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# PLATE TECTONIC MODEL FOR THE OLIGO-MIOCENE EVOLUTION OF THE WESTERN MEDITERRANEAN *

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## ABSTRACT

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This paper outlines a plate tectonic model for the Oligo-Miocene evolution of the western Mediterranean which incorporates recent data from several tectonic domains (Corsica, Sardinia, the Kabylies, Balearic promontory, Iberia, Algero-Provençal Basin and Tunisian Atlas). Following late Mesozoic anticlockwise rotation of the Iberian peninsula (including the Balearic promontory and Sardinia), late Eocene collision occurred between the Kabylies and Balearic promontory forming a NE-trending suture with NW-tectonic polarity. As a result of continued convergence between the African and European plates, a polarity flip occurred and a southward-facing trench formed south of the Kabylie—Balearic promontory suture. During late Oligocene time an E—W-trending arc and marginal basin developed behind the southward-facing trench in the area of the present-day Gulf of Lion. Opening of this basin moved the Corsica—Sardinia—Calabria—Petit Kabylie—Menorca plate southward, relative to the African plate. Early Miocene back-arc spreading in the area between the Balearic promontory and Grand Kabylie emplaced the latter in northern Algeria and formed the South Balearic Basin. Coeval with early Miocene back-arc basin development, the N—S-extension in the Gulf of Lion marginal basin changed to a more NW—SE direction causing short-lived extension in the area of the present-day Valencia trough and a 30° anticlockwise rotation of the Corsica—Sardinia—Calabria—Petit Kabylie plate away from the European plate. Early—middle Miocene deformation along the western Italian and northeastern African continental margins resulted from this rotation. During the early late Miocene (Tortonian), spreading within a sphenochasm to the southwest of Sardinia resulted in the emplacement of Petit Kabylie in northeastern Algeria.

## INTRODUCTION

Through Deep Sea Drilling Project (DSDP) results there now exist fewer disagreements on the timing of sedimentation, volcanism and deformation in

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the western Mediterranean region. Little unanimity exists, however, with regard to the process(es) involved in the region's genesis and evolution (Moullade, 1977). Moreover, differing interpretations of western Mediterranean evolution have resulted simply from the initial configuration of the microplate mosaic (Laubscher and Bernouilli, 1977).

Although continental drift and microplate rotations were employed by Argand as early as 1924 to explain western Mediterranean tectonics and geography, the area has continued to spawn alternative developmental mechanisms. These include (Moullade, 1977): (1) "Oceanization, sensu stricto" (Hsü, 1977) of continental crust (Van Bemmelen, 1969, 1972a, b; De Roever, 1969; Ritsema, 1970); (2) "Atlantic-type oceanization" (i.e. formation of oceanic crust via crustal extension and continental drift) (Hsü, 1971; Smith, 1971; Ryan et al., 1973b; Dewey et al., 1973; Alvarez et al., 1974; Alvarez, 1976; Cohen et al., 1980a); and (3) "Pacific-type oceanization" (i.e. formation of oceanic crust through back-arc marginal basin development (Boccaletti and Guazzone, 1974; Biju-Duval et al., 1977; Cohen et al., 1980b). It remains unclear what role and to what extent each of these mechanisms has played.

I attempt here to reconstruct the Oligo-Miocene evolution of the western Mediterranean using recently published geological data and within the "mo-

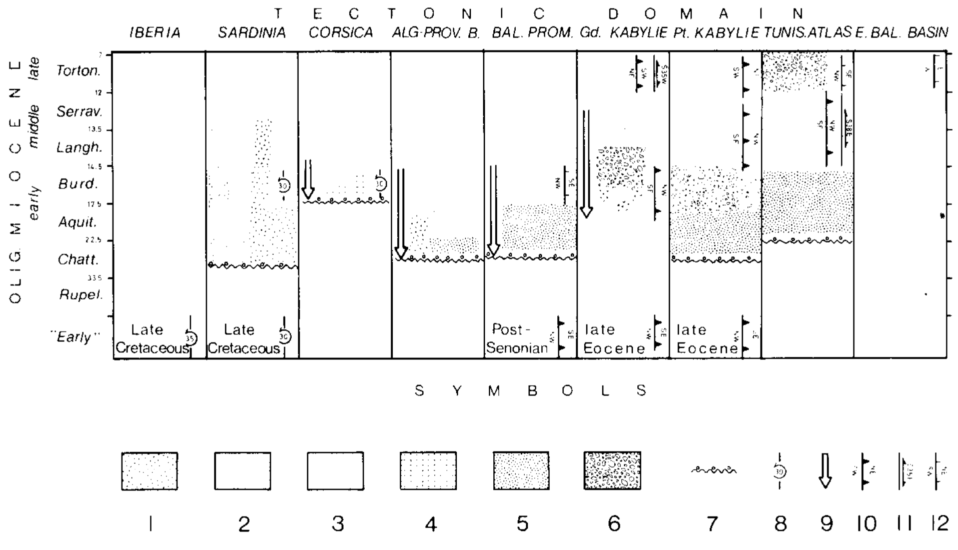


Fig. 1. Time—space diagram for tectonic domains in western Mediterranean region (Iberia, Sardinia, Corsica, Algero-Provençal Basin, Balearic Promontory, the Grand Kabylie, the Petit Kabylie, Tunisian Atlas and East Balearic basin). *1* = volcanism; *2* = deep-water marls; *3* = turbidites; *4* = carbonates; *5* = coarse epiclastics; *6* = molasse; *7* = marine transgression; *8* = plate rotation (sense and magnitude shown); *9* = subsidence; *10* = major thrust faulting and folding (vergence shown); *11* = conjugate shear faults (acute bisector trend shown); *12* = normal faulting (trend shown).

bilist" framework of plate tectonics. Hopefully, the model will itself elicit further spatial and temporal (pre-Oligo-Miocene time) constraints.

The model is outlined following a presentation of data from several critical tectonic domains. This is summarized in Fig. 1 and discussed in detail below.

## TECTONIC DOMAINS

### *Sardinian, Corsican, Provençal and Iberian paleomagnetics: microplate rotations*

Geological parallels in Sardinia and Provence (France) including: (1) the nature of pre-Alpine, Hercynian basement; (2) Mesozoic sedimentary sequences; and (3) pre-Miocene structural histories (Chabrier and Mascle, 1975) indicate that the two domains were contiguous until the early Miocene when Sardinia rotated away (Fig. 2) (Chabrier and Mascle, 1975; Westphal et al., 1976). Early paleomagnetic investigations showed that, since the Permian, Sardinia rotated 60° anticlockwise, relative to Europe (Zijderveld

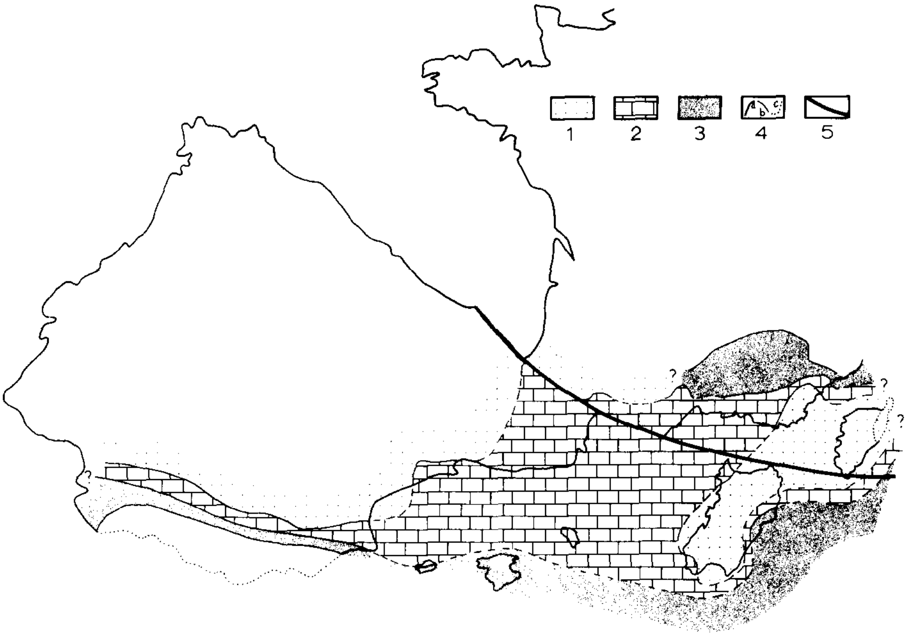
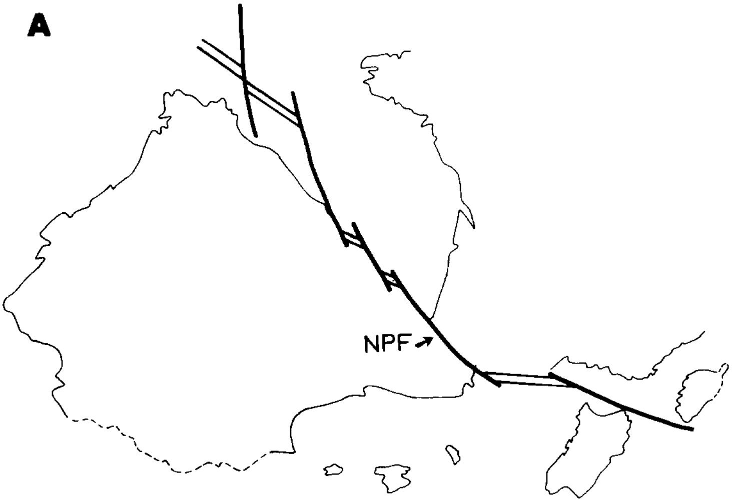


Fig. 2. Early Cretaceous paleogeography. Restoration showing relative positions of tectonic domains. *1* = emergent; *2* = shelf carbonates; *3* = marls and marly limestones with Calpionellids and ammonites; *4* = contacts: (*a*) known, (*b*) inferred, (*c*) Alpine nappes; and *5* = trace of future North Pyrenean fault (data from Bourgois et al., 1970; Westphal et al., 1978).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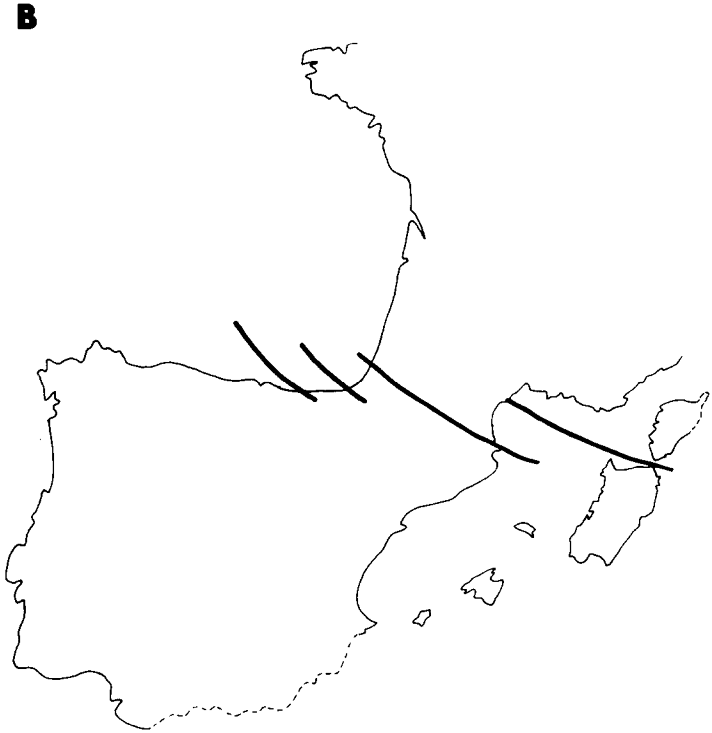
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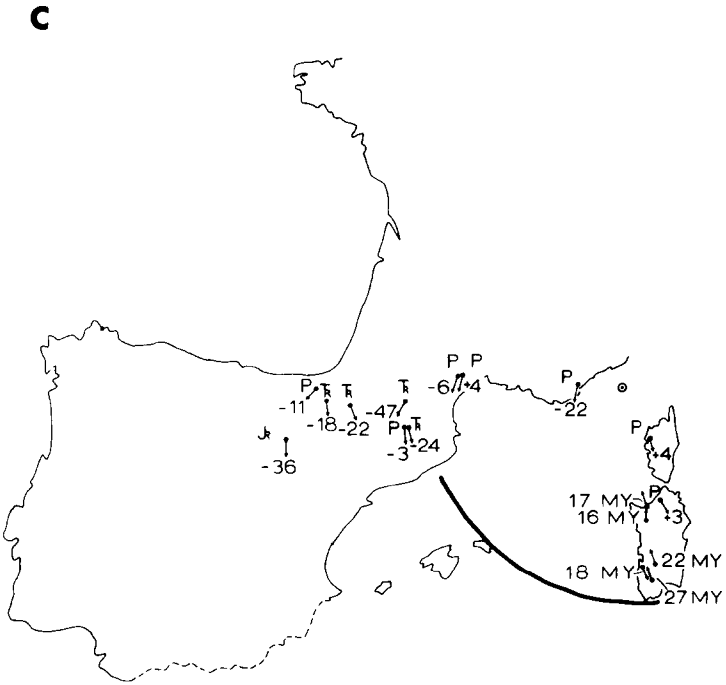


Fig. 3. Schematic tectonic interpretation of paleomagnetic data from Provence, Corsica, Sardinia and Iberia and marine magnetics in Bay of Biscay. A and B, respectively, prior to and following mid-Cretaceous 35° anticlockwise rotation of Iberian plate (including Balearic promontory and Sardinia); C, following early Miocene 30° anticlockwise rotation of Corsica and Sardinia. Major transform faults and paleomagnetic data of Van der Voo and Boessenkool (1973), Bellon et al., (1977), Westphal (1976) and Westphal et al., (1976) (declinations, inclinations and ages) are also shown. *NPF* = North Pyrenean Fault. See text for discussion.

et al., 1970; Westphal et al., 1976). More recent studies suggest that during 30—17 Ma Sardinia maintained an orientation some 30° from its present geographic location. During 17—15 Ma, Sardinia rotated 30° anticlockwise to its present position (Coulon et al., 1974a, b; Bellon et al., 1977). Clearly then, an earlier component of anticlockwise rotation, of about 30°, must have occurred between Permian and early Miocene time.

Paleomagnetic and geological data from Corsica and Provence (Esterel) suggest that the two were also formerly contiguous (Fig. 2) (Nairn and Westphal, 1968; Westphal, 1976; Westphal et al., 1976). Permian lava flows in Esterel demonstrate a declination difference of 30° with lavas of similar age and petrochemistry in Corsica (Fig. 3C) (Nairn and Westphal, 1968; Westphal et al., 1976). This angular difference is the result of post-Permian anticlockwise rotation of Corsica relative to Europe. If Corsica is rotated clockwise 30° about a pole east of Nice (Fig. 3C), the paleomagnetic data are reconciled and two major occurrences of Permian lavas, southeast of Cannes (France) and north of Ota (Corsica), become aligned and continuous.

Iberian paleomagnetic data indicate that the peninsula rotated 35° anticlockwise between the late Jurassic and late Cretaceous (Fig. 3A, B) (Van der Voo, 1969; Van der Voo and Boessenkool, 1973). Marine magnetic anomalies in the Bay of Biscay evidence its mid-Cretaceous (90—95 Ma) opening (Fig. 3A) (Kristoffersen, 1978). Sinistral movement along the North Pyrenean fault in Iberia accommodated both the rotation of Iberia and opening of the Bay of Biscay (Choukroune et al., 1973). Rotation of the Iberian plate was facilitated not simply by spreading in the Bay of Biscay (LePichon et al., 1971), but probably as well by accretion in the area of the present-day Gulf of Lion (Fig. 3A) (Van der Voo and Boessenkool, 1973; Westphal et al., 1978).

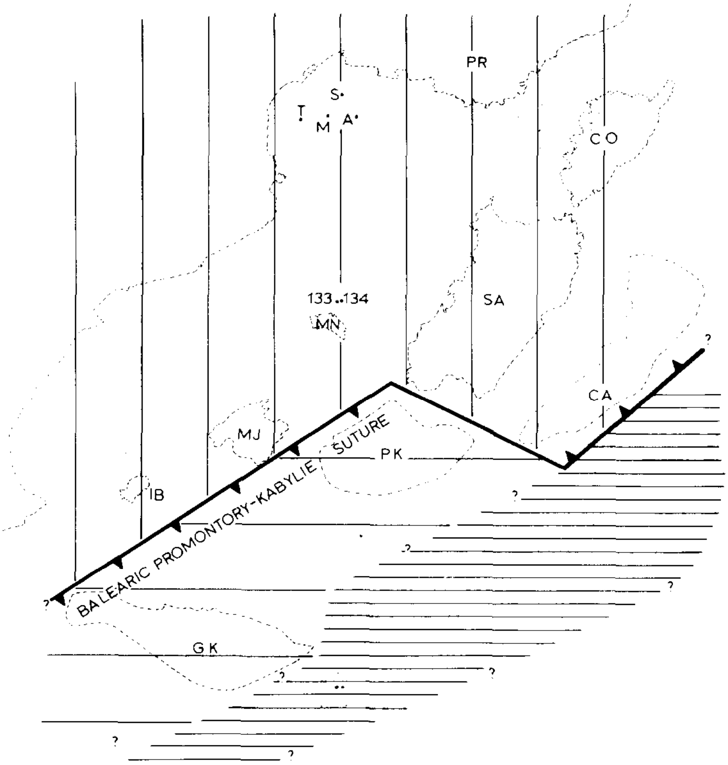
These paleomagnetic data suggest that Sardinia and Iberia experienced an earlier anticlockwise rotation, relative to stable Europe (Provence), of approximately 30°, probably during the mid-Cretaceous. This movement was later followed by an early Miocene rotation, with similar sense and magnitude as before, of Corsica and Sardinia (Fig. 3C). To explain the domains' differing magnitudes of rotation, then, it is necessary to postulate: (1) the eastward continuation of a known plate boundary (along the North Pyrenean fault) between Corsica and Sardinia and (2) two periods of movement (Fig. 3).

### *Kabylie and Balearic promontory structure: collision*

The Tertiary structural evolution of the Grand Kabylie involved a major phase of deformation during the late Eocene (?early Oligocene). NE—SW to E—W trending isoclinal folds were formed and major imbricate thrust slices were emplaced towards the northwest (Bouillin, 1975; Delteil et al., 1976) during this event. A late Eocene deformative phase also affected the Petit Kabylie, producing NE—SW to NNE—SSW fold trends (Raoult, 1975). This event was followed by a limited Oligo-Miocene transgression after which a molasse containing clasts of metamorphic provenance was deposited (Raoult, 1975).

Structural studies in Ibiza and northwest Majorca (Fig. 4) demonstrate similar tectonic histories for these terrains (Bourgois et al., 1970; Chauve et al., 1978). In Ibiza, allochthonous Triassic—lower Cretaceous units define

Fig. 4. Tectonic framework and schematic cross-sections of Balearic promontory—Kabylie collision in late Eocene time. Map: widely spaced lines are Iberian—Balearic promontory (vertical) and Kabylie (horizontal) plates; closely spaced horizontal lines represent oceanic crust. Sections: (A) The pre-Eocene tectonic polarity is towards the northwest; (B) Eocene collision and suturing; (C) Oligocene polarity flip with a new, south-facing subduction zone developing south of the Kabylies. See text for discussion.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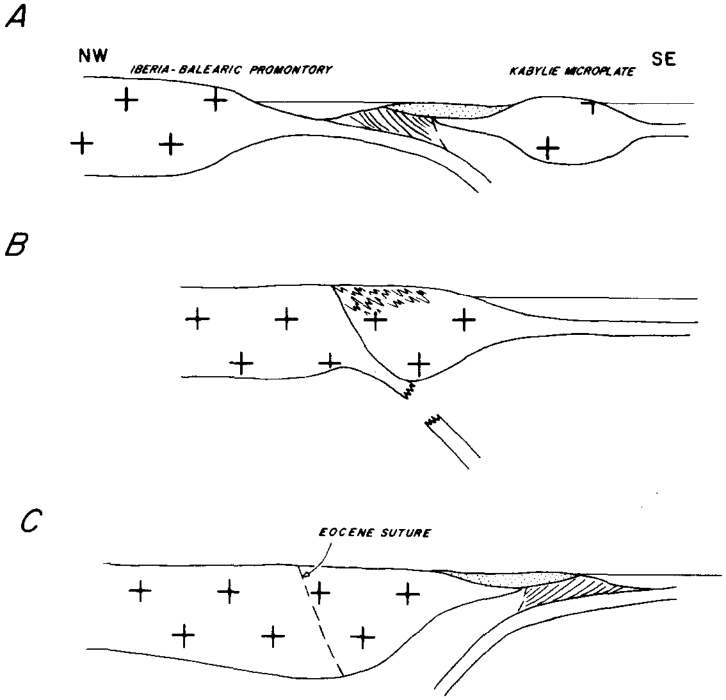
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three NW-vergent imbricate thrust slices: (1) a northern, structurally lowest platform carbonate unit (Eubarca thrust sheet); (2) an intermediate structural unit with slope facies affinities (Llentrisca-Rey thrust sheet); and (3) a southern, structurally highest pelagic and hemipelagic unit (Ibiza thrust sheet) (Bourgois et al., 1970). This tectonic assembly represents the juxtaposition of formerly continuous, NW—SE, respectively, shelf-slope-rise sedimentary realms.

Triassic—lower Cretaceous units in northeast Majorca also comprise three NW-vergent thrust sheets (Bourgois et al., 1970). In the structurally highest sheet, the stratigraphic record also includes the Senonian (Bourgois et al., 1970). Deformation resulting in this imbricate thrust stack is thus post-latest Cretaceous.

In Menorca and northeastern Majorca, absence of pre-late Oligocene and post-Lutetian strata suggests that these areas were emergent during this time (Bourrouilh, 1973).

Chauve et al. (1978) concluded from structural and stratigraphic studies that Menorca was formely located to the north of its present position relative to Majorca. They hypothesized the existence of a dextral strike-slip fault between Menorca and Majorca which was active in latest Oligocene time.

Although no ophiolites attributable to an Eocene suture are known in the Kabylies and Balearic promontory, it is suggested that the deformational history outlined above for the Kabylies and Balearic promontory resulted from Eocene-age collision of these two domains (Fig. 4). The suture perhaps may be found in the present-day South Balearic basin.

### *Sardinian and Kabylie petrochemistries: marginal arcs*

Geochemical studies of Oligo-Miocene volcanics in Sardinia demonstrate three spatial trends: (1) a transition in volcanic character from tholeiitic in the south to calc-alkaline in the north (Coulon and DuPuy, 1975); (2) a chemical zonation expressed by northward increasing values of K, Rb, Li, Sr and Ba (Coulon et al., 1973; Coulon and DuPuy, 1975, 1977); and (3) progressive northward enrichment of LREE in volcanics (Coulon and DuPuy, 1977). These trends are each superimposed on a systematic northward-decreasing age trend of Sardinian volcanics.

The data evidence the former presence of an active northward-dipping Benioff zone beneath Sardinia during at least 30—15 Ma (Fig. 4) (Coulon et al., 1973; Coulon and DuPuy, 1975, 1977).

Aquitanian (19.1 ± 1.0 Ma) andesites and andesitic tuffs are intercalated among turbidites and olistostromes in the Grand Kabylie (Magne and Raymond, 1974; Bizon and Gelard, 1975). Slightly younger submarine andesitic flows, lapilli tuffs and andesitic breccias are found intercalated within Burdigalian strata in the Petit Kabylie (Bolfa et al., 1952; Vila, 1971).

Because these domains: (1) are believed to have been adjacent in the Oligocene (Alvarez, 1976); (2) experienced late Oligocene to early Miocene calc-alkaline volcanism; and (3) because the Sardinian arc faced south, I postulate that a NE-trending marginal arc-trench system with southern tectonic polarity must have existed in Sardinia and the Kaylies during this time (Fig. 4).

### *The Grand Kabylie and Balearic promontory structure and sedimentology: post-suture break-up*

The Grand Kabylie Neogene sedimentary history is initially characterized by the deposition of early Miocene (late Aquitanian—early Burdigalian) turbidites, andesites and andesitic tuffs (Magne and Raymond, 1974; Bizon and Gelard, 1975). These are overlain by Burdigalian—Langhian molasse and basaltic volcanics and in turn by Langhian—Serravallian marls (Magne and Raymond, 1974), indicating a progressive deepening with time.

Late Chattian—Aquitanian epiclastics rest discordantly on older units in northwest Majorca. These units are in turn unconformably overlain by Burdigalian transgressive deposits. Evidence for a similar sedimentary history exists in Ibiza (Bourgois et al., 1970). In northeast Majorca, Aquitanian continental molassic facies sediments and a littoral fauna, representing an earliest Miocene NW-directed transgression, are documented (Bourrouilh, 1973). During the Burdigalian, however, as in the example of the Grand Kabylie, there is evidence for turbidites and olistostromes. Of note, these contain clasts of unquestionable Majorcan provenance. Moreover, graywackes there contain Paleozoic-age clasts whose source can only have been to the southeast of Majorca (Bourgois et al., 1970; Bourrouilh, 1973).

NE-trending early Miocene normal faults characterizing an extensional tectonic regime occur in northeastern Majorca and Menorca (Bourrouilh, 1973). Two prominent NE-striking escarpments immediately south (Emile Baudot) and north of the Balearic promontory developed prior to the Messinian (Mauffret, 1976) and are probably genetically related to the above Burdigalian faulting (Auzende et al., 1974; Biju-Duval et al., 1974).

The progressive early—middle Miocene deepening of a basin between the Grand Kabylie and the Balearic promontory is thus very well evidenced. The NE-trending escarpments probably represent early Miocene faults formed along the basin's margins. Sedimentary infilling of the basin occurred from distinct source terrains to the northwest (Balearic promontory) and southeast (the Grand Kabylie) and may be explained by the break-up of these formerly contiguous domains (discussed below).

### *The Grand Kabylie and North African structure: post-break-up subduction*

Following Eocene collision with the Balearic promontory, the Grand Kabylie experienced a late Oligocene—early Miocene refolding event and renewed south-directed thrusting (Boullin, 1975; Delteil et al., 1976). This deformation was therefore coeval with the above basin development between the Grand Kabylie and the Balearic promontory. These events were followed

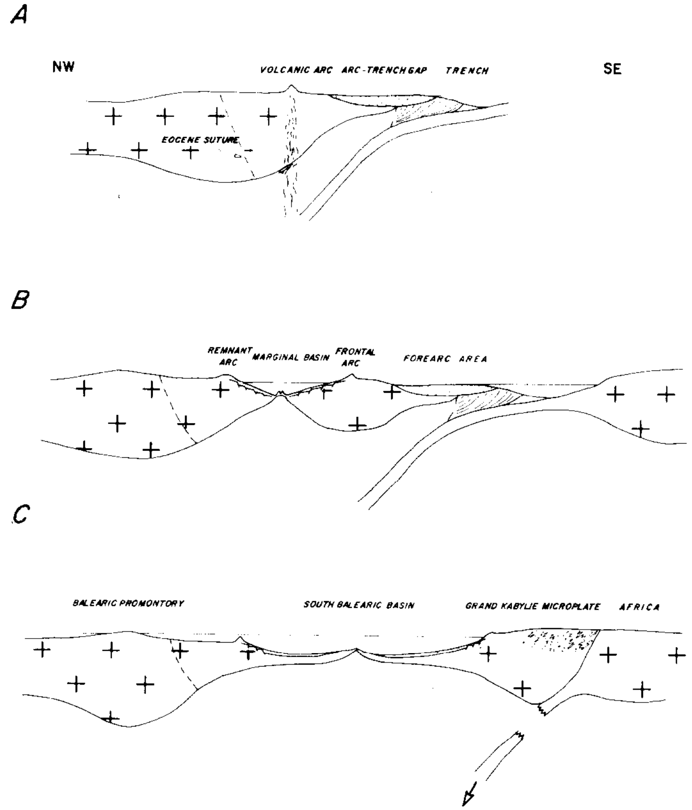

Fig. 5. Schematic cross-sections depicting Miocene evolution of marginal basin between the Balearic promontory and the Grand Kabylie. A. Aquitanian, B. Burdigalian, C. Langhian-Serravallian. Maximum width of South Balearic basin is attained as the Grand Kabylie is sutured to African plate.

in the Grand Kabylie by middle Miocene gravity-driven nappe emplacement (Delteil et al., 1976; Caire, 1978).

The early Miocene deformational phase resulted in the juxtaposition, with southward tectonic polarity, of three paleogeographically distinct terrains: (1) a northern (internal), structurally highest terrain composed of ultra-Kabyle flysch, Paleozoic Kabyle basement and southern Kabyle flysch; (2) an intermediate terrain composed of Massylian flysch, its Triassic—Jurassic carbonate sub-basement and Tellian trough basement; and (3) a southern (external), structurally lowest terrain composed of para-autochthonous and autochthonous pre-Saharan slope and African platform sequences (Caire, 1978).

I postulate that the intermediate flysch terrain probably formed in the subduction zone of a south-facing arc-trench system. Within this framework (Fig. 5), the early Miocene andesitic volcanics and the progressive sedimentary in-filling and deepening of the basin between the Grand Kabylie and the Balearic promontory represent the arc and back-arc region (marginal basin), respectively, related to this north-dipping subduction zone. Hence a polarity flip must have occurred following collision and suturing of the Kabylies and Balearic promontory (Fig. 5).

The absence of late Eocene—Oligocene units in the Tunisian Atlas (Kujawski, 1969) may indicate that the area was emergent during the Paleogene. I suggest that late Eocene—Oligocene strata were eroded during uplift when the area of northern Tunisia, as part of the northward-subducting African plate, flexed outboard of the north-dipping subduction zone (Fig. 5) (cf. Bodine and Watts, 1979).

This tectonic setting culminated in the collision of the Grand Kabylie and the North African continental margin (Fig. 5). The suture from this collision is probably concealed at present beneath the middle Miocene-emplaced gravity nappes (Caire, 1978). This is remarkably similar to the post-Alpine collision gliding of the Prealps in front of the Pennine nappes (Delteil et al., 1976).

### *Algero-Provençal basin sediments and magnetics: continental rifting*

Four *Total* drill holes have penetrated Paleozoic continental basement in the Gulf of Lion (Cravatte et al., 1974) (Fig. 6). In three of the four sites, basal Aquitanian lagoonal—littoral—continental strata rest either unconformably on this basement or on an intermediary basal conglomerate, suggesting that submergence of Gulf of Lion basement was Aquitanian or earlier.

Aquitanian alkali basalt (Cann and Hsü, 1973) and welded dacite ash from DSDP sites 122—123 in the Valencia trough (Fig. 6) suggest that the trough was an extensional regime during the earliest Miocene.

Miocene strata in Corsica give evidence for a major Burdigalian—early Langhian marine transgression (Orszag—Sperber, 1978). This incursion was followed almost immediately by an emergence beginning in the Langhian and continuing through early Tortonian (Orszag—Sperber, 1978).

Magnetic anomalies in the northern Algero-Provencal basin (Galdeano and Rossignol, 1977) describe a crude "zed" pattern (Fig. 6). This "zed" has an E—W-trending "roof" between 42° 30′N 3° 30′E and 43°N 8° 30′E, a NE—SW trending diagonal between 43°N 8° 30′E and 40° 30′N 5° 30′E, and an E—W-trending "base" between 41° 30′N 8° 30′E and 40°N 6°E. This pattern of anomalies, though crude, is most similar to anomalies described in the eastern Pacific by Menard and Atwater (1968) which are attributed to changes in spreading direction.

These data are consistent with an early period (?Chattian—Aquitanian) of continental rifting along an E—W-trend within the present-day Gulf of Lion. The orientation of this early rifting may have been influenced by the presence of a preexisting line of weakness in the Gulf of Lion. This may have been derived from the mid-Cretaceous rotation of the Iberian plate (see Fig.

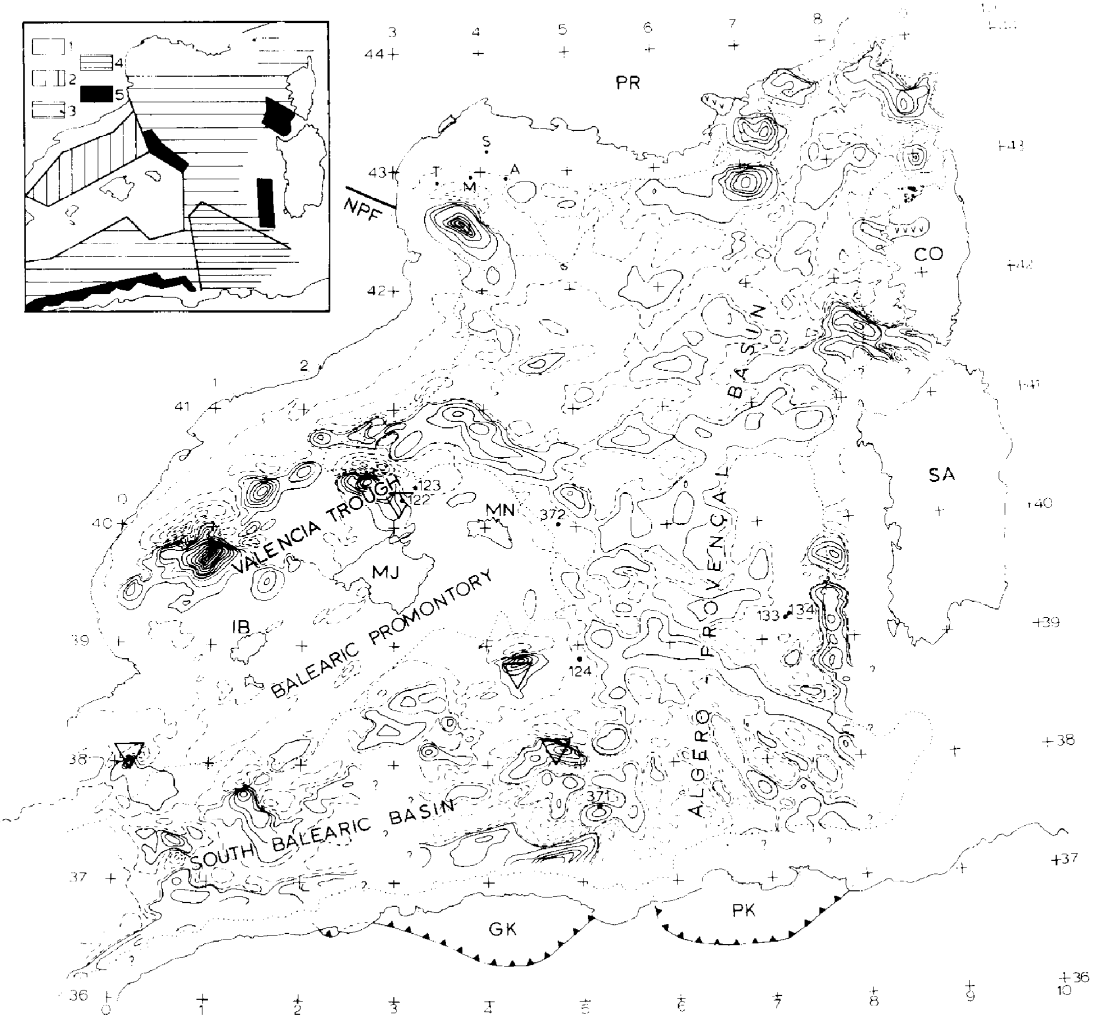

Fig. 6. Locality map of western Mediterranean region. Contours are positive (solid) and negative (dashed) magnetic anomalies compiled by Galdeano and Rossignol (1977), at 50 $\gamma$ intervals. *Total* drill sites (*A* = Autan I, *M* = Mistral I, *T* = Tramontane I, *S* = Sirocco I) and DSDP sites (122—123, 133—134, 371—372) are also shown. Permian volcanics in southern France (*PR*) and Corsica (*CO*) denoted by v symbols. Kabylie allochthons in North Africa (*PK* = Petit Kabylie, *GK* = Grand Kabylie) delimited by barbed line. Other symbols: *SA* = Sardinia; *MN* = Menorca; *MJ* = Majorca; *IB* = Ibiza; *NPF* = North Pyrenean fault; dots = 2000 m isobath; open triangles = submerged volcanoes. Inset: interpretation of magnetics (modified from Galdeano and Rossignol, 1977); *1* = continental crust; *2* = transitional crust; *3* = probable oceanic crust; *4* = oceanic crust; *5* = slope anomalies.

3). N—S-rifting then apparently changed its direction of accretion and NW—SE spreading began. This later period of spreading occurred during the Burdigalian (17—15 Ma) at the rapid rate of 16 cm $yr^{-1}$ (Bellon et al., 1977). The marine transgression in Corsica and its 30° anticlockwise rotation (along with Sardinia) may be explained as a result of this rapid Burdigalian spreading.

### *The Petit Kabylie and Tunisian Atlas structures: microplate—continental margin collision*

Following Eocene collision with the Balearic promontory (Fig. 4) and a limited Oligo-Miocene transgression, subaerial to submarine conditions prevailed in the Petit Kabylie during the Burdigalian (Bolfa et al., 1952). Submarine andesitic flows, lapilli tuffs and andesitic breccias are intercalated within Burdigalian molasse suggesting that calc-alkaline volcanism occurred prior to and during the Burdigalian (Bolfa et al., 1952; Vila, 1971).

Renewed deformation began in the Petit Kabylie in middle Miocene resulting in southward-directed nappe emplacement (e.g. Numidian flysch complex). Structural analysis indicates that following the Eocene—Oligocene hiatus (Kujawski, 1969), SE-vergent imbricate thrust sheets, buckle folds and conjugate shear faults developed during the middle Miocene (Langhian—Serravallian) in the Tunisian Atlas (Caire et al., 1971; Glaçon and Rouvier, 1972; Rouvier, 1977; Carr and Miller, 1979; Cohen and Schamel, 1980; Cohen et al., 1980a). Dynamic analysis suggests that the maximum principal compressive stress ($\sigma_1$) responsible for this progressive deformation was oriented S38°E and horizontal (Cohen and Schamel, 1980; Cohen et al., 1980a). No metamorphic tectonites associated with this fold-thrust belt are known in northern Tunisia, suggesting exposure of a more external portion of the fold belt.

Since the pattern of calc-alkaline volcanism preceding middle Miocene deformation seen in the Petit Kabylie exactly mirrors that seen in the Grand Kabylie and since the timing of deformation in the Tunisian Atlas and the Petit Kabylie immediately post-date the opening of the Algero-Provencal basin, I suggest that these developments are genetically related (Fig. 5). Coeval with Burdigalian spreading in the Algero-Provencal basin was the 30° anticlockwise rotation of Corsica and Sardina (Bellon et al., 1977). If the Petit Kabylie was formerly contiguous with Sardinia, in addition to the Balearic promontory (Cohen et al., 1980a), then not only would it experience an anticlockwise rotation away from the latter as the Algero-Provencal basin opened but its early Miocene calc-alkaline volcanic history would be genetically related to a similar south-facing subduction zone as in the case of Sardinia. This is exactly the tectonic setting described above to explain the Oligo-Miocene volcanic history in Sardinia. I therefore postulate that the middle Miocene deformation in the Petit Kabylie and the Tunisian Atlas represents a collision resulting form Petit Kabylie's anticlockwise rotation with the Corsica—Sardinia—Calabria-plate during opening of the Algero-Provencal basin.

### *The Petit Kabylie and Sardinian structures and marine magnetics: spreading*

Following middle Miocene deformation in the Petit Kabylie and northern Tunisia, a period of extension developed in the eastern Atlas characterized by the deposition of molasse within NE-trending grabens and by bimodal volcanics, K/Ar dated at 10.4—6.6 Ma (Glaçon and Rouvier, 1972; Vass et al., 1974; Cohen and Schamel, 1980; Cohen et al., 1980a).

Southwest of Sardinia the marine magnetics pattern describes a fan of alternating positive and negative anomalies (Bayer et al., 1973) converging on a point located near 39°02′N 5°18′E (Fig. 6). Along the western edge of this anomaly fan, the magnetic trends are aligned approximately N—S; west of the fan, in the area of the South Balearic basin, however, anomalies generally trend NE—SW (Fig. 6).

This fan is interpreted as a sphenochasm which was responsible for the displacement of the Petit Kabylie away from Sardinia (Bayer et al., 1973; Cohen et al., 1980a). Since the area of the sphenochasm is covered by Messinian evaporites, its age is bracketed by the salinity crisis and middle Miocene deformation in the Petit Kabylie and the Tunisian Atlas (Cohen et al., 1980a). This Tortonian age coincides with the age range of volcanism in northern Tunisia, which is attributed to a period of regional extension.

### *The Petit Kabylie and the Grand Kabylie structures: collision*

Major post-Numidian-flysch-emplacement (post-Middle Miocene) shear faulting developed in the Petit Kabylie along two predominant trends: (1) largely continuous, approximately E—W-trending sinistral faults bounding the front of the allochthonous Petit Kabylie and (2) NE-trending dextral faults along which 10—20 km displacement has occurred (Raoult, 1975).

The E—W-trending set, near Constantine, is found in association with 9.3 ± 0.5 and 10.9 ± 0.5 Ma volcanics (H. Bellon, unpublished K/Ar dates, J-F. Raoult, 1979, written communication). These include olivine-bearing potassic trachytes and olivine + high andesine-bearing andesites (Raoult and Velde, 1971). Farther west, the E—W-trending set swings into a more WNW—ESE trend and is associated with radiolarites, pillow lavas, gabbros and serpentinites. These ophiolites structurally underlie the allochthonous Dorsale Kabyle (Paleozoic) basement to the northeast (Boullin et al., 1977). The structural stack is folded along NW-trending axes, vergent to the southwest (Boullin et al., 1977).

In the northeastern part of the Grand Kabylie, Laval (1974) mapped major (>10 km displacement) N70°E-trending sinistral wrench faults that also offset the Numidian flysch complex. South of Alger, Bles (1971) defined NW—SE trending, NE-vergent isoclinal folds and syn-post folding shear faults. The latter are conjugate with N65°E sinistral and N05°W dextral components. The sinistral faults have the same orientations as those mapped by Laval (1974). Dynamic analysis for the conjugate shears gives a maximum principal compressive stress ($\sigma_1$) oriented S35°W. This $\sigma_1$ orientation derived from shear faults thus appears to be spatially (orthogonal to fold trends) and temporally (syn-post folding) related to fold development as well (cf. Cohen and Schamel, 1980).

These data are consistent with a post-middle Miocene collision between the Petit Kabylie and North Africa which applied a SW-directed maximum principal compressive stress on the latter. The conjugate faults in the Grand Kabylie were probably formed at this time. The belt of ophiolites structurally beneath the Dorsale Kabyle basement in western the Petit Kabylie, and its eastward continuation as a series of E—W-trending sinistral faults, is interpreted as the suture of this collision. The 10.9—9.3 Ma volcanics associated with the eastward continuation of the E—W-trending fault set limit the time of post-middle Miocene emplacement to the Tortonian. This coincides temporally with opening of the sphenochasm southwest of Sardinia, suggested to have been responsible for the southwestward displacement of the Petit Kabylie.

## THE MODEL

### *Early movements*

Figure 2 shows a suggested paleogeography that preceded the Cretaceous opening of the Bay of Biscay, sinistral movement along the north Pyrenean fault system and anticlockwise rotation of Iberia (Van der Voo, 1969; Van der Voo and Boessenkool, 1973; Kristoffersen, 1978). The eastward continuation of the trace of the North Pyrenean fault system lies south of Corsica. Previous reconstructions have placed its extension either north of Corsica (Tapponnier, 1977) or south of Sardinia (Dewey et al., 1973). During opening of the Bay of Biscay, the Iberian plate (including the Balearic promontory and Sardinia) rotated 35° anticlockwise (Fig. 3) about a pole located near 50°N 3°18'E (LePichon and Sibuet, 1971).

The accretionary plate boundary responsible for this movement is presently preserved in the Bay of Biscay as a series of fossil ridge-transform fault segments (Williams, 1975; Kristoffersen, 1978). Van der Voo and Boessenkool (1973) and Westphal et al. (1978) postulate that the eastward extent of this plate boundary formerly continued through continental crust of the Iberian and European plates, in the area of the present-day Gulf of Lion (Fig. 3).

Following this movement, Iberia's rotation history, as deduced from paleomagnetic studies, was completed (Fig. 3A). Approximately half of Sardinia's 60° post-Permian rotation history was achieved during this movement (Fig. 3A). Thus Sardinia, as part of the Iberian plate, underwent an *earlier* rotation than Corsica. This contrasts with the hypothesis of Alvarez et al. (1974), who suggest that Sardinia underwent a *later* rotation than Corsica, to open the Straits of Bonifaccio. The hypothesis that Corsica and Sardinia behaved as a single plate since the Hercynian, based on fracture analyses

(Arthaud and Matte, 1977), conflicts with the paleomagnetic data.

During middle—late Eocene, collision between the Balearic promontory and the Kabylies occurred along the southwestern edge of the Iberian plate (Fig. 4). Major NE-trending, NW-vergent structures in the Kabylies indicate a NW-tectonic polarity for this collision (Bourgois et al., 1970; Vila, 1971; Bouillin, 1975; Raoult, 1975; Delteil et al., 1976; Caire, 1978). The absence of Eocene arc-related volcanics in the Balearic promontory or Kabylies suggests that either: (1) no arc terrain associated with this zone of closure ever developed or (2) the arc terrain has since been tectonically eroded.

### *Late Oligocene*

During the late Paleogene an approximately E—W-trending accretionary plate boundary developed in the area of the present-day Gulf of Lion. This orientation may have been dictated by a pre-existing E—W-trending line of weakness representing the eastward continuation of the Iberian plate boundary into the Gulf of Lion (Figs. 3, 7) (Van der Voo and Boessenkool, 1973; Westphal et al., 1976). Timing for the initiation of rifting is limited by the presence of basal Aquitanian lagoonal—littoral—continental strata in the four *Total* sites in the Gulf of Lion (Cravatte et al., 1974). These data indicate that the initial extension must have pre-dated the earliest Miocene sedimentary deposits. Extension is thus considered as late Oligocene; foundering of continental crust commenced by Aquitanian (Ryan, 1976).

In Fig. 7 the developing E—W-rift system is defined by the overlap of similarly trending positive magnetic anomalies in the Gulf of Lion (Galdeano and Rossignol, 1977). The geometry deduced from these anomalies suggests that three E—W-rift segments were connected by approximately N—S-trending dextral transform faults. The dextral transform bounding the western, Cabo Creus ridge segment probably continued south between Menorca and Majorca (Chauve et al., 1978).

During latest Oligocene—earliest Miocene extension along the E—W-rift system, the Corsica—Sardinia—Calabria—Petit Kabylie—Menorca plate moved south with respect to a more southern oceanic plate (Fig. 8). This is consistent with paleomagnetic data from Sardinian volcanics (Bellon et al., 1977). Foundering of pre-existing continental crust during this extension is supported by sedimentological data indicating progressive deepening of the present-day Gulf of Lion during latest Oligocene—early Miocene time (Cravatte et al., 1974). Oligo-Miocene andesitic volcanics in Sardinia are related to a south-facing subduction zone to the south. The arc was active during at least 30—15 Ma (Coulon et al., 1973; Coulon and DuPuy, 1975; Bellon et al., 1977).

Since volcanism began as early as 30 Ma (Savelli, 1975), subduction to the south of Sardinia, along the southern boundary of the Corsica—Sardinia—Calabria-Petit Kabylie—Menorca plate, must have been initiated prior to this time (Fig. 8). South-facing subduction therefore developed prior to the ini-

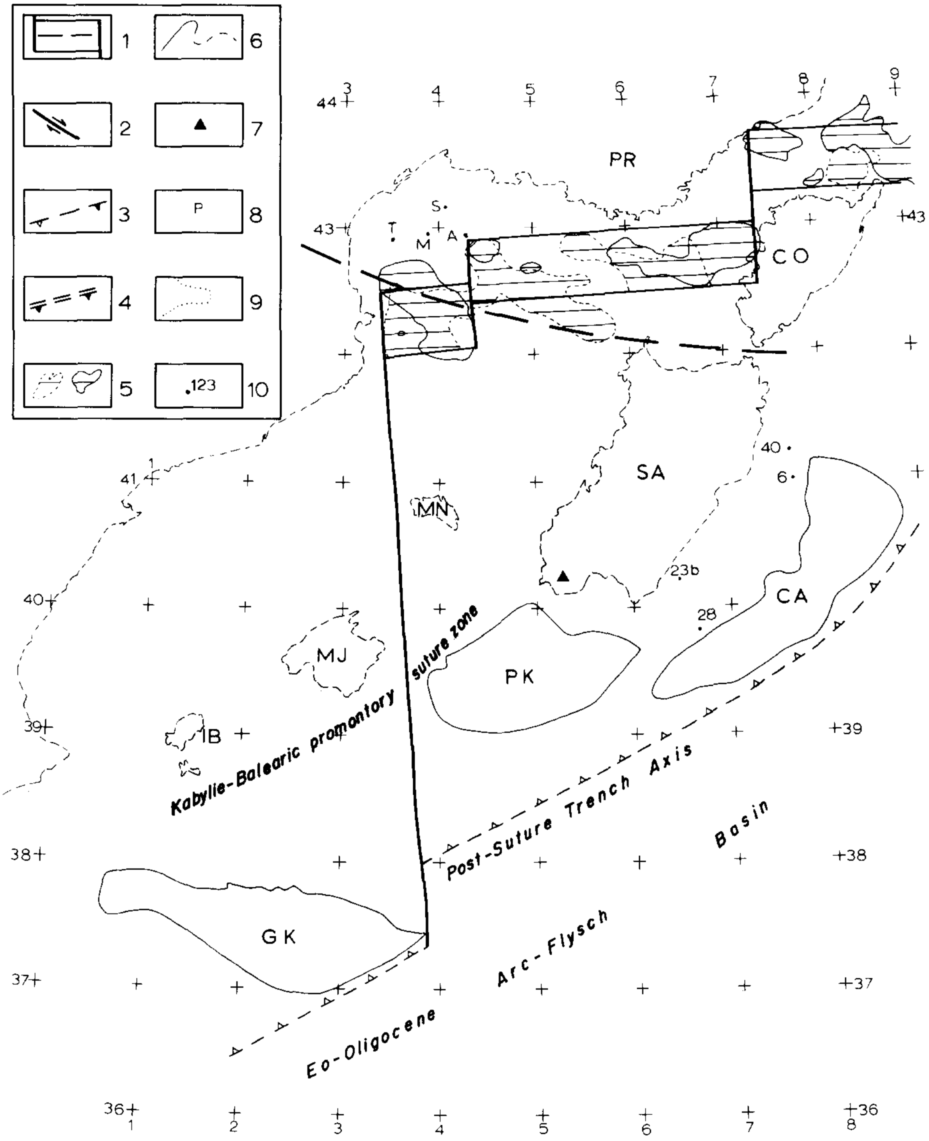

Fig. 7. Early late Oligocene reconstruction. EW-trending rift develops in the Gulf of Lion along a pre-existing line of weakness. The line is represented by the eastward continuation of the North Pyrenean fault system (dashed line) (cf. Fig. 3). Overlap of E—W-trending positive magnetic anomalies (solid and dashed lines) defines three segments of the late Oligocene ridge. The north vergent, late Eocene Kabylie—Balearic promontory suture and related ?arc-flysch basin, south of the Kabylies are shown. This (post-suture) Oligocene-age trench with reversed polarity (cf. Fig. 4) accommodates continued northward movement of Africa relative to Europe. *Total* and CNR drill sites are shown. *1* = ridge segment; *2* = transform fault (arrows where active); *3* = trench (unfilled teeth where active); *4* = suture; *5* = newly formed positive magnetic anomalies; *6* = 2000 m isobath (solid line) and present continental margin (dashed line); *7* = arc volcanism; *8* = pole to spreading system; *9* = eastern limit of Messinian evaporites; *10* = DSDP, CNR and *Total* drill sites.

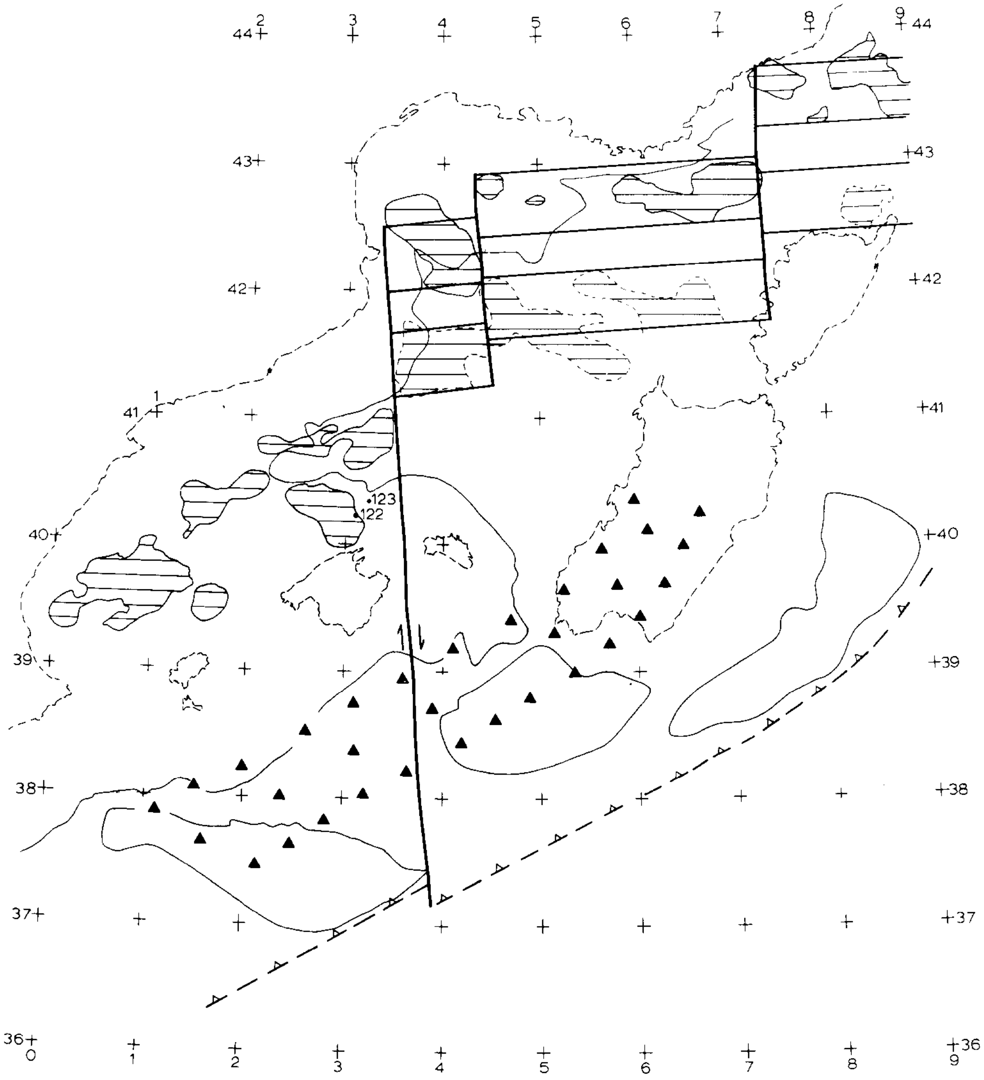

Fig. 8. Latest Oligocene—earliest Miocene reconstruction. Extension along the E—W-trending accretionary boundary in the Gulf of Lion is completed. This results in a relative southward movement of the Corsica—Sardinia—Calabria—Petit Kabylie—Menorca plate. Movement is accommodated along an approximately N—S-trending dextral transform fault between Menorca and Majorca. Subduction of previously formed Eocene—Oligocene ?arc-flysch basin, south of the Kabylies, occurs along a N-dipping Bennioff zone. Calc-alkaline volcanism related to this subduction develops along an arc, concave to the northwest, through Sardinia and north of the Kabylies. Readjustment of spreading from N—S to NW—SE begins, causing extension and alkalic volcanism in the Valencia trough. Symbols as in Fig. 7.

tiation of N—S-rifting in the Gulf of Lion and following the collision of the Kabylies with the Balearic promontory.

These data imply that following late Eocene collision above a south-dipping Benioff zone (Fig. 4), a polarity flip occurred and a north-dipping Benioff zone developed in the late Oligocene (Fig. 5). The time span represented by this interim, 10—15 Ma, is reasonable for slow (1—3 cm $yr^{-1}$) average convergence rates.

The absence of late Eocene—Oligocene strata in the northern Tunisian Atlas is interpreted to indicate that this part of the north African plate represented the outer swell of a plate subducting northwards under Sardinia (Fig. 5). It thus probably experienced uplift and emergence as a result of ?late Oligocene plate flexure (cf. Bodine and Watts, 1979) resulting in the documented erosion of Eocene—Oligocene units.

### *Early—middle Miocene*

The volcanic arc represented in Sardinia probably extended to the west through the area south of the Balearic promontory because calc-alkaline volcanism ocurred in the Kabylies during early Miocene (Bolfa et al., 1952; Vila, 1971; Rivière et al., 1977). Moreover, since there is evidence to indicate major early Miocene SE-directed imbricate thrusting occurred in the Kabylies as well as Aquitanian—Langhian subsidence of a basin between the Balearic promontory and the Grand Kabylie, I postulate that these data imply the development of back-arc spreading in the area between the Grand Kabylie and the Balearic promontory (Figs. 4 and 5).

The back-arc spreading probably culminated in middle Miocene emplacement of the Grand Kabylie in North Africa. Within this tectonic framework the above data represent the following tectonic elements (Fig. 5): (1) SE-vergent imbricate thrusting in the Grand Kabylie represents deformation in the fore-arc (subduction zone) area; (2) volcanics of the northern part of the Grand Kabylie represent the frontal (volcanic) arc; (3) the progressive sedimentary transition to deeper water assemblages represents infilling during subsidence of the back-arc basin with two distinct source areas: (a) Paleozoic clasts derive from the Dorsale Kabyle basement terrain in the Grand Kabylie to the south and (b) greywackes with unequivocal Majorcan-provenance derive from the Balearic promontory to the north; (4) a NE-trending series of submerged volcanoes south of the Balearic promontory, in the South Balearic basin, represent the remnant arc terrain. Evidence for its along-strike continuation to the southwest exists in Malaga (Spain) where volcanics with similar petrochemical affinites and ages are found (Rivière et al., 1977); and (5) NW-vergent thrusting and folding in the northern Balearic promontory represents the back-arc area. This deformation was caused by gravity-gliding (Bourrouilh, 1973; Bourgois et al., 1970; A. Mauffret, 1979, personal communication) following marginal basin opening.

Coeval with early Miocene back-arc spreading, N—S-rifting to the north

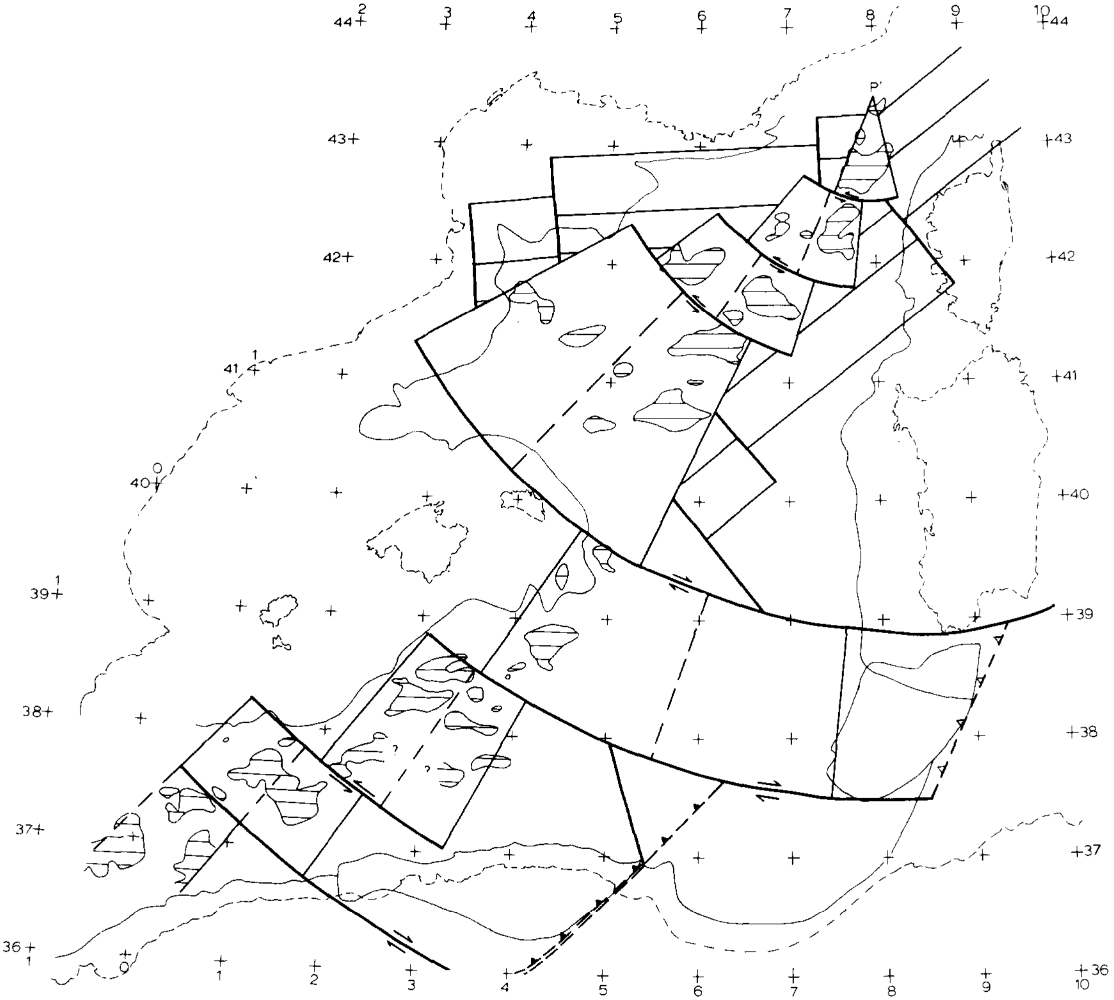

Fig. 9. Late early—middle Miocene reconstruction. Formation of the Algero-Provencal and South Balearic basins. The Corsica—Sardinia—Calabria—Petit Kabylie plate rotates 30° anticlockwise about a pole ($P'$) near 43°25'N 8°00'E relative to Europe. Back-arc spreading in the area of the Kabylies—Balearic promontory results in marginal basin formation behind the Kabylies and the effects the emplacement of the Grand Kabylie in Algeria. Opening of the Algero-Provencal basin results in contemporaneous collision of the Petit Kabylie with the Tunisian continental margin and (not shown) Corsica—Calabria with the western Italian continental margin. Symbols as in Fig. 7.

apparently attempted to readjust its direction of extension to NW—SE (Fig. 9). This readjustment may have been accommodated by the development of NW—SE extension in the area of the present-day Valencia trough. The Aquitanian alkali basalt and welded dacite ash at DSDP 122—123 and a major NE-trending escarpment immediately north of the Balearic promontory are consistent with incipient continental rifting. NW—SE spreading along a NE-trending ridge system began in the Algero-Provencal Basin at approximately 17 Ma. Spreading about a pole near 43°25'N 8°E (*P'*, Fig. 9), the Corsica—Sardinia—Calabria—Petit Kabylie plate rotated 30° anticlockwise relative to stable Europe. This rotation accounts for the paleomagnetic data from post-Permian lavas in Corsica and, together with the earlier (mid-Cretaceous) 35° rotation of the Iberian plate (which included Sardinia and the Balearic promontory), explains Sardinia's 60° post-Permian rotation history. Geochronologic and paleomagnetic data from Sardinian volcanics suggest that rotation of the Corsica—Sardinia—Calabria—Petit Kabylie plate occurred during 17—15 Ma. At the latitude of southern Sardinia, movement would have been at the rapid rate of 16 cm $yr^{-1}$. The major Burdigalian—Langhian transgression in Corsica may relate to this rapid opening.

Subduction of older (?Tethys) oceanic crust to the east of the Corsica—Sardinia—Calabria—Petit Kabylie plate must have been coeval with opening of the Algero-Provencal basin. This closure resulted in contemporaneous (late early—middle Miocene): (1) collision of Corsica with the northern Italian continental margin and the formation of the northern Apennines (Radicati di Brozolo and Giglia, 1973; Boccaletti and Guazzone, 1974; Kligfield et al., 1977; Carmignani et al., 1978; Kligfield, 1980; Cohen et al., 1980b); (2) collision of Calabria with the southern Italian continental margin and opening of the Tyrrhenian (marginal) basin (Boccaletti and Guazzone, 1974; Ogniben, 1973; Carrara and Zuffa, 1976; Alvarez, 1978); and (3) collision of the Petit Kabylie with the North African continental margin and the formation of the eastern Atlas (Caire et al., 1971; Claçon and Rouvier, 1972; Rouvier, 1977; Carr and Miller, 1979; Cohen et al., 1980a). The structural vergence of each of these fold belts is ESE suggesting that the direction of subduction was WNW. This is consistent with the polarity deduced for the late Oligocene subduction to the south of Sardinia (Fig. 7).

### *Early late Miocene*

Following middle Miocene collision of the Petit Kabylie with the North African continental margin and emplacement of the Grand Kabylie in northern Algeria, NE-trending graben development and Tortonian basaltic volcanism occurred. This extensional regime reflects a probable change in plate geometry from that shown in Fig. 9 to that in Fig. 10. The SE-convergence of the Petit Kabylie towards the Tunisian continental margin terminated and spreading was initiated along a NW—SE trending sphenochasm, southwest of Sardina (Fig. 10) (Bayer et al., 1973; Cohen et al., 1980a).

Earlier workers (Boccaletti and Guazzone, 1974; Alvarez et al., 1974) have suggested a more direct SE-translation of the Petit Kabylie from its late Oligocene location south of Menorca to its present location, analogous to the Miocene movement history of the Grand Kabylie. Bayer et al., (1973), how-

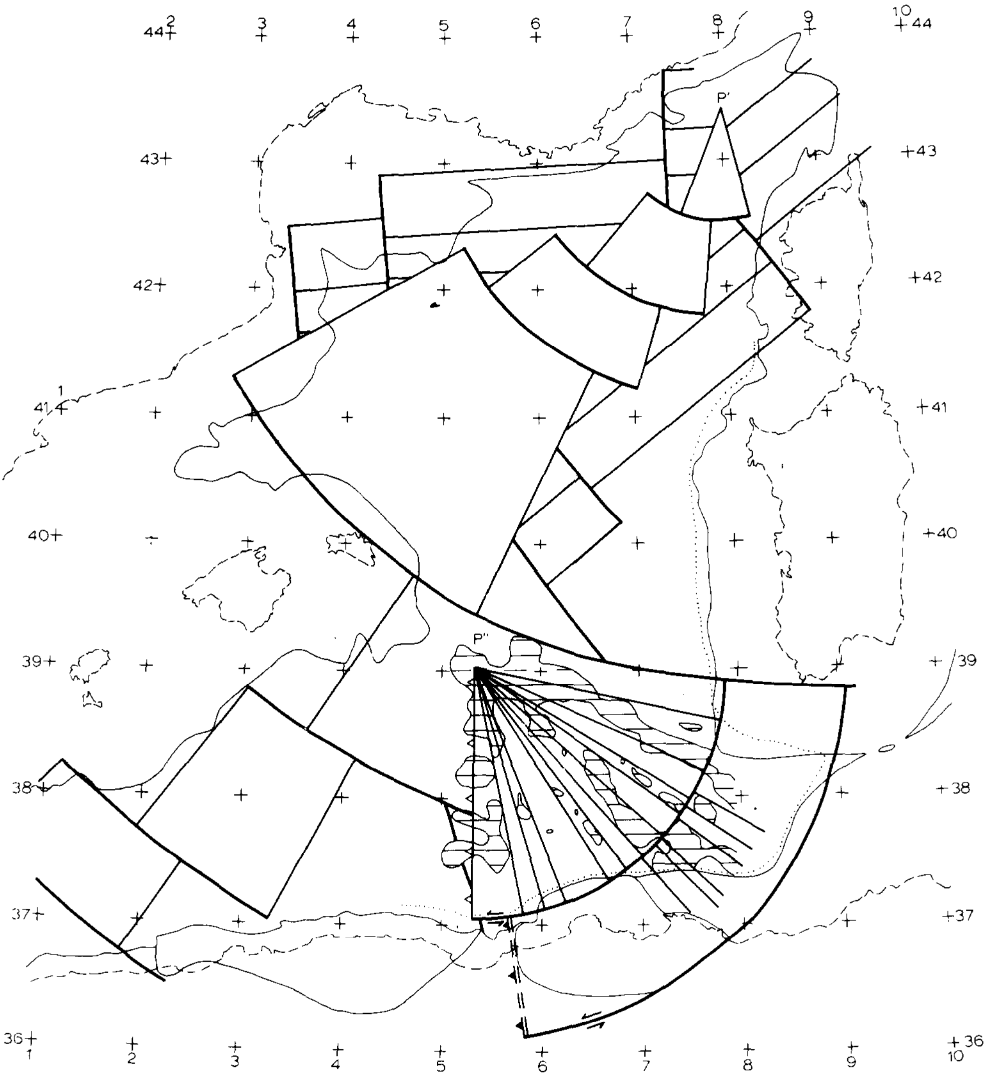

Fig. 10. Early late Miocene reconstruction. Development of a sphenochasm to the southwest of Sardinia. Following collision of the Petit Kabylie with the northern African continental margin, a sphenochasm develops and begins spreading. The Petit Kabylie rotates clockwise away from Sardinia. Subduction along a N—S-trending trench to the west of the sphenochasm consumes oceanic crust formed both previous to and during spreading. Consumption of this relatively new and hot crust results in underplating of the South Balearic basin west of the trench. Cessation of spreading occurs when the ridge itself is subducted and the Petit Kabylie collides again with North Africa. Gravity and marine magnetic data suggests that the "South Menorca Horst" of Mauffret (1976) and its associated volcanics and normal faults, which trends N—S between Menorca and Algeria, may delimit the position of the subducted ridge axis.

ever, defined magnetic anomalies southwest of Sardinia which suggest a radial pattern of spreading about a pole (*P''*, Fig. 10) located near 39° 02′N 5° 18′E. The petit Kabylie's displacement history probably relates to this radial pattern. Following an initial southeastward movement away from Menorca as part of the Corsica—Sardinia—Calabria plate, the Petit Kabylie moved southwest, away from Sardinia, as the sphenochasm opened.

NW-trending isoclinal folds and conjugate shear faults with their acute bisector trending N35° E—S35° W in the Grand Kabylie and major E—W-trending sinistral and NE—SW trending dextral faults in the Petit Kabylie affect the middle Miocene-emplaced Numidian flysch complex. To the east of the Petit Kabylie the E—W-trending fault set is associated with Tortonian olivine-bearing volcanics; to the west, it is associated with ophiolites (Raoult and Velde, 1971; Raoult, 1975; Bouillin et al., 1977). These data are interpreted to indicate a post-middle Miocene maximum principal compressive stress ($\sigma_1$) acted on the Grand Kabylie and northern Africa and was oriented NNE—SSW. It probably derived from the southwestward movement of the Petit Kabylie away from Sardinia. The duration of sphenochasm opening is given by the age of deformation and by the post-spreading Messinian evaporites within the sphenochasm (Fig. 10). The deduced Tortonian age corresponds very well with the age of both bimodal volcanics in northern Tunisia and olivine-bearing volcanics in the Petit Kabylie.

In the absence of any indication of northward movement of Corsica and Sardinia, a subduction zone to the west of the sphenochasm is geometrically required to accommodate its opening (Fig. 10). Although *prima facia* evidence for the former presence of the trench is lacking, several lines of evidence suggest that it existed where shown in Fig. 10: (1) the deflection of free air gravity anomalies into N—S-trending (negative) "trough" and (positive) "ridge" couplet, respectively, along and immediately west of the postulated trench axis (Morelli et al., 1975); (2) a N—S-trending Bouguer gravity anomaly "trough" between positive (>200 mgal) "ridges", located south of Menorca (Morelli et al., 1975); and (3) the juxtaposition of magnetic anomalies with distinctly different trends (NE—SW to the west, N—S to the east, respectively) across the postulated trench axis (Galdeano and Rossignol, 1977).

Drilling at DSDP sites 125 and 371, on the postulated trench axis, unfortunately failed to provide positive evidence for the trench's former existence: both holes bottomed out in Messinian evaporites, which post-dated consumption along the trench. However, the bathymetric ridge ("South Menorca Horst" of Mauffret, 1976) responsible for the observed Bouguer anomaly is associated with N—S-trending normal faults and pre-Messinian volcanics (Mauffret, 1976). These features, as well as the drastic thickness differences of Messinian evaporites found on the horst compared with that on either side, are all consistent with the hypothesis that the "South Menorca Horst" formed in the Tortonian as a result of ridge subduction. I suggest that the horst as well as its associated volcanics and normal faults may represent the present-day position of the subducted sphenochasm axis.

Subduction along the trench thus consumed oceanic crust formed both previous to (during rotation of the Corsica—Sardinia—Calabria—Petit Kabylie plate away from Europe) and during spreading along the sphenochasm axis (during rotation of the Petit Kabylie away from Sardinia). The evolution of similar ridge—trench systems in the northeastern Pacific is described by Menard (1978). Due to the relatively high temperature of this just-formed oceanic crust and its low thermal contrast with the surrounding mantle, its descent may have resulted in underplating of the South Balearic basin floor, west of the trench axis (cf. Vlaar and Wortel, 1976; DeLong and Fox, 1977; Molnar and Atwater, 1978) rather than extensive arc volcanism.

The above interpretation suggests that early late Miocene opening and clockwise rotation of a sphenochasm, southwest of Sardinia, was responsible for the emplacement of the Petit Kabylie in North Africa. This rotation caused a SW-directed maximum principal compressive stress to act on the North African continental margin resulting in major deformation. Deformation and subduction ceased when the sphenochasm ridge axis was itself subducted. Its present location is probably below the South Menorca Horst.

## CONCLUSIONS

The present synthesis incorporates a wide variety of data into a kinematic model for the Oligo-Miocene evolution of the western Mediterranean. It differs in detail from previous plate tectonic models notably in the interpretation of: (1) the rotational histories of Corsica, Sardinia and Iberia; (2) the movement history of the Petit Kabylie; and (3) the sea-floor magnetic data. Earlier syntheses have not employed the magnetic data, perhaps due to their sometimes ambiguous patterns and difficulties in their correlation (Alvarez et al., 1974). The ambiguous patterns are probably related to the nature of the anomalies themselves, having been formed during a phase of rapid (16 cm $\mathrm{yr}^{-1}$) spreading. Difficulty in their interpretation may be compounded by the thick sedimentary blanket that rests atop the Mediterranean oceanic-crust. Although the present plate tectonic synthesis is *not based upon an interpretation of the magnetic data* and the interpretation offered here may not be unique, it is nonetheless consistent with and supported by presently available data.

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