern extension (toward Tunisia) of N-S trending Tyrrhenian margin extensional structures. The effects of compression due to the northern movement of Africa and motion along the Calabrian Arc, and the NW-SE structural trend related to the formation of the Strait of Sicily, are somewhat less obvious. It is possible that the convergence of tectonic-stratigraphic trends in the study area indicates a triple junction. This aspect of plate motion remains to be proven. Our assessment of the available data, however, indicates that there is a correlation between the complex configuration of this region and the geologically recent evolution of the adjacent deep (Tyrrhenian, Algéro-Balearic, and Ionian) Mediterranean basins.

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