3. A REVIEW OF CIRCUM-TYRRHENIAN REGIONAL GEOLOGY[1]

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The Tyrrhenian basin (Fig. 1) is located in a very complex structural setting, between the Alpine units of the Alps-Betic belt on one side in Corsica and Sardinia, and the Apenninic units of the Tellian-Sicilian-Apenninic belt on the other side. Finally, the evolution of the Tyrrhenian basin and of the Calabrian arc are linked together.

This paper attempts a synthetic review of the geology of the perityrrhenian emerged areas. It contains facts and ideas derived from an enormous number of bibliographic sources dealing with those zones. The references reported in each major section are not intended to be exhaustive. They represent the papers we selected and utilized extensively for the review, and provide a list of additional basic references for the interested reader.

THE SARDINIA-CORSICA BLOCK

These islands constitute a segment of the European Alpine system that was displaced and rotated during lowermost Miocene time by the formation of the western Mediterranean basin.

References for this section are Amaudric du Chaffaut, 1980; Anonymous, 1974; Argand, 1924; Barberi et al., 1974; Beccaluva et al., 1976, 1978; Bigi et al., in press; Boccaletti and Guazzone, 1970; Carmignani et al., 1986; Caron et al., 1980; Chabrier and Mascle, 1974, 1975, 1984; Cherchi and Montadert, 1982; Cherchi and Tremolieres, 1984; Cocozza, 1972; Cocozza et al., 1974; Coulon, 1977; Dal Piaz, 1974; Nardi, 1968; Orszag-Sperber, 1978; Thomas, 1986; and Vai, 1980.

1. The Pre-Alpine Basement

Pre-Alpine basement crops out in Sardinia (Fig. 2) and in western Corsica (Fig. 3). Paleozoic and possibly Precambrian rocks are often strongly deformed and metamorphosed. Several tectonic events are recognized, belonging mainly to the Hercynian orogeny; pre-Hercynian (Sardic) folding is known in southern Sardinia. An axial metamorphic belt occurs in northern Sardinia and southern Corsica with amphibolite facies which is sometimes strongly migmatised, and with sporadic relics of older granulitic and eclogitic facies. The metamorphic gradient and the deformations decrease southwestward in Sardinia and northeastward in Corsica. The general structural trends are northwest-southeast. The units are much less metamorphosed in southwest Sardinia and include Cambrian and Devonian dolomites of platform to deep-water facies. The whole area has been intruded by several generations of granitoids ranging in age from 315 to 280 million years (Ma). The general Paleozoic evolution of the whole area shows affinities with that of the Central Massif and of Provence in France.

2. The Alpine Cycle

In Sardinia, formations belonging to the Alpine cycle (Fig. 4) occur with different facies in different places: (1) Late Triassic to Late Cretaceous carbonate platform facies with strong Provencal affinity in west Sardinia; (2) Mesozoic continental and shallow-water facies predominate in central and east Sardinia. All these sequences are gently folded and block-faulted, with the deformation increasing eastward. Some decollements occur in west Sardinia along evaporitic layers of Late Triassic age; the age of such deformation is mainly late Eocene, but east-west Aquitanian compressional structures have also been detected.

Several true Alpine units are present in Corsica (Figs. 5 and 6). They are strongly deformed and metamorphosed.

The autochthonous units show a metamorphic or granitoid basement and a metasedimentary cover that begins with Malm carbonates. The parautochthonous units show either a Hercynian basement and flyschlike cover sequences (Malm to Upper Cretaceous) or Permian volcanics and a more or less complete sequence of Mesozoic cover similar to the Briançonnais Zone of the western Alps. The nappe units show strong polyphase deformation and metamorphism in high-pressure/low-temperature conditions. Two main groups of nappes occur: (1) metasedimentary nappes ("schistes lustres"), mainly composed of calc-schists with clear Piemontese affinity; (2) ophiolite-bearing nappes, with dismembered oceanic basement and a cover that is usually metamorphosed, with strong Piemontese and Ligurian affinities.

Metamorphism and deformation developed since Late Cretaceous time. Pre-Eocene phases had a westward vergence, Eocene phases an eastern (Apulian) one. Late Oligocene deformations are rather surficial.

3. Postorogenic Sequences of the Alpine Cycle (Fig. 7)

Postorogenic sequences occur inside late-tectonic grabens in three different areas: (1) the Sassari-Campidano trough in Sardinia; (2) the Bonifacio, Corte, and Nebbio basins in Corsica; (3) the Corsican eastern coastal plain. Moreover, very small basins exist in eastern Sardinia (Orosei).

The Sassari-Campidano trough results from a north-trending polyphased rifting. The main phase is late Oligocene to early Miocene in age and is correlated to the opening of the Provencal basin. Pre-rift sequences (late Eocene-early Oligocene) are continental. Syn-rift sequences display an evolution from continental to marine detrital facies. They include thick intercalcations of calc-alkaline volcanics related to a westward-dipping subduction zone coeval with the opening of the Provencal basin and to the counterclockwise rotation of the Corsica-Sardinia block. Post-rift sequences include silty marls followed by lagoonal-lacustrine facies, suggesting a gentle but continuous subsidence. Such intervals are tilted and faulted, though not severely, and crossed by alkaline volcanics 4.9 to 5.7 Ma old, characterizing a Messinian tensional tectonic event. Early Pliocene follows unconformably, but it is very thin or even missing in places. Some 3 Ma ago a new tensional tectonic event was marked by more alkaline volcanics. In the Campidano portion of the trough, a late Pliocene to Pleistocene subsidence is re-

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[1] Kastens, K. A., Mascle, J, Auroux, C., et al., 1987. *Proc., Init. Repts. (Pt. A), ODP*, 107.

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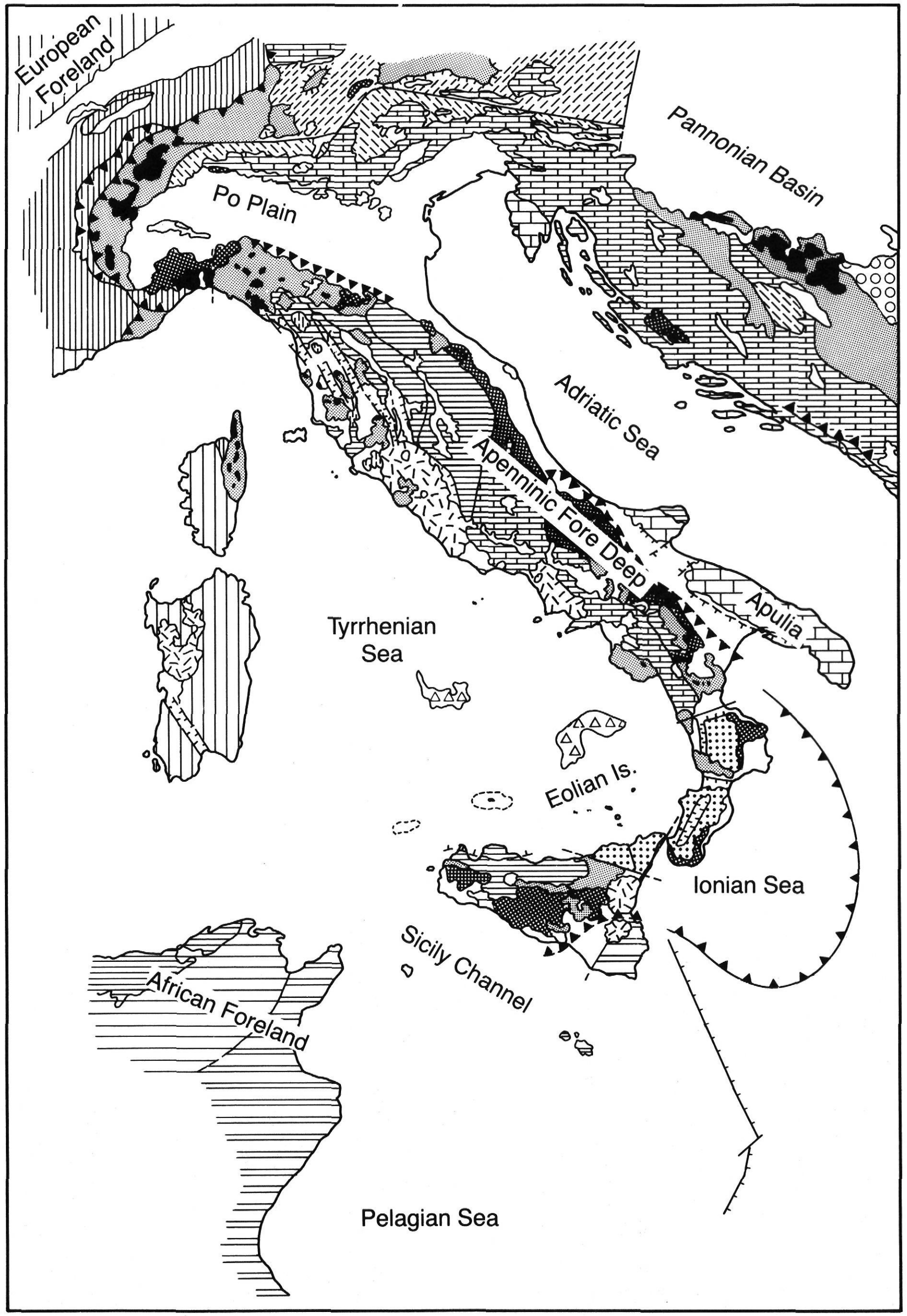


Post-orogenic successions.

Late-orogenic successions.

Tertiary and Quaternary volcanic and plutonic rocks.

TYRRHENIAN SEA

Volcanic seamounts (mainly tholeiitic).

"EUROPEAN" UNITS
(Both stable and mobilized European crust)

Foreland.

Continental margin deformed by alpine orogenesis
(ancient crystalline nuclei and their sedimentary cover).

INTERNAL UNITS

a b

Mesozoic and Cenozoic pelagic successions, with alpine ophiolites; (a) locally carbonate platforms. (b) frequent metamorphism, usually allochthonous.

Calabria-Peloritani Zone.

Golija, Vardar, Pelagonian Zones.

"AFRICAN" UNITS
(Both stable and mobilized African crust)

1
2 3

Foreland. 1: undeformed; 2: folded 3: carbonate platforms of the Adriatic plate).

Continental margin deformed by alpine orogenesis:

a b

(a) Mesozoic carbonate platforms (and related Cenozoic flysches); carbonate units of the austroalpine nappes; (b) Mesozoic basins and pelagic shallows (and related Cenozoic flysches).

a b c

(a) Pre-Triassic basement of the Southern Alps, generally metamorphic (b) metamorphic units of the austroalpine nappes; (c) Tuscan "Autochthon".

Thrust fault

Normal fault

Figure 1. Main structural units of the central Mediterranean area. After Praturlon (1975).

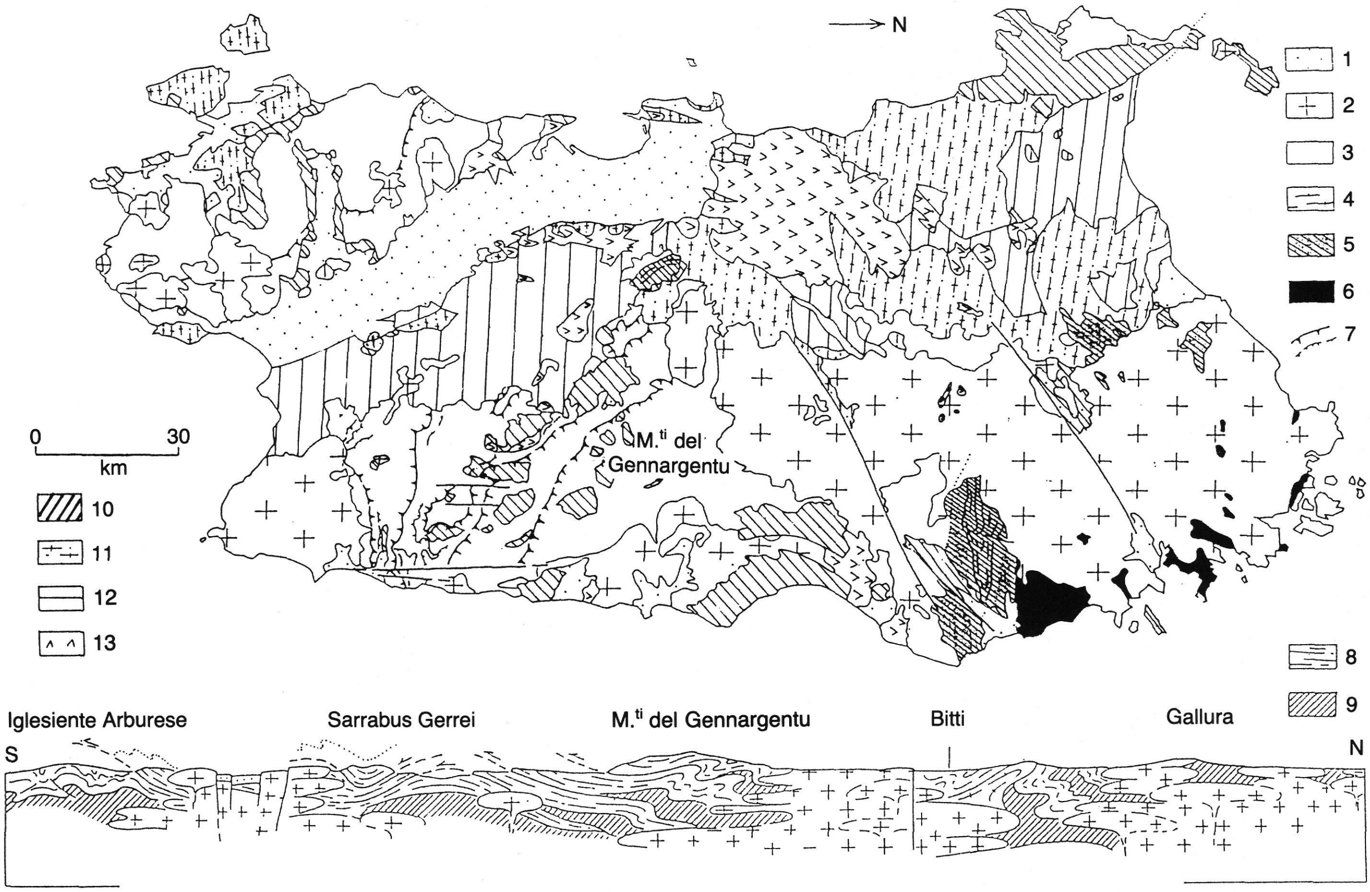


Figure 2. Geological map of Sardinia and schematic cross section of the Hercynian structures. 1. Quaternary; 2. Granitoids; 3. Anchimetamorphic Paleozoic of southern Sardinia and greenschist facies metamorphites; 4. Orthogneiss; 5. Intermediate pressure amphibolite facies; 6. Migmatites (intermediate pressure amphibolite facies) with relics of granulite of eclogite facies; 7. Major and minor thrusts; 8. Sedimentary cover; 9. Basement; 10. Sedimentary cover (Permian to Eocene); 11. Oligocene-Miocene calc-alkaline volcanites; 12. Oligocene-Miocene sedimentary rocks; 13. Quaternary volcanites. Modified after Carmignani et al. (1980).

corded by fluviodeltaic sequences about 600 m thick. Two short-lasting and minor compressional events are identified at Burdigalian and Messinian times.

In the central Corsica basins, shallow-water bioclastic carbonates of early Burdigalian age unconformably overlie the Alpine units.

In the Corsica eastern coastal plain late Burdigalian conglomeratic layers with Ostreids again unconformably overlie the Alpine units. They are followed by a thick Langhian shallow-water formation, whose thickness increases toward the Tyrrhenian Sea. After a hiatus encompassing Serravallian to early Tortonian, thick marine sequences reappear in Tortonian time, followed by Messinian deltaic facies that mark the end of sedimentation.

The small basins of eastern Sardinia (Orosei Gulf) are characterized by coarse deltaic formations. The basins are located close to fault scarps and are associated with alkaline volcanism whose latest manifestations are 0.14 Ma old.

THE NORTH TYRRHENIAN AREA

The northern Tyrrhenian Sea connects eastern Corsica to the northern Apennines (Fig. 8). The western portion (between Corsica and Elba islands) contains a very thick sedimentary sequence, the extension of the eastern Corsica coastal basin. The eastern part is directly connected to the northern Apennines, with horst and graben structures developing after upper Tortonian time above previously deformed east-verging thrust units. Important granitic to granodioritic bodies of upper Tortonian (Elba, Montecristo Islands) to Pliocene (Giglio Island) age also occur in the area.

THE APENNINES

The Apennines are characterized by Neogene deformations with an Apulian-African vergence, which sometimes affect older Alpine units with European vergence. The orogenic system will be described from north to south.

NORTHERN APENNINES

The northern Apennine segment merges to the north with the Maritime Alps and is bounded to the south by the Ancona-Anzio Lineament (Figs. 9–11).

References for this section are AGIP, 1974; Bartolini et al., 1983; Boccaletti and Guazzone, 1970; Castellarin and Vai, 1986; Dallan Nardi and Nardi, 1974; Elter, 1980; Elter et al., 1975; Fazzini and Gelmini, 1984; Haccard et al., 1972; Merla, 1952; Nardi, 1968; Ogniben et al., 1975; Patacca and Scandone, 1986; Pieri and Groppi, 1981; Ricci-Lucchi et al., 1982; Sestini, 1970; and Sturani, 1973.

1. The Chain

1. A. Internal Units

The internal units are mostly characterized by an oceanic substrate, with Jurassic ophiolites of the Tethyan domain, and

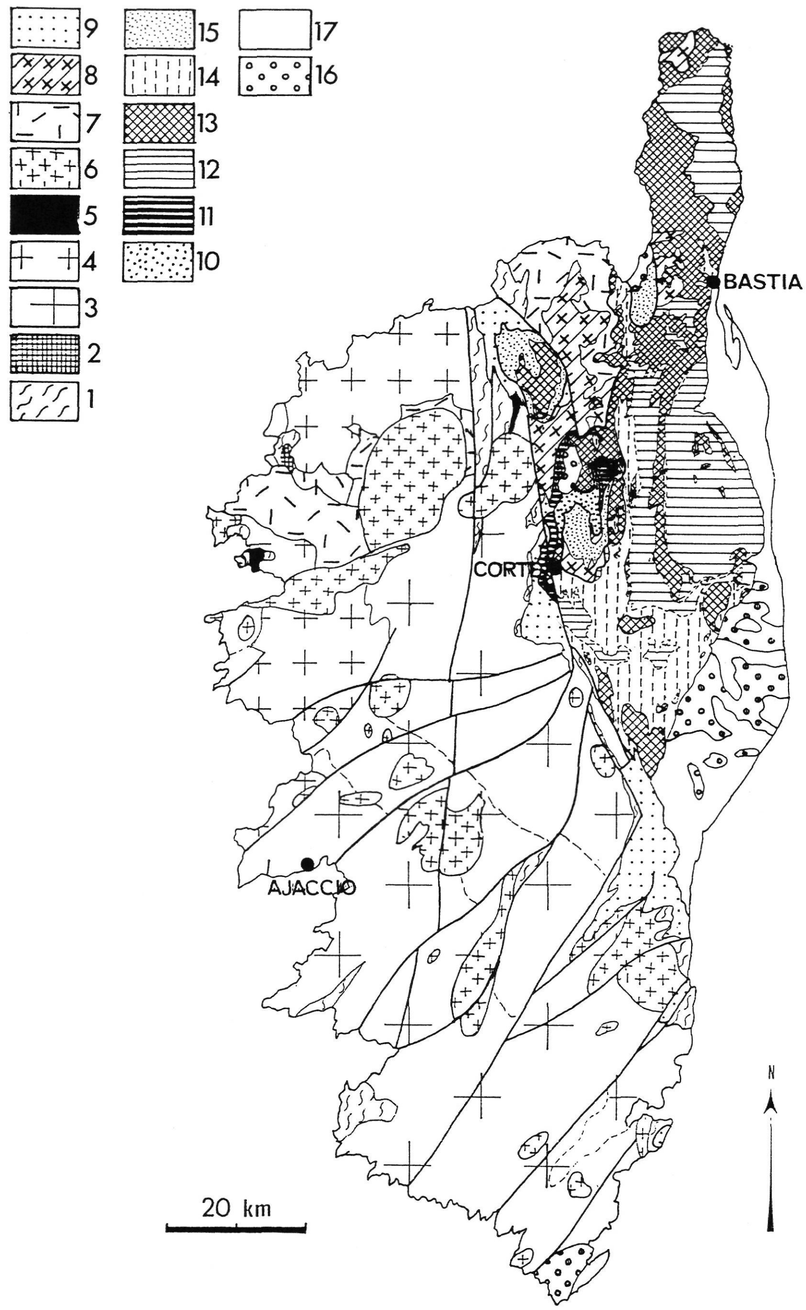


Figure 3. Geological map of Corsica. 1. Pre-Hercynian metamorphic basement; 2. Ordovician to Devonian; 3. Calc-alkaline batholiths; 4. Subalkaline batholiths; 5. Late Carboniferous and Permian; 6. Ring-dike complexes; 7. Calc-alkaline volcanites and volcano-detritic rocks; 8. Granitoids and metamorphites in Alpine Corsica; 9. Autochthonous sedimentary cover; 10, 11, 12. Allochthonous sedimentary units; 13. Ophiolites; 14. Supraophiolitic Ligurian "schistes lustres"; 15. Uppermost allochthonous units; 16. Miocene; 17. Quaternary. After Amaudric du Chaffaut (1982).

by their cover of deep-water sediments and/or flysch deposits of Mesozoic to Paleogene age. These are known as the Ligurian units, and include superposed nappes which often contain highly chaotic materials (argille scagliose) mainly along the northern side of the Apennines. Nappe emplacement occurred during Paleocene-upper Eocene with a European vergence (Ligurian phase). Final destination occurred during Miocene phases (Aquitanian-Burdigalian and Tortonian) with an opposed (Apulian) sense of transport. Presently such units are dissected into grabens of Messinian to post-Messinian age, related to the extensions accompanying stretching in the Tyrrhenian Sea. Various magmatic manifestations (granites, subvolcanic bodies, etc.) accompany this extension along the inner margin of the chain.

The Canetolo nappe is an internal unit composed of Tertiary deposits with an important fraction of andesitic volcanogenic sandstones; it was deformed between Aquitanian and middle Miocene. It is obviously related to the Sardinian calc-alkaline arc and to the development of the western Mediterranean basin.

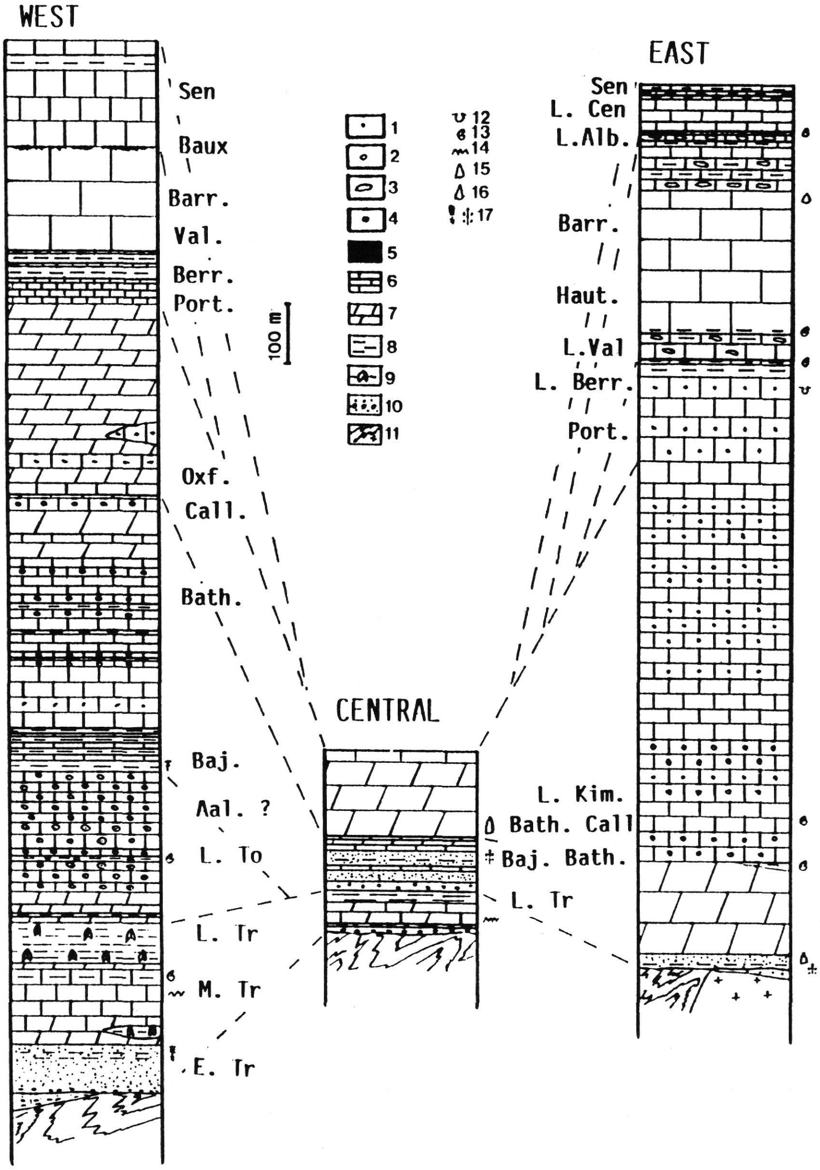


Figure 4. Mesozoic-Eocene lithostratigraphy of Sardinia. E.: Early; M.: Middle; L.: Late; Tr.: Triassic; To.: Toarcian; Aal.: Aalenian; Baj.: Bajocian; Bath.: Bathonian; Call.: Callovian; Oxf.: Oxfordian; Kim.: Kimmeridgian; Port.: Portlandian; Berr.: Berriasian; Val.: Valanginian; Haut.: Hauterivian; Barr.: Barremian; Baux.: Bauxite; Alb.: Albian; Cen.: Cenomanian; Sen.: Senonian. 1: Hercynian metamorphic basement; 2: Hercynian granites; 3: conglomerates and coarse sandstones; 4: sandstones; 5: siltstones; 6: evaporites (mainly gypsum); 7: dolomites; 8: massive platform limestones; 9: micrites; 10: marls; 11: bauxites; 12: calpionellids; 13: ammonoids; 14: rhizocorallium; 15: nerineids; 16: orbitolinids; 17: plant fragments (*Equisetum* and leaves). After G. Chabrier (pers. comm.).

1. B. External Units

The substrate of the external units is continental and is known from outcrops and from wells. It starts with a Hercynian sequence, including albitic schists, lenses of *Orthoceratydae* limestones, volcaniclastic sequences ("Porfiroidi"), and schists with plant debris. Above quartzarenitic to quartzruditic deposits (Triassic), the cover includes neritic dolomites (Upper Triassic-Lower Liassic) containing the famous Carrara marbles (Hettangian). From Sinemurian to Paleogene time a pelagic sequence composed of radiolarites and cherty and foraminiferal limestones developed everywhere with occasional hiatuses and condensed intervals (seamounts). To the east and south of the region (central Apennines and northern Adriatic Istria area), carbonate platform facies last throughout the whole Mesozoic. The Tertiary cover varies according to the different domains.

1. B. 1. Internal (Tuscan) Domain

In the internal domain, units metamorphosed in the greenschist facies (Apuane, Massa units) are overthrust by the unmetamorphosed Tuscan nappe. The sequences making up all units are essentially the same (except for the metamorphism that developed up to lower Miocene) and terminate with a flysch deposit (Pseudo-Macigno and Macigno Formations) spanning from

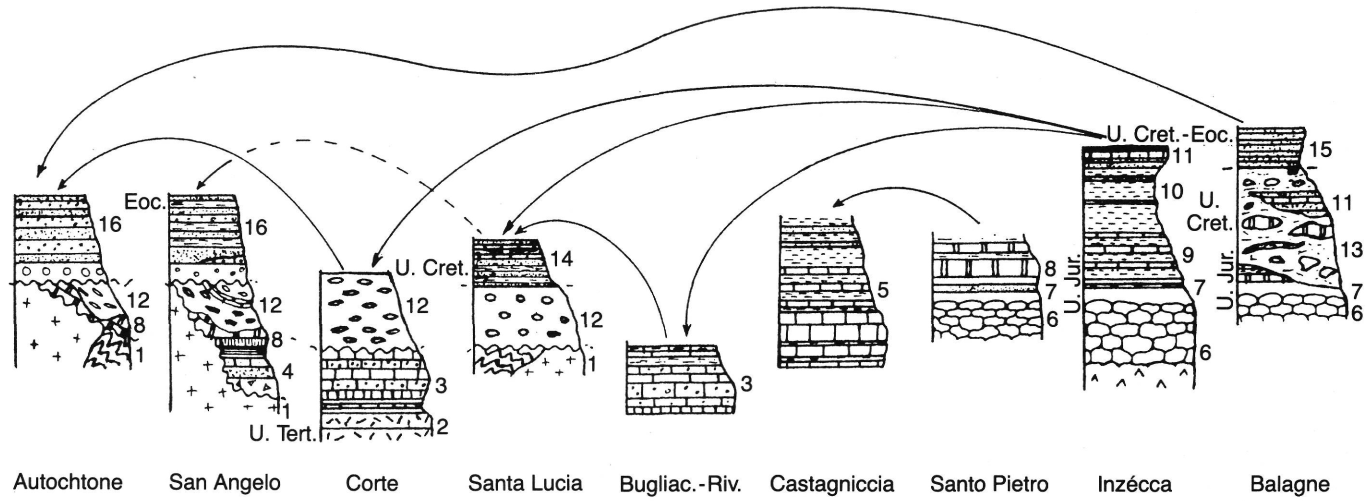


Figure 5. Mesozoic-Eocene lithostratigraphy of Corsica. 1. Metamorphic and granitic basement; 2. Triassic dolomites; 3. Liassic(?) limestones and breccias; 4. Middle Jurassic of San Angelo unit; 5. Castagniccia unit; 6. Ophiolites; 7. Radiolarites; 8. Terminal Jurassic limestones; 9. Schists and limestones (Lower Cretaceous conglomerates); 10. Schists and quartzites; 11. Eocene calcarenites; 12. Upper Cretaceous(?) conglomerates; 13. Wildflysches; 14. Flysch of Santa Lucia unit (Upper Cretaceous); 15. Allochthonous gritty formation of Balagne (terminal Cretaceous-Eocene); 16. Eocene conglomerates and flysches. After Caron et al. (1980). Eoc. = Eocene. U. Cret. = Upper Cretaceous.

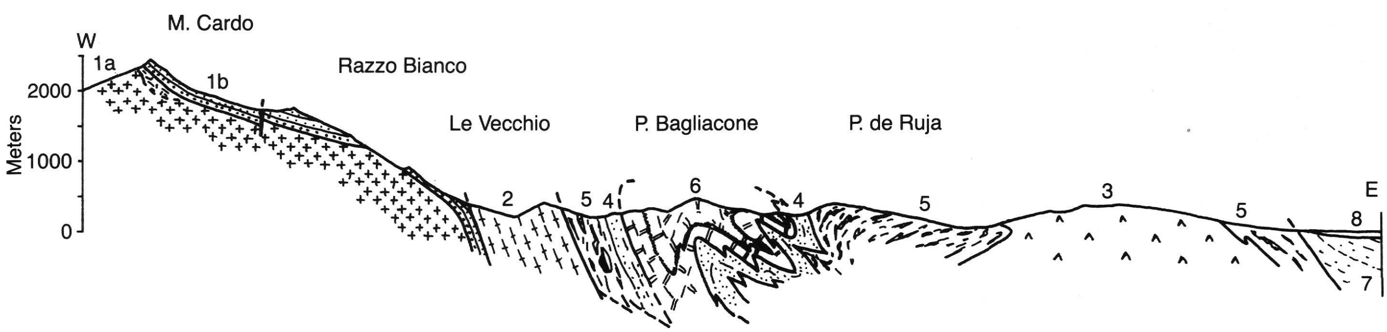


Figure 6. Structural cross section of Alpine Corsica. 1. Parautochthonous units (1a) crystalline basement, (1b) sedimentary cover Mesozoic-Eocene); 2. Crystalline sheet (parautochthonous); 3–5. Ophiolite-bearing (Ligurian) "schistes lustres" (3, ophiolite, 4, metaradiolarites, 5, calc-shists); 6. Piemontese "schistes lustres" unit marbles; 7. Miocene of eastern Corsica; 8. Quaternary. Modified after Amaudric du Chaffaut (1982).

Oligocene to lower Miocene. The Massa unit is a nappe of basement, the Apuane unit is the lowermost structural element cropping out in tectonic windows, and the Tuscan nappe is a cover unit detached above Upper Triassic cargneules horizons and is thrust for at least 40 km above more external domains. External to its front extends the Cervarola nappe, consisting of flysch deposits of middle to early Miocene age. The latter unit is interpreted as deriving from a trough external to the Burdigalian thrust front, displaced by Tortonian and later tectonic phases.

Compressional tectonism in the Tuscan domain spans essentially from Aquitanian-Burdigalian (sub-Ligurian phase) to upper Miocene (Tuscan phase). Distension follows from ?upper Tortonian-Messinian to present times accompanied by graben formation with marine, lacustrine, and continental deposits and with subvolcanic to effusive bodies (mainly Pliocene and Pleistocene in age).

1. B. 2. External (Umbrian) Domain

The external domain contains sequences comparable to those of the Tuscan domain except for the Tertiary terrigenous deposits, represented here by the Marnoso-arenacea Formation of Miocene age. This domain is moreover considered autochthonous to parautochthonous because of its general buckling fold style above Triassic evaporitic horizons. Nevertheless, east-verging thrusts and overturned faulted folds are strongly developed. Fold axes describe an arcuate belt, convex to the east-northeast, limited by the central Apennines to the south and by the Po plain to the north.

Compressional deformations occurred from Tortonian-Messinian to Pliocene, getting younger and affecting progressively more and more external areas moving to the east.

2. The Foredeep and Foreland (Fig. 12)

The present foredeep, characterized by negative Bouguer gravity anomalies, is essentially post-Messinian in age and occurs as a wide arc buried beneath sediments of the Po plain and of the northern Adriatic Sea. In such areas the base of the Pliocene sequences can reach depths of more than 9 km below sea level; the deposits appear deformed and thrust in a row of discrete arcuate structures. The main compressional events occurred in Messinian, early Pliocene, middle Pliocene, and late Pliocene-Pleistocene. The progression of compressional/gravitative deformation toward the foreland was accompanied by the movement of the Ligurian chaotic nappes up to the margin of the Po plain and was paralleled by extensional deformations in the chain sensu stricto.

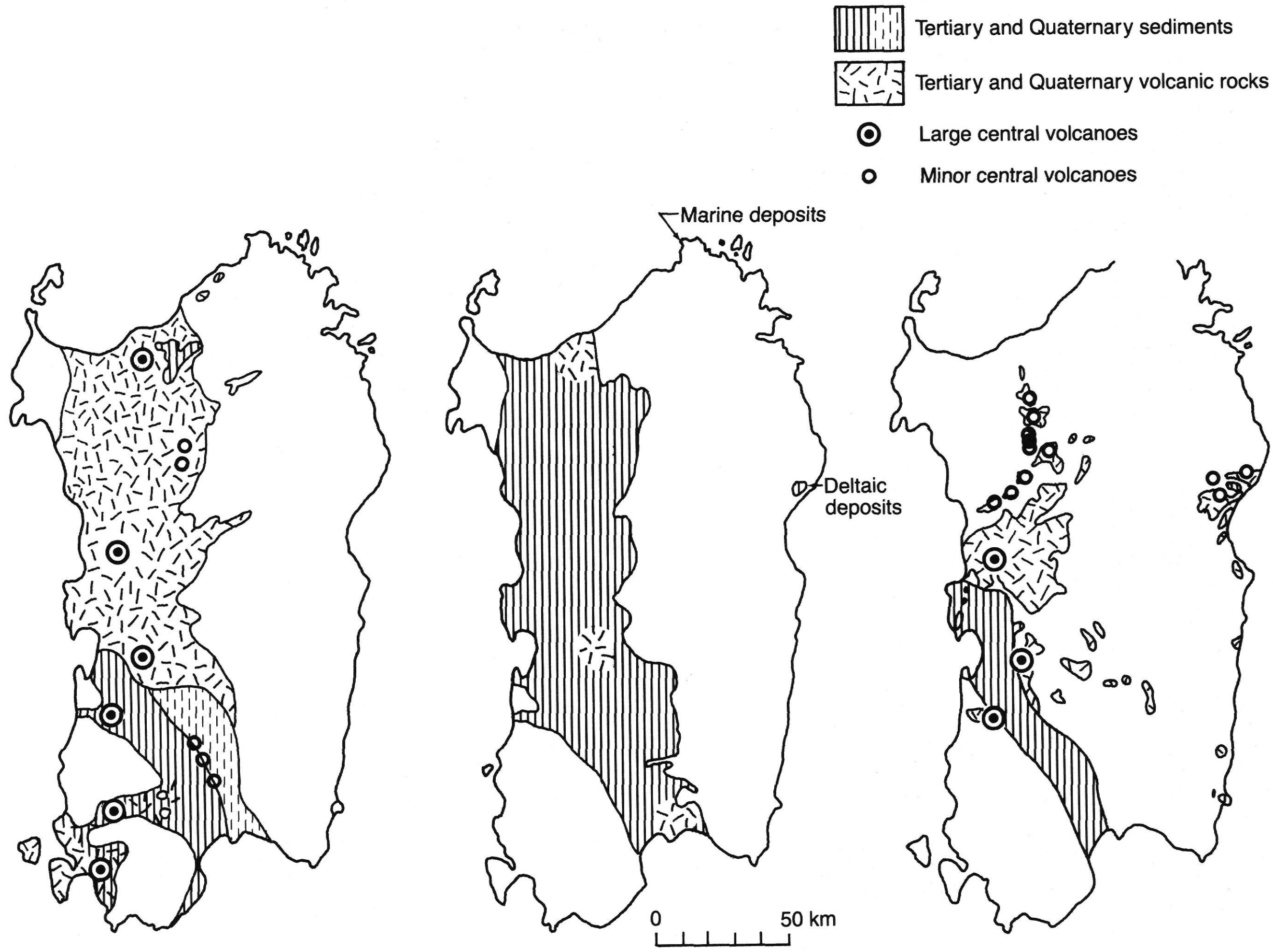


Figure 7. Postorogenic formations in Sardinia. Left: Oligocene sedimentary and volcanic rocks. Center: Miocene sedimentary and volcanic rocks. Right: Pliocene and Pliocene-Quaternary volcanic rocks. After Cocozza, et al. (1974).

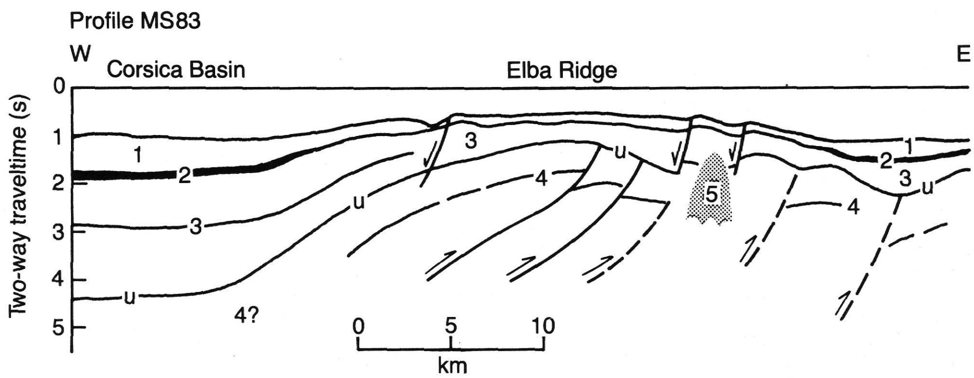
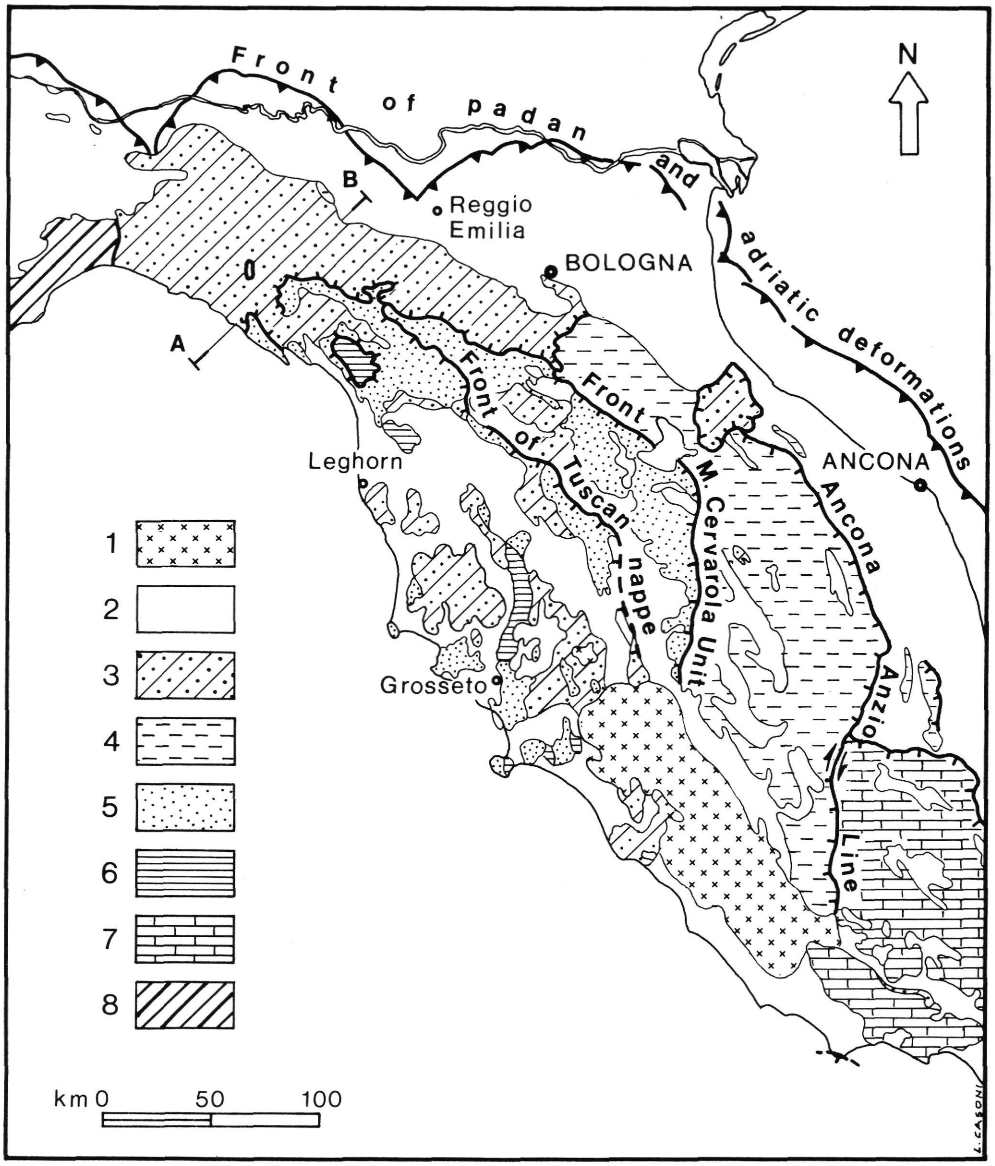


Figure 8. Schematic cross section of the northern Tyrrhenian Sea from a seismic reflection profile. 1. Pliocene-Quaternary sediments; 2. Messinian deposits; 3. Miocene pre-evaporitic sediments; U. Unconformity related to a hiatus of late Oligocene–Miocene age; 4. Imbricated sequences made up of Upper Cretaceous-middle Eocene flysch units; 5. Possible magmatic body. After Bacini Sedimentari (1982).



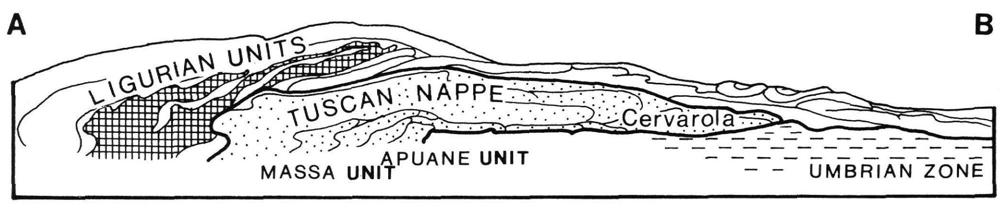


Figure 9. Schematic structural map and cross section of the northern Apennines. 1. Neogene and Quaternary volcanics; 2. Neogene and Quaternary late to postorogenic sequences; 3. Ligurian units; 4. Umbrian domain; 5. Tuscan nappe; 6. Apuane and Massa units; Tuscan basement; 7. Carbonate sequences of the Latium-Abruzzi platform; 8. Alpine units. Map modified after Fazzini and Gelmini (1984); cross section after Elter (1980).

The undeformed foreland is represented by very narrow portions of the Po plain and by parts of the Adriatic Sea, connecting the Istrian peninsula to the Apulian foreland of southern Apennines, where continental basement has also been found by drilling (e.g., Assunta well off Venice).

CENTRAL APENNINES

The central Apennine segment is bounded to the north by the Ancona-Anzio Lineament, and merges to the south with southern Apennines (Figs. 13 and 14).

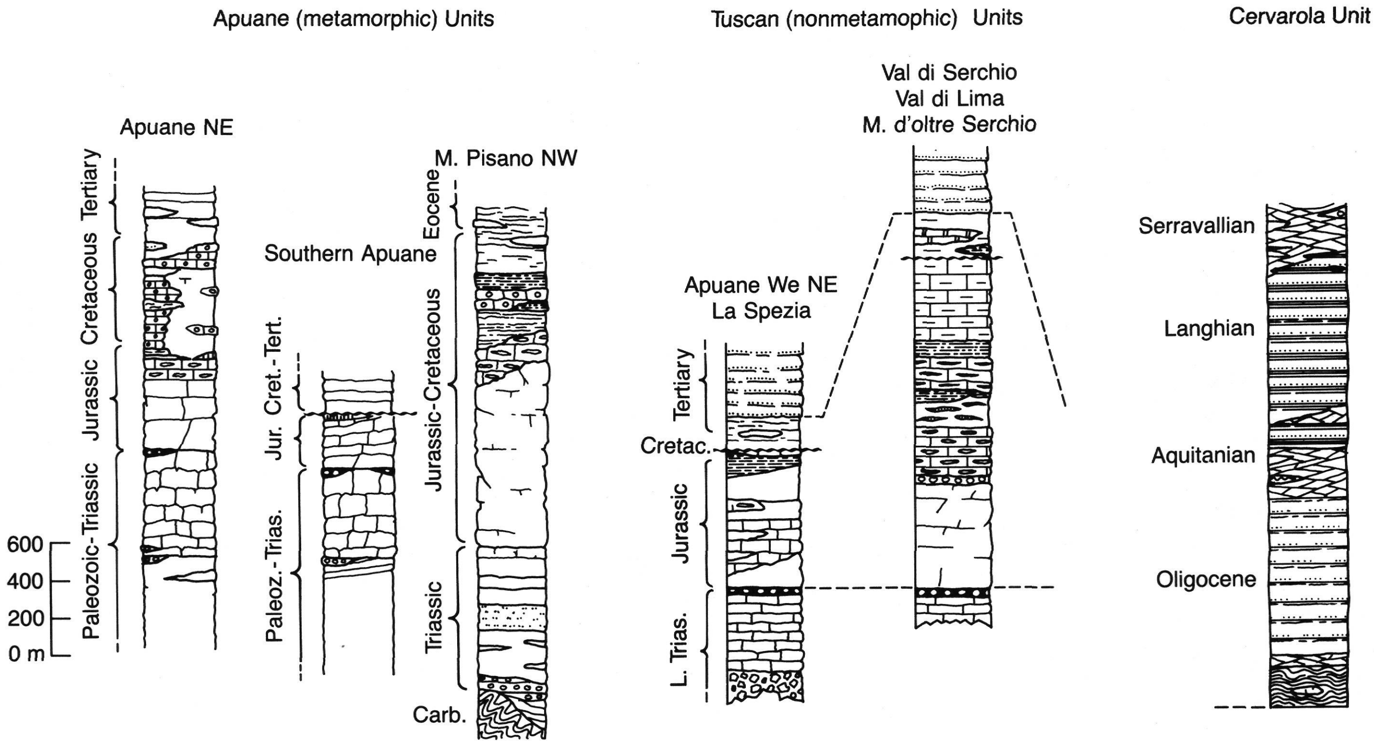


Figure 10. Mesozoic-Tertiary lithostratigraphy of northern Apennines. Modified after Dallan Nardi and Nardi (1974).

References for this section are Castellarin et al., 1978; Channell et al., 1978; Crescenti, 1977; Gasparini and Praturlon, 1983; Lavecchia et al., 1985; Locardi et al., 1977; Parotto, 1980; Parotto and Praturlon, 1975; and Praturlon, 1980.

1. The Chain

The substrate is very poorly represented (Zannone Island) and may correspond to the continental basement described for the northern Apennines. The cover is represented by neritic sediments of Mesozoic age, the Latium-Abruzzi carbonate platform, and by Tertiary detrital sediments. The Ancona-Anzio line is a north-trending lineament that after lower Liassic separated the Latium-Abruzzi carbonate platform (to the east) from the basinal deposits of the Tuscan/Umbrian domains of northern Apennines (to the west). Similar tectonic/facies boundaries separated the platform from the more external Apulian carbonate platform, with formation of an intermediate Marsica/Molise basinal domain.

The Latium-Abruzzi platform experienced partial emersion in Upper Cretaceous, with extensive bauxite development, while being split into several blocks with various drowning and subsidence rates.

Compressional tectonism (Fig. 15) does not appear to affect the presently emerged chain until Tortonian-Messinian times. Previous deformations were confined in the westernmost Apenninic border and inside the presently drowned Tyrrhenian hinterland. The Tortonian phase split the Latium-Abruzzi platform into blocks separated by furrows receiving synorogenic flysch deposits. Such blocks were thrust onto each other, with a general vergence north-northeastward, mainly during Messinian. In the meantime, a dextral wrenching developed along the Ancona-Anzio Lineament, with maximum horizontal throw of some 50 km in the northernmost area. During the Pliocene, the Umbrian domain of northern Apennines thrust for several kilometers toward the east above the platform facies of central Apennines. Similar thrust/wrenching mechanisms may also have occurred along other lineaments located further south.

Distension along horst and graben structures developed after the Messinian and mostly after the lower Pliocene, along the Tyrrhenian side of the chain, with important magmatic manifestations. The most widespread products are the high-potassic (Mediterranean) volcanics of the Roman province, essentially Pleistocene in age.

2. The External Areas, Foredeep and Foreland (Fig. 15)

The areas north of the Latium-Abruzzi carbonate platform experienced very strong and rapid subsidence in Messinian-Pliocene times, with deposition of some 3 km of terrigenous sediments (Laga basin). Subsidence continued farther east in the Pliocene, and compressional deformations affected the Laga basin with north- and east-trending folds and thrusts. External to the deformation front, we presently observe a wide and thick sedimentary basin lying just north of the Apulian foreland. The latter appears somewhat affected by the more external deformations of the chain (Maiella, Gargano faults).

SOUTHERN APENNINES

The southern Apennines occur as far south as the Catanzaro Isthmus inside the Calabrian arc, where Apenninic elements are still found in small tectonic windows under the Calabride nappes (Figs. 16, back pocket, and 17).

References for this section are Caire, 1969, 1975; Casnedi et al., 1984; Channell et al., 1979; Ciaranfi et al., 1983; Crescenti, 1977; D'Argenio et al., 1975, 1980; Di Girolamo, 1979; Grandjacquet and Mascle, 1978; Ippolito et al., 1983; Ogniben, 1969, 1973; Ortolani, 1979; Ortolani and Aprile, 1977; Pescatore, 1976, 1982; Pescatore and Ortolani, 1973; Scandone, 1972; Selli, 1962; and Vezzani, 1975.

1. The Chain

1. A. Internal Units

No continental basement is known in outcrops along the whole chain segment down to the Calabrian arc. However, crys-

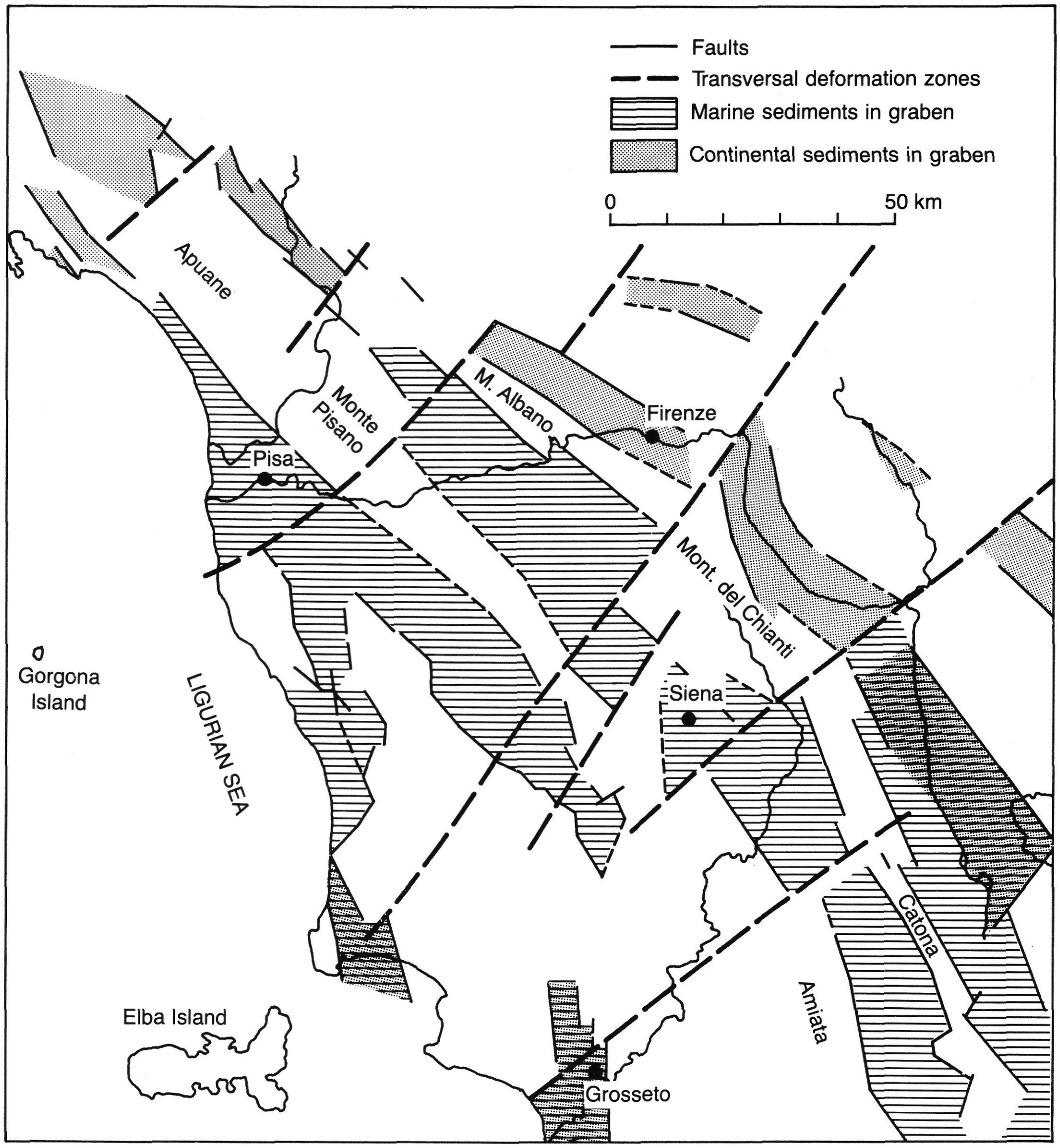


Figure 11. Pliocene and Quaternary in Tuscany. After Bartolini et al. (1983).

talline-metamorphic clasts of internal (Tyrrhenian) provenance occur largely in Tertiary (mainly post-middle Miocene) deposits of both internal and external units of the chain. The internal, structurally highest units thus represent cover nappes, although scattered ophiolitic bodies suggest the proximity to the Ligurian domain of the Tethyan realm as source area. The bulk of internal units consists of calcareous flysch (Upper Cretaceous to Eocene) of *Helminthoides* type, with a suite of variegated clays and shales. All these elements, making up the Sicilide and Cilento units, appear very severely deformed, and often chaotic by multiple deformation phases, extending at least from early Miocene to late Pliocene-Pleistocene times. They occur sporadically across the whole chain, up to the very front of deformation in the foredeep.

1. B. External Units

External units are also cover units deriving from deformation of the Apulian margin of the Mesozoic Tethys. After stretching, the margin was articulated in a series of carbonate platforms with intervening deep basins. Due to the strong present deformation, different palinspastic reconstructions have been proposed for the margin. The most widely accepted include, from the inner to the external portions of the margin: (1) the Campania-Lucania carbonate platform; (2) the Lagonegro basin (became an entity in Triassic); (3) the Latium-Abruzzi platform; (4) the Molise basin (Mesozoic); and (5) the Apulian platform that also represents the present foreland.

The strongest compressional deformations occurred in lower Miocene, accompanied in places (San Donato Unit) by metamorphism in greenschist facies. Compressions, however, went on at least until Tortonian times. Paleomagnetic data show that tectonic emplacement was accompanied by anticlockwise rotation of the nappes. Every major event was marked by deposition of detrital deposits, sometimes deformed by later pulses. The Irpinian units, for instance, contain a wildflysch sequence of Miocene age interpreted by some authors as deposited in a migrating trench during the Burdigalian phase. Mature quartzarenitic sequences of the Numidian flysch also occur in the southern Apennines, but their paleogeographic significance is still controversial.

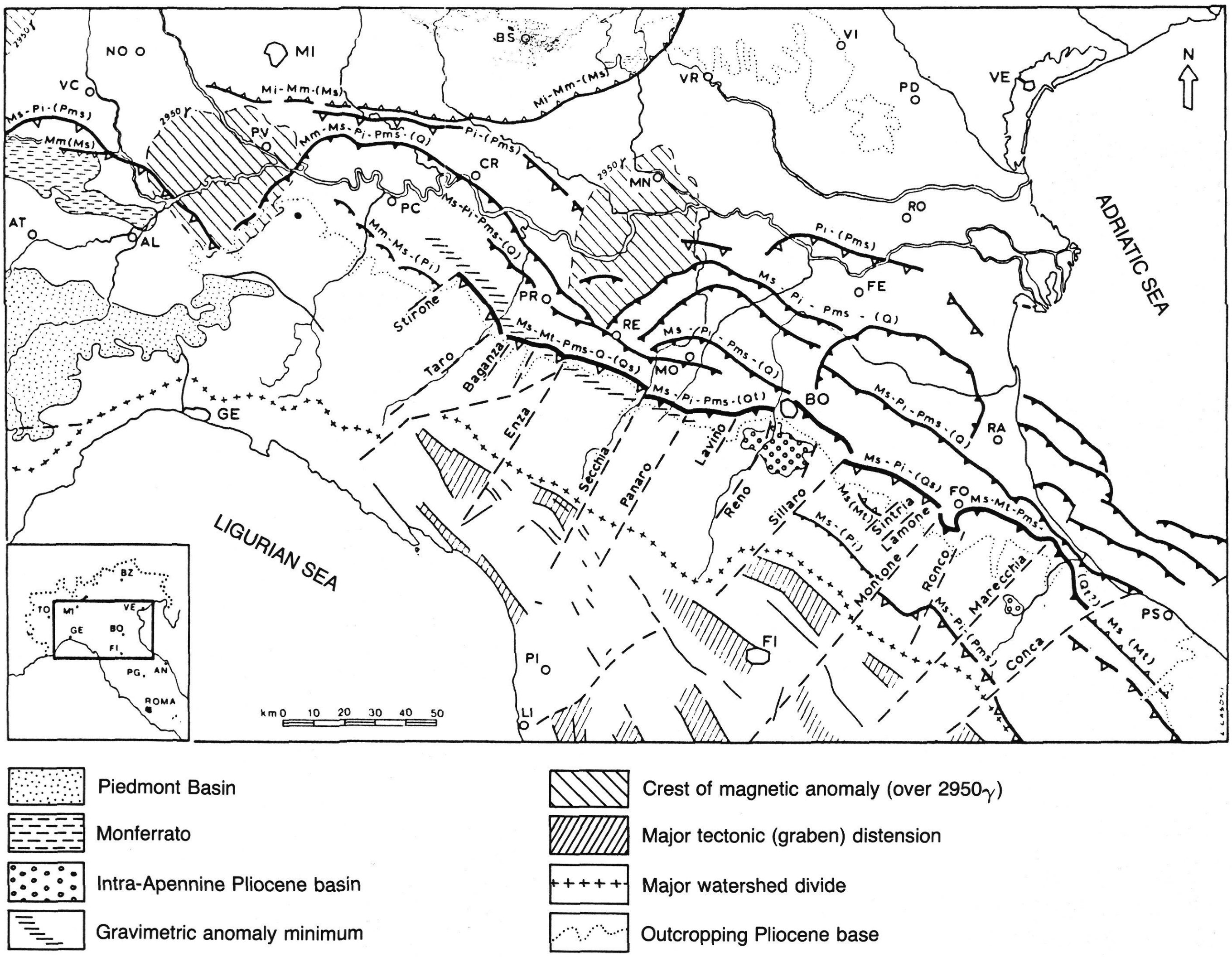


Figure 12. Major compressional fronts in the northern Apenninic foredeep. Mi, Pi, . . . Age of tectonism along thrust fronts. Mi: early Miocene; Mm: middle Miocene; Ms: late Miocene; Pi: early Pliocene; Pms: middle to late Pliocene; Q: Quaternary; Qs: late Quaternary; Qt: Holocene. After Castellarin and Vai (1986).

Small postorogenic basins (San Arcangelo basin, etc.) start forming after the Tortonian on top of the nappe pile. Toward the Tyrrhenian margin, extremely strong extensional tectonism with drowning of the chain occurs essentially in late Pliocene to recent times. These events are matched by important volcanic manifestations, mostly of calc-alkaline affinity at the beginning and of high-potassic type in Pleistocene (Pontinian, Campanian, Phlegrean, Eolian areas).

2. The Foredeep and Foreland (Fig. 18)

The present foredeep developed through various stages essentially after Messinian times. It was produced by sinking of the Apulian foreland along northwest-striking faults that can be followed as far south as Kefallinia Island off Greece. Marine Pliocene deposits of the foredeep appear deformed, together with their carbonate substrate of the Apulian platform, internal to the present front of chaotic allochthonous nappes. As in the northern Apennines, several compressional/gravity-related phases seem to have occurred from Messinian to Pleistocene.

The foreland is represented by the reefal and perireefal carbonates of the Apulian platform, mostly Cretaceous in age, with extensive bauxite formation and thin scattered cover of Tertiary calcarenites.

THE SICILIAN-MAGHREBIAN CHAIN

Sequences similar to those in the Apennines crop up in central and western Sicily, and continue westward into the Tellian Atlas of North Africa. As is the case for southern Apennines, they are tectonically covered by the Calabrian units making up the Peloritani segment of the arc (Figs. 19 and 20).

References for this section are Amodio-Morelli et al., 1976; Besse et al., 1984; Broquet, 1968; Broquet et al., 1984; Caire, 1964, 1969, 1975; Catalano and D'Argenio, 1982; Catalano et al., 1978; Channell et al., 1979; Di Grande, 1969; Di Grande and Grasso, 1979; Duee, 1969; Grandjacquet and Mascle, 1978; Kafka and Kirkbride, 1959; Letouzey and Tremolieres, 1980; Mascle, 1973; Ogniben, 1960, 1973; Patacca et al., 1979; Schmidt di Friedberg et al., 1960; and Truillet, 1968.

1. Internal Units

The internal units contain more or less developed flysch facies. A detailed analysis of the various stratigraphic sequences (Fig. 21) allows the following subdivisions: (1) "Flysch units" mainly of Cretaceous-Eocene age. The oldest sediments are either Middle to Late Jurassic or Early Cretaceous. Flysch facies begin in Lower Cretaceous, whilst Upper Cretaceous and Eo-

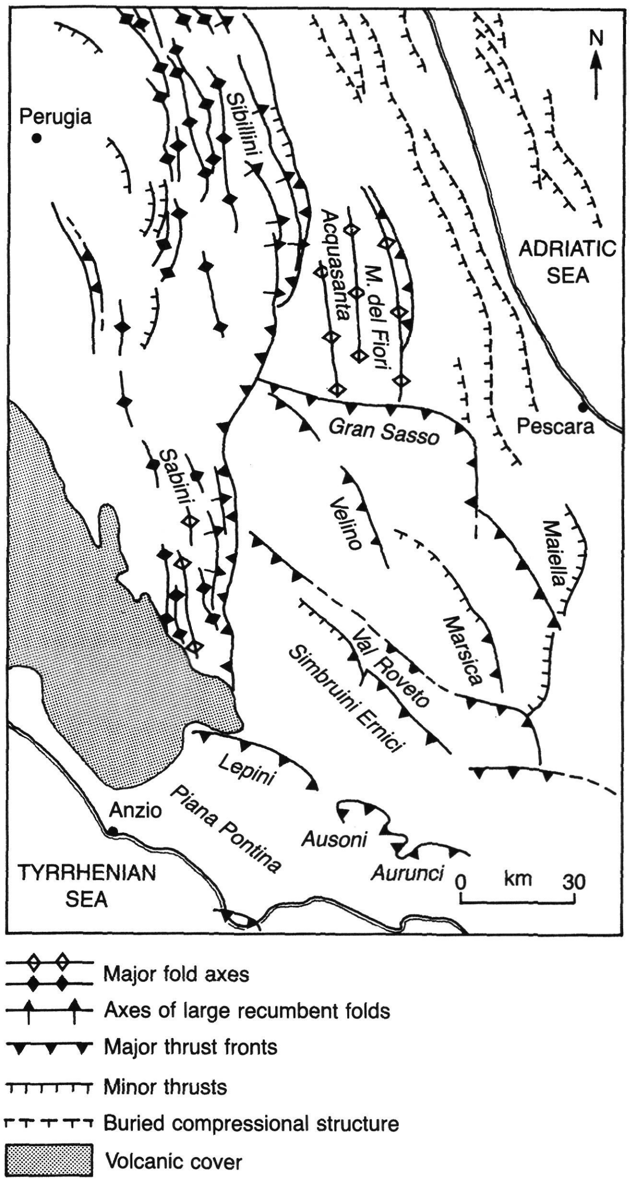


Figure 13. Structural sketch of central Apennines. After Castellarin et al. (1978).

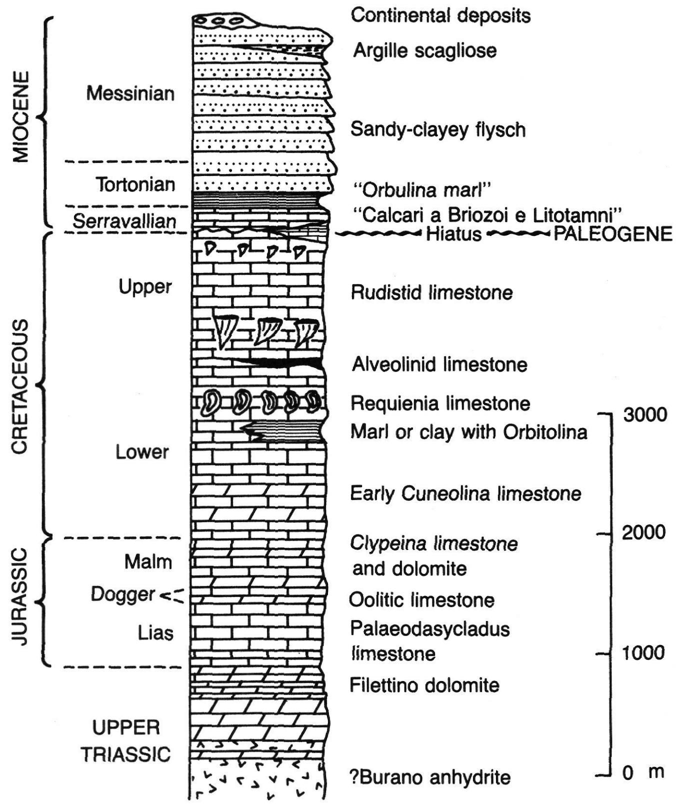


Figure 14. Lithostratigraphy of the Latium-Abruzzi carbonate platform. After Parotto and Praturlon (1975).

cene are mainly pelagic. (2) Units with Oligocene-Miocene detrital sequences. Oligocene-Miocene? terrains display a deep-sea fan facies (Reitano, Capo d'Orlando) with crystalline-metamorphic detritus. The subsequent Miocene units are quartzarenitic (Numidian flysch) and the origin of this mature material is still controversial (African, Betic, Sardinian, etc.).

Several phases of folding and sliding complicate the structure of these units. They are very similar to the Maghrebian flysch nappes of northern Africa, particularly with respect to facies sequence and deformation history.

2. External Units

The oldest formations of the external units crop out in central Sicily, with marine, mainly detrital, Permian and possibly Carboniferous sediments. The cover units are all characterized by thick carbonate sequences of Triassic age. Apart from the Imerese basinal nappe, the facies are always of carbonate platform, sometimes reefal. From Liassic until Cretaceous time the paleogeography is differentiated. The innermost domain is a carbonate, often reefal, platform (Panormide), flanked by a deep basin (Imerese) and by an external complex margin with starved carbonate facies and evidences of extensional synsedimentary tectonism. Detrital quartz has been important in the region only since Oligocene time.

The major compressional deformations are south-verging thrusts of Serravallian-Tortonian age that produce synsedimentary effects. Paleomagnetic data indicate that tectonic units were rotated in a clockwise sense during emplacement, with higher angular values moving upward in the thrust pile.

3. The Foredeep (Foreland Basin) (Fig. 22)

In Sicily, the foredeep is constituted by the Caltanissetta and Salaparuta basins, characterized by strong subsidence from Langhian-Serravallian to Quaternary times (6.5 km thick). An external (southward) migration of depocenters is observed with time as seen in other foreland basins. The displacement is accompanied by contemporaneous migration of the internal tectonized boundary, which results in a progressive tectonization of more and more external areas. At each time, the tectonization front contains several thrust units (flysch nappes, external units); most of them are highly plastic and easily reworked and slid. They thus contribute to the rapid filling of the basin; the result is a tectonic-sedimentary progradation of the active front. The Messinian salinity crisis event occurs in two different settings. Toward the foreland we observe an asymmetric basin with a southern margin and an axial hollow, both with little or no reworking effects. Toward the front it was the locus of intense reworking of thick deposits, and the evaporitic facies appear strongly diluted among detritic and olistotromic sequences. Although at the scale of the basin, the deformations can be regarded as continuous from late Miocene to Quaternary, some important unconformities are found. They occur in Tortonian,

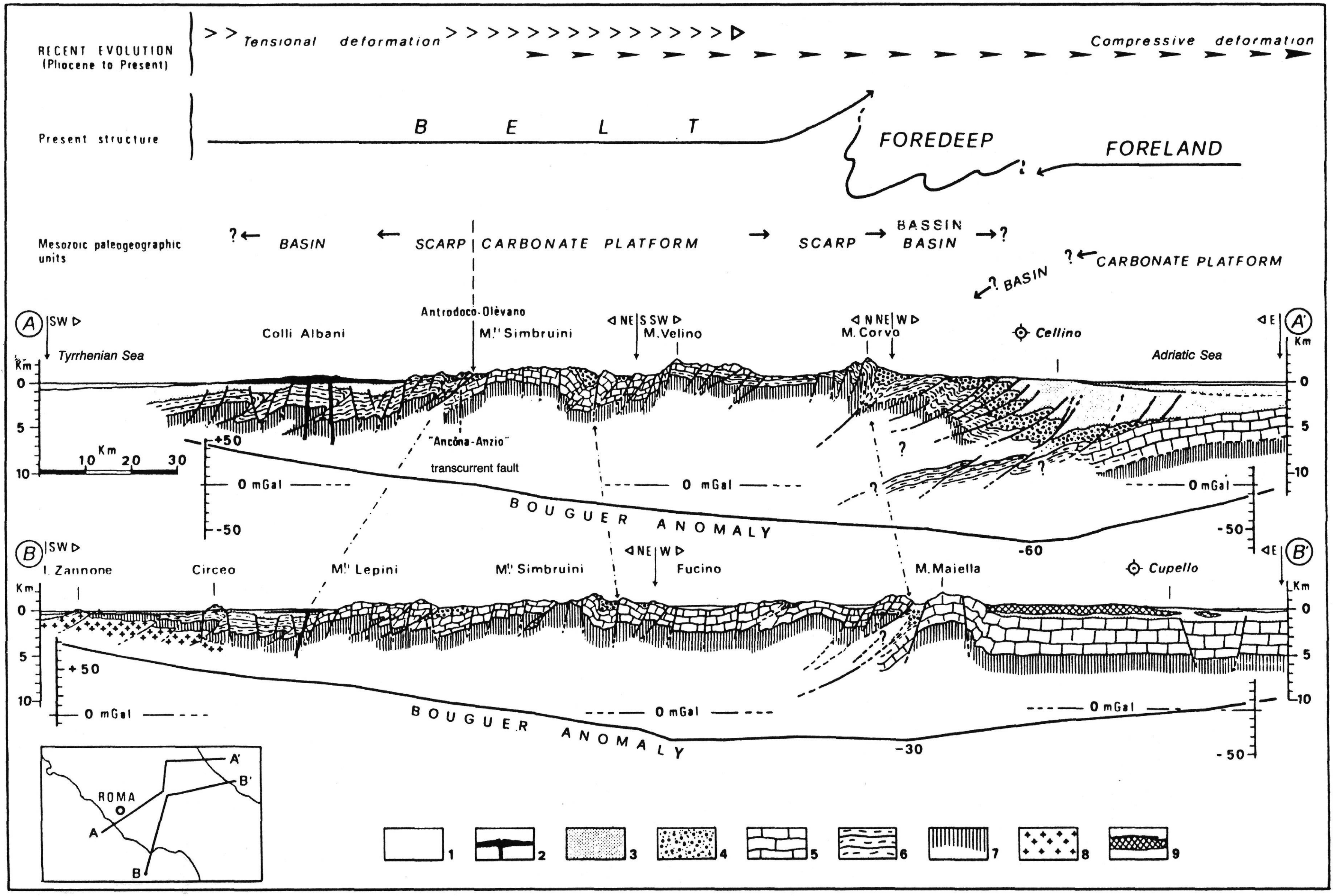


Figure 15. Geological cross section of central Apennines. 1. Seawater; 2. Pleistocene volcanites; 3. Pliocene-Quaternary; 4. Tertiary flysch deposits; 5. Carbonate platform deposits (Jurassic-Paleogene); 6. Basinal deposits (Mesozoic-Paleogene); 7. "Basal complexes" (Pre-Jurassic); 8. Substrate; 9. Allochthonous internal nappes. After Parotto (1980).

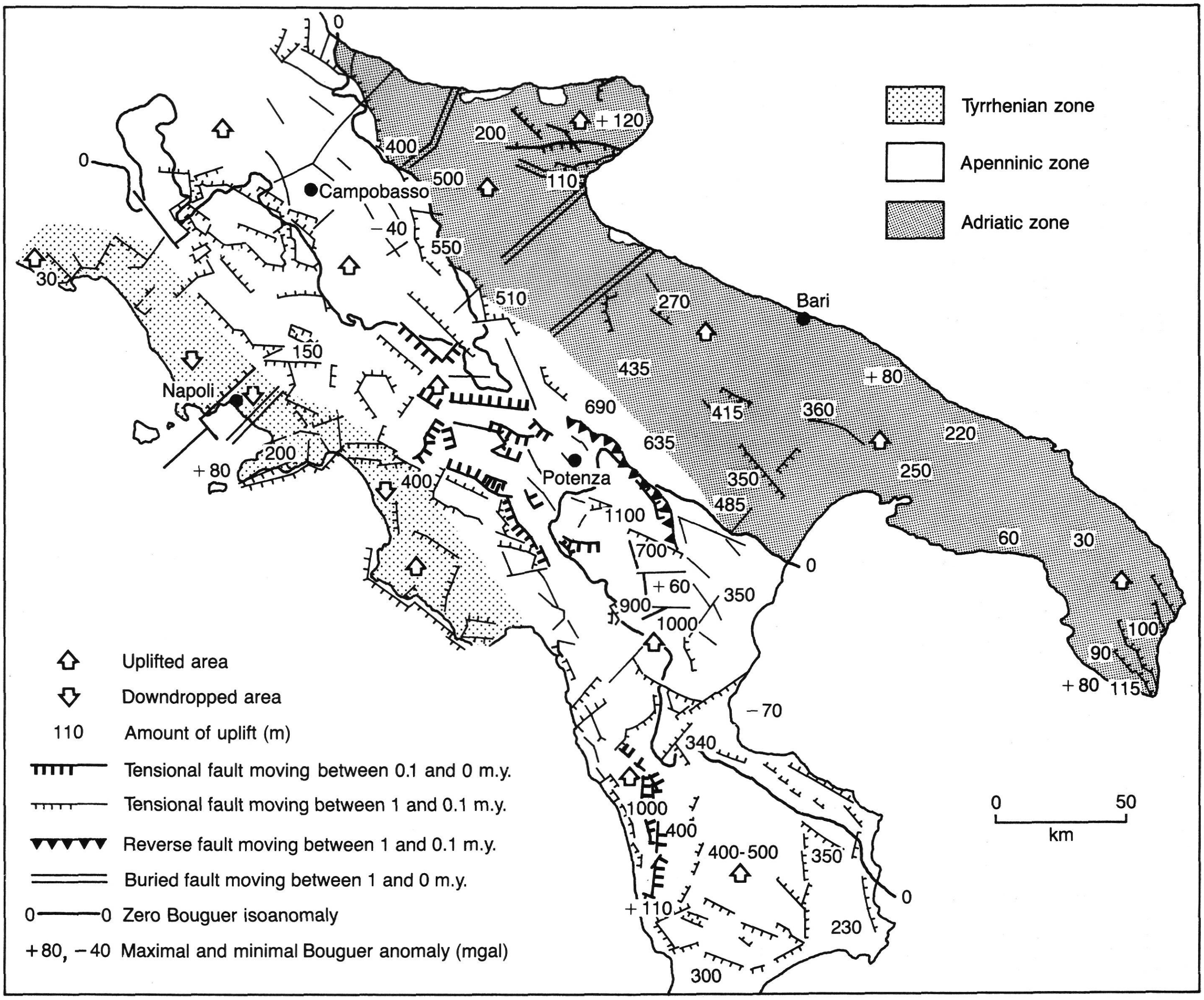


Figure 17. Map of the Pleistocene to Recent vertical movements in the southern Apennines. After Ciaranfi et al. (1983).

Messinian, at the end of early Pliocene, and during the Quaternary. They become younger toward the external basin and in fact represent a progressively migrating unconformity.

The Etna alkaline volcano is emplaced during the Quaternary close to the boundary between foredeep and foreland.

4. The Foreland

In Sicily the foreland is represented by the Hyblean realm, which essentially corresponds to a Tertiary (Oligocene-Neogene) carbonate platform. The Mesozoic interval is known mainly from oil wells and indicates two different domains (Ragusano and Siracusano). Essentially the Mesozoic to Eocene sequences include facies referrable to a pelagic plateau with the exceptions of some volcanic ridges (guyots) in Late Cretaceous and Eocene times, on top of which small rudistid reefs are sometimes formed. Volcanism of alkaline type occurs in Late Triassic, Middle Jurassic, Late Cretaceous, and Neogene to Pleistocene times in correspondence to the main phases of regional tensional deformation.

The foreland is mainly characterized by extensional faults, striking N40°–50°E and N100°–120°E. However, two short-lasting compressional events occur in Oligocene and Pliocene. Moreover, paleomagnetic data show a post-Tortonian anticlockwise rotation of some 15° with respect to stable Africa.

The Sicilian foreland appears therefore significantly different from the Apulian one, mainly with regard to volcanism and sedimentary sequences.

THE PELAGIAN SEA (Fig. 23)

References for this section are Colantoni, 1975; and Winnock, 1981.

The Pelagian Sea is mainly a shallow-water area that separates Sicily from the African landmass. It is occupied by the Pelagian carbonate platform everywhere except in its northern sector where the Gela basin represents the seaward extension of the Caltanissetta basin.

Several narrow troughs, oriented N120°–140°E dissect the platform. They derive from Late Cretaceous and Neogene to Quaternary extensional/strike slip tensions, with coeval emplacement of alkaline volcanics. Pantelleria and Linosa islands represent Neogene to Quaternary emerged volcanoes.

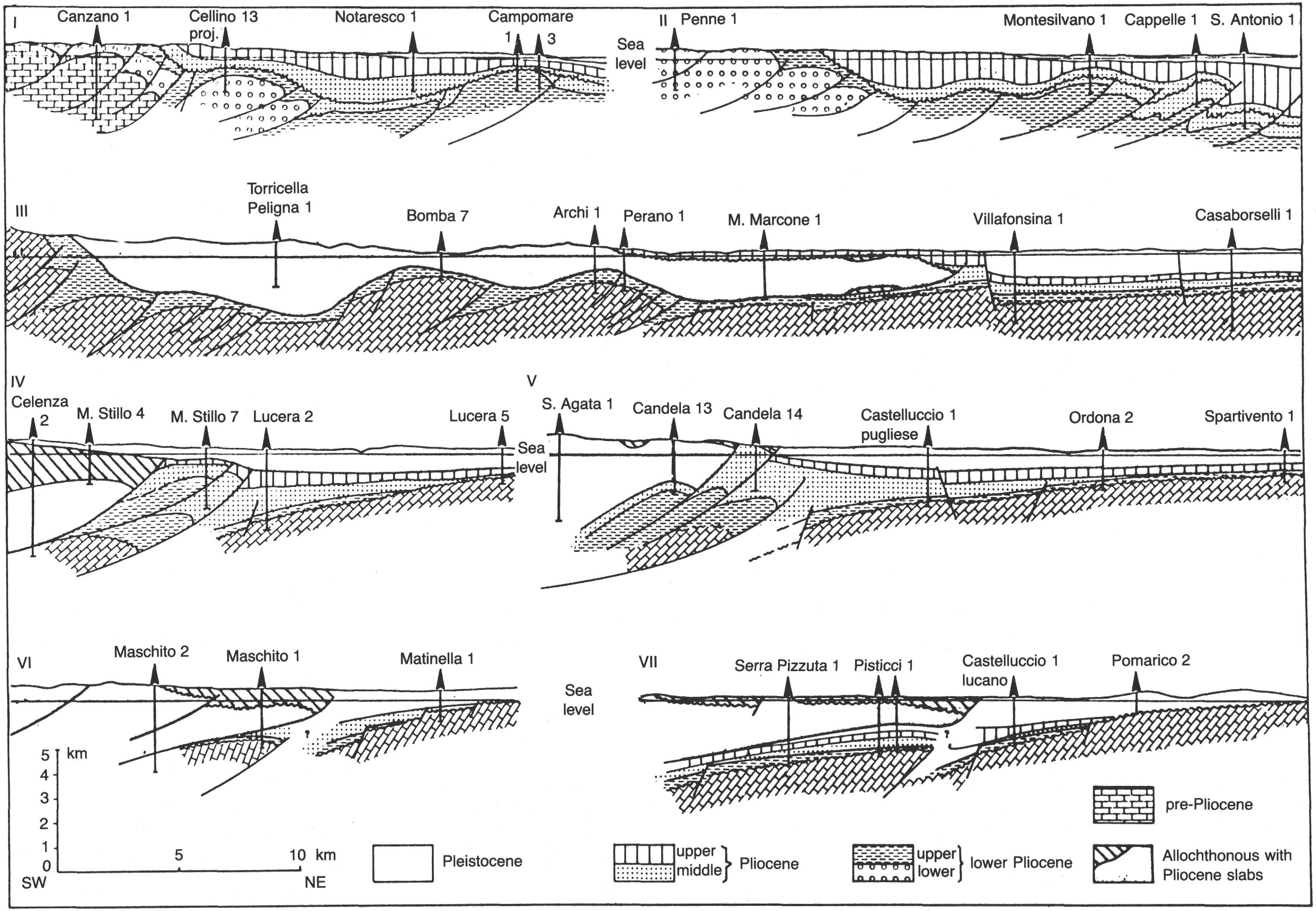


Figure 18. Geological cross-sections in the southern Apenninic foredeep. After Casnedi et al. (1984).

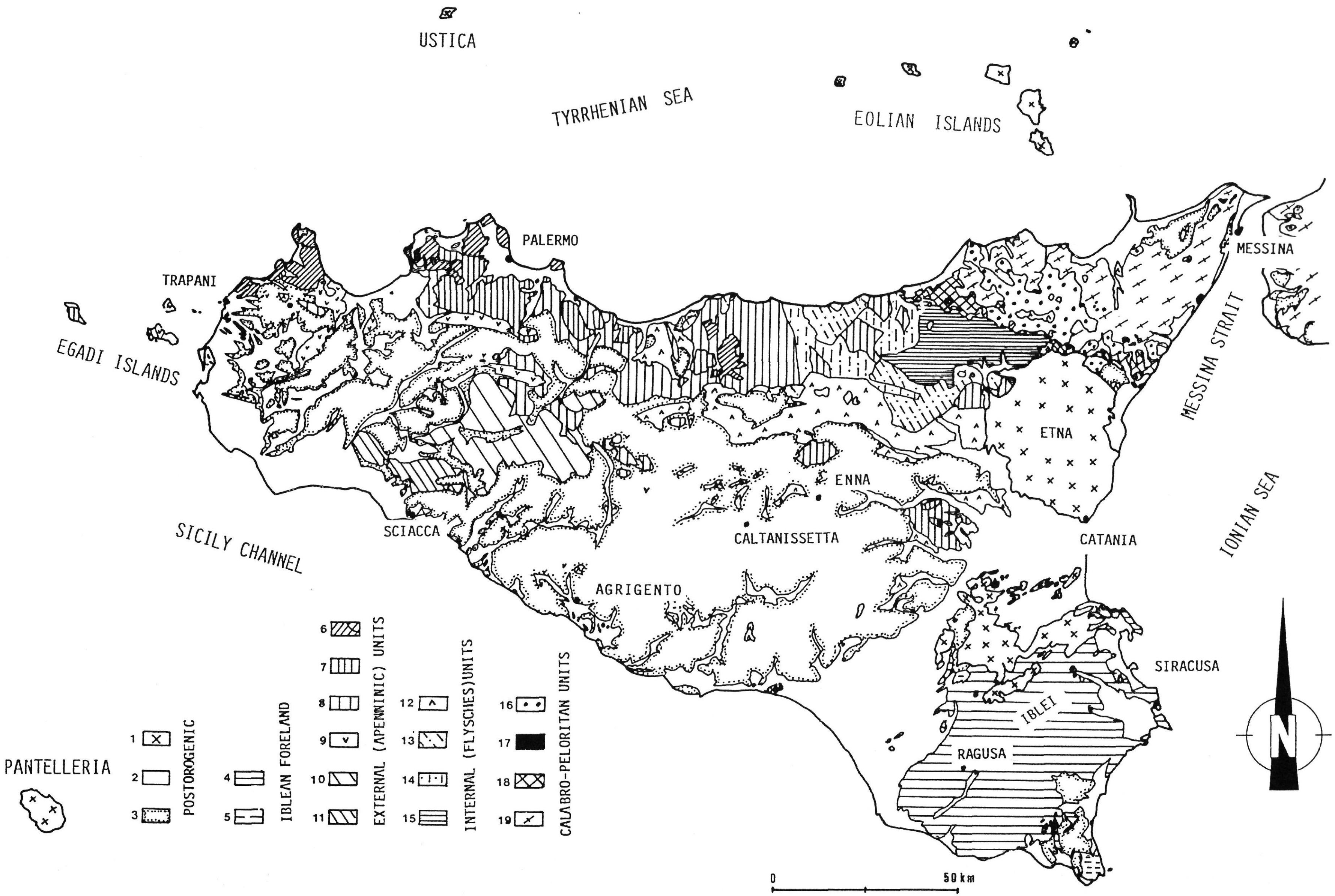


Figure 19. Structural map of Sicily. 1. Neogene to Quaternary volcanism; 2. Quaternary; 3. Central Sicily: Post-Burdigalian to Pliocene; Perloritan massif: Burdigalian to Pliocene; Hyblean Plateau: Pliocene; 4. Hyblean Oligocene-Miocene; 5. Hyblean pre-Oligocene; 6–11. External units (6. Panormide nappes; 7. Imerese (Mesozoic-Eocene); 8. Imerese Oligocene-Miocene (external Numidian); 9. Trapanese units; 10. Sicanian (Campofiorito) units; 11. Sicanian (Sciacca) Platform); 12–15. Internal flysch nappes (12. argille scagliose nappe and resedimented olistostromes; 13. Reitano (Troina, Capizzi) nappes; 14. Monte Soro flysch nappe; 15. Intermediate Numidian nappes.) 16–19. Peloritan units (16. Oligocene-Miocene cover; 17. Novara-type Mesozoic; 18. Longi-Taormina-type Mesozoic-Eocene; 19. Pre-alpine basement). Modified after Broquet et al. (1984).

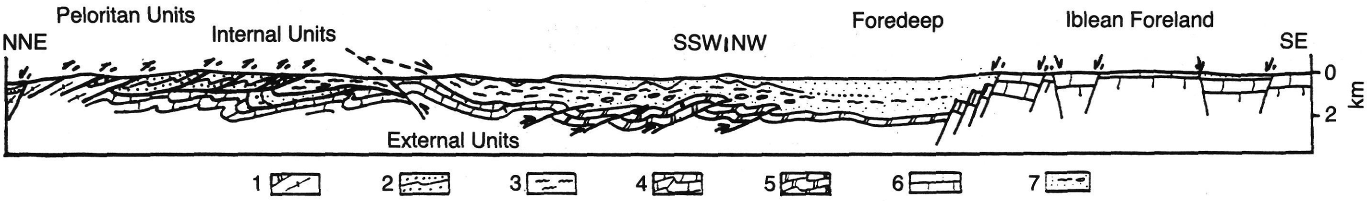


Figure 20. General schematic structural section of Sicily. 1. Peloritan units (basement and sedimentary cover); 2. Internal units (flysch); 3. Internal unit of argille scagliose and resedimented olistostromes; 4. External units (Panormide, Imerese); 5. External units (Trapanese and Sicanian); 6. Hyblean foreland; 7. Sicilian foredeep (sediments and resedimented units). After Grandjacquet and Mascle (1978).

THE CALABRIAN ARC (TYRRHENIAN ARC)

References for this section are Amodio-Morelli et al., 1976; Barberi et al., 1974; Boccaletti et al., 1984; Bouillin, 1984; Bouillin et al., 1986; Caire, 1975; Di Nocera et al., 1979; Durand Delga and Fontbote, 1980; Ghisetti and Vezzani, 1979; Grandjacquet and Mascle, 1978; Moussat et al., 1985; Ogniben, 1974; and Scandone, 1979.

1. The Calabrian-Peloritanian Substrate (Figs. 16 and 18)

The Calabrian-Feloritanian substrate crops out in the Peloritanian massif (northeast Sicily) and in the Calabrian massifs of Aspromonte, Serre, and Sila. It is strongly deformed by Alpine tectonism, and the following superposed main units are present: (1) The upper unit is a dioritic-kinzigitic nappe that may represent pre-Hercynian or Hercynian basement. (2) The lower units as well as the uppermost units of Serre and Aspromonte are mainly phyllitic and contain metasedimentary (dominantly detrital) and metavolcanic Paleozoic sequences.

The main deformations and metamorphism belong to the Hercynian cycle, as also suggested by late tectonic Hercynian granitoid intrusions; however, Alpine deformations are superimposed and overprinting.

The characters of the basement strongly recall those of the Kabilian-Rifan-Betic domains of western Mediterranean areas, although some affinities with the Sardinian basement also occur.

2. The Permian-Mesozoic-Eocene Cover (Fig. 20)

The cover unconformably overlies the basement and contains two major different sequences: (1) The uppermost units (Novara, Stilo) show a Mesozoic sequence which starts with continental Dogger deposition followed by carbonate platforms of Late Jurassic age; the general sequence is similar to that of central Sardinia; (2) The lower units (Taormina, Longi) show pre-rift carbonate platform formations conformably overlying the detrital Permo-Triassic Verrucano Formation. Paleogeographic differentiation occurs during a syn-rift middle Liassic phase. During Mesozoic and early Eocene the structural paleoenvironment is a starved margin with thin intervals of pelagic limestones and cherts. The main phase of penetrative deformation occurs in middle Eocene time.

3. The Oligocene-Miocene Cover (Fig. 20)

The middle Eocene deformations are followed by a strong erosional phase. Postorogenic basins start developing after late Oligocene times with continental facies which evolve in pre-Burdigalian into thick detrital sequences. Apart from lesser amounts of volcanic deposits (here represented only by thin tuffitic layers) the fillings recall those of the Sassari-Campidano trough in Sardinia.

The Calabrian formations, however, are folded and thrusted together with their substratum. They are conformably overlain by a Burdigalian calcareous molasse that looks very similar to the Nebbio molasse of Corsica.

4. Other Alpine and Apenninic Units of the Calabrian Arc (Fig. 16)

Two major groups of other Alpine and Apenninic units are observed: (1) ophiolite-bearing units, with rather incomplete oceanic sequences and sedimentary pelagic cover, occur only in northern Calabria. Metamorphism in high-pressure/low-temperature conditions is often present, similar to that affecting the analogous Piemontese units of Corsica; (2) carbonatic units representing the southward extension of the Campania-Lucania platform of southern Apennines are found in small tectonic windows north of the Catanzaro isthmus (northern Calabria).

5. The Small Basins of the Tyrrhenian Side of the Calabrian Arc (Figs. 17 and 24)

After upper Tortonian, the internal parts of the arc experienced extensional tectonism with formation of small basins filled by one or more cycles of continental to marine deposits. During Messinian and Pliocene, the source areas were located in the external part of the arc, to the east in Calabria, and to the south in Sicily.

Moreover a very extensive volcanism occurs internal to the Calabrian arc in the Eolian islands. It is mainly calc-alkaline in nature and Pleistocene in age. Later products, however, also exhibit a shoshonitic chemistry.

6. Late Tortonian to Recent Tectonic Evolution of the Calabrian Arc

The network of recent fractures shows two dominant directions: N40°E and N120°E. The arc suffered general N120°E extension since late Tortonian time. Several short-lasting compressional events occurred in Messinian, early Pliocene, and middle Pleistocene (Fig. 25).

THE IONIAN SEA (Fig. 26)

References for this section are Boccaletti et al., 1984; Finetti, 1982; Jongsma et al., 1985; Monopolis and Bruneton, 1982; Morelli et al., 1975; Rossi and Sartori, 1981; and Weigel, 1974.

The Ionian Sea is a deep marine area (maximum depth about 4100 m). Its southern boundary is represented by a typical passive margin (northern African margin), while the eastern and western limits are two steep scarps: the Malta and the Apulia-Kefallinia escarpments. The abyssal Ionian plain is bordered to the southeast by the eastern Mediterranean ridge and to the north by the Messina cone and external Calabrian arc. Both elements contain a thick pile of deformed sediments external to the Aegean and to the Calabrian arcs. Elements of the external Calabrian arc/Messina cone can be correlated to the deformation system of the external areas and foredeep of the southern Apennines and, in part, Sicily.

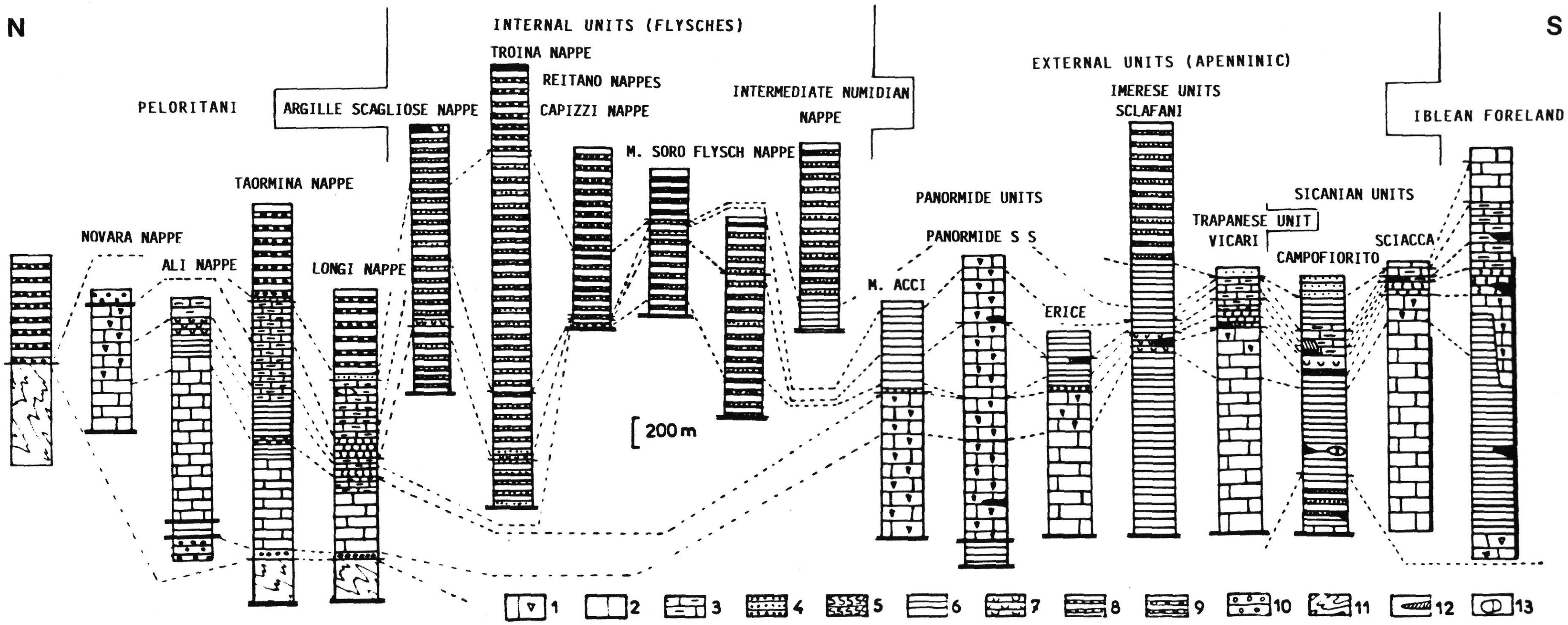


Figure 21. Pre-Burdigalian sedimentary environments in the various lithostructural units of Sicily. 1. Reefal platform; 2. Neritic platform; 3. Pelagic platform; 4. Platform showing detrital material; 5. Marginal facies; 6. Basin facies; 7. Siliceous facies; 8. Flysch facies; 9. Molasse facies; 10. Continental conglomerates; 11. Continental crust; 12. Tuffites and volcanites; 13. Sedimentary klippe. The lithostratigraphic profiles have been constructed using data of outcrops or of deep wells (double lines on the right side of the log); double lines at the base of the log characterize a tectonic contact. The disposition of the various sections conforms to their actual superposition (with the exception of a few outcrops of argille scagliose nappe over the Peloritan). After Broquet et al. (1984).

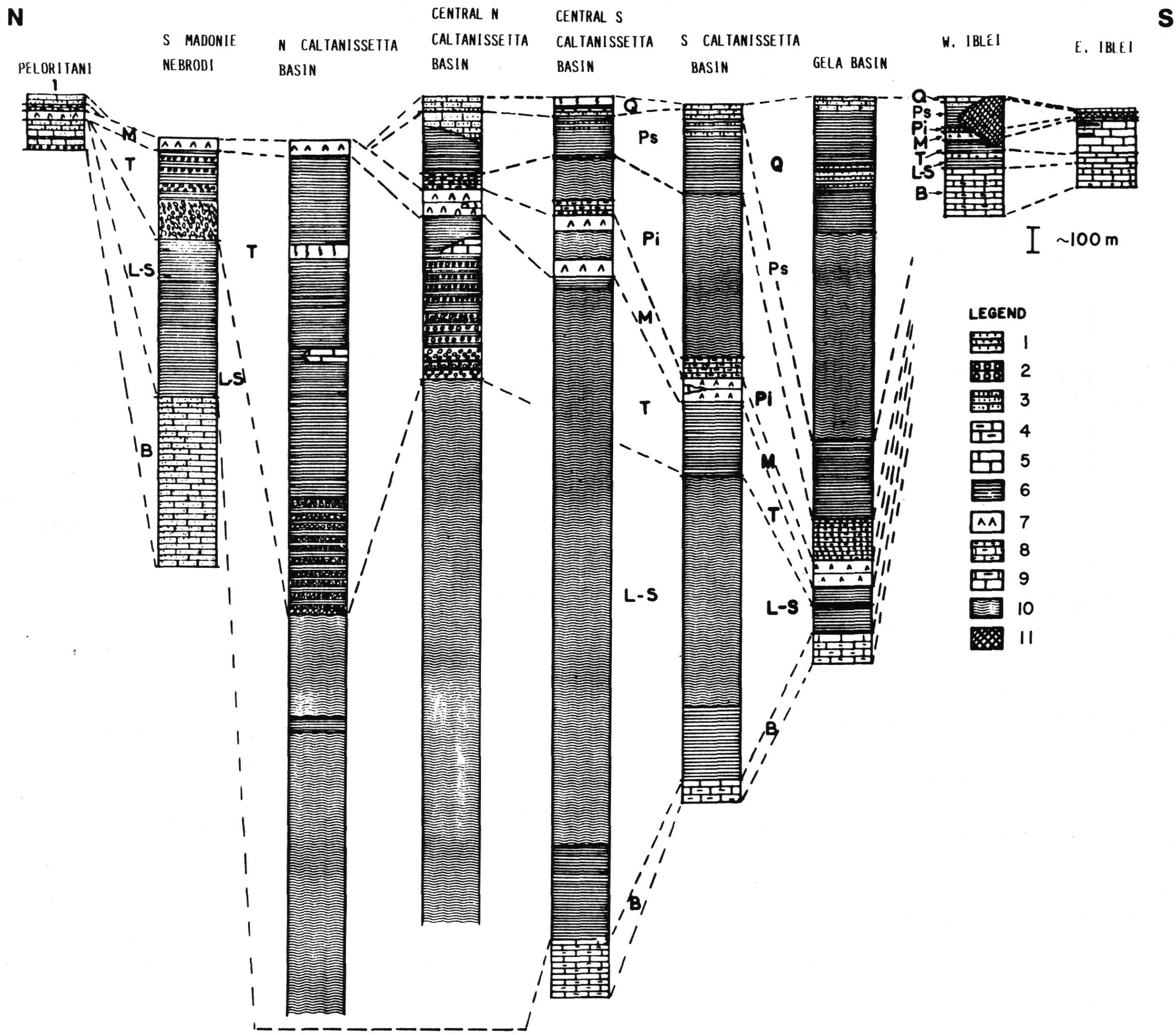


Figure 22. Neogene and Quaternary of Sicily. 1. Sands; sandy clays; 2. Conglomerates; 3. Sandy calcarenites; 4. Chalk (Trubi); 5. Calcarenites, reefs; 6. Marls, sandy marls, clays; 7. Messinian (gypsum, salt, sulfur-bearing limestones, tripoli), 8. Argillaceous limestones; 9. Rhythms with calcarenites and argillaceous limestones; 10. Allochthonous bodies (argille scagliose, "argille brecciate," olistostromes); 11. Tuffitic sandstones and volcanites; B. Burdigalian; L-S. Langhian-Serravallian; T. Tortonian; M. Messinian; Pi. lower Pliocene; Ps. middle to upper Pliocene; Q. Quaternary. After Broquet et al. (1984).

Scant geological and geophysical data show that in the abyssal plain the sedimentary interval is some 6 km thick and at least of Late Cretaceous age. Below this cover the crust is quite thin (some 6 km).

NOTES ON THE GEOLOGY OF THE ACOUSTIC BASEMENT IN THE TYRRHENIAN SEA

References for this section are Barberi et al., 1974; Beccaluva et al., 1985; Bigi et al., in press; Colantoni et al., 1981; Sartori, 1986; and Selli, 1974.

The acoustic basement of the Tyrrhenian Sea contains two main groups of rocks: pre-Tortonian crystalline, metamorphic, sedimentary, and magmatic lithotypes that represent the seaward extension of the structural domains of the surrounding lands, and post-Tortonian magmatic rocks that are related to the Neogene development of the basin.

1. Pre-Tortonian Rocks (Fig. 27)

Information on pre-Tortonian rocks comes from dredge, drilling, and submersible samples from *in-situ* rock outcrops or from clasts included in post-Tortonian breccias, widespread on many sialic seamounts. Assignment of one or more lithotypes to a given domain is always tentative; in several cases, however, structural pertinence has been determined with some confidence.

For instance, Tethyan ophiolites, sometimes with their radiolarite to cherty cover deposits, both of Piemontese and Ligurian type, have been found in many places located along the ideal

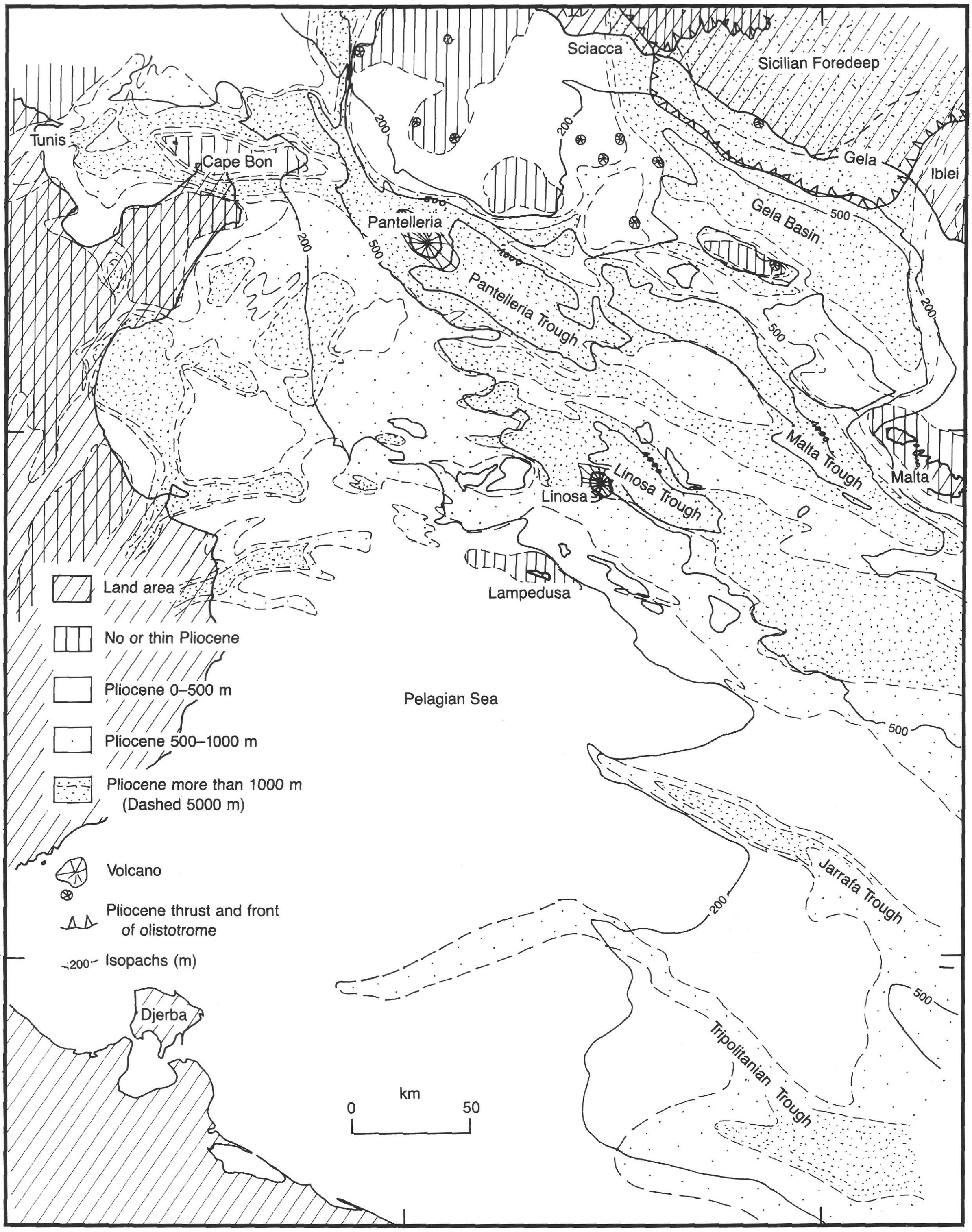


Figure 23. Map of Pliocene isopachs in the Pelagian Sea. After Winnock (1981).

connection between Alpine Corsica and northern Calabria. So far, they have never been recovered south of the Catanzaro isthmus, suggesting that the Mesozoic Tethyan realm closed at that latitude. Elements pertaining to the margins and basins of the Tethyan realm (e.g., *Helminthoides*-like flysch, etc.) seem to parallel the distribution of ophiolites.

Fragments of basement and cover nappes similar to those found in the Calabrian arc and/or in the Kabilide domain of North Africa appear to have a wide distribution inside the Tyrrhenian basin. This suggests that the Calabrian arc is not only the most bent, but also the most stretched, segment among the domains surrounding the basin.

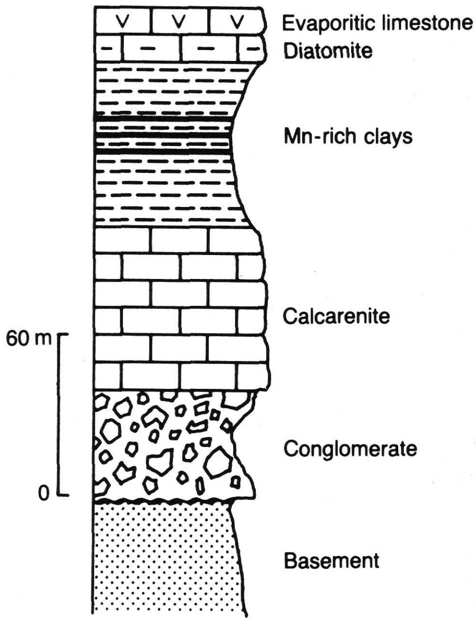


Figure 24. Schematic lithostratigraphy of a typical postorogenic basin along the Tyrrhenian side of the Calabrian arc. After Di Nocera et al. (1979).

Many samples from the inner margins of the chains, but also from the very center of the basin to the east of the Central Fault, belong to the carbonate platform-basin systems of Mesozoic age typical of southern Apenninic and Sicilian external units.

Elements of the Hercynian basement and Mesozoic cover of Sardinia are widespread east of the island, but seem to be confined to the west of the Central Fault. This feature strongly controlled the phases of stretching and oceanization of the basement. As indicated by the characters of the acoustic basement, it may represent an ancestral boundary among different structural domains, rejuvenated, as a zone of potential weakness, during the Neogene basin formation.

2. Post-Tortonian Magmatic Rocks (Figs. 28 and 29)

Examining all submarine, mainland, and island manifestations, the magmatic rocks can be grouped into three time cycles: upper Tortonian to Messinian; Pliocene; and Pleistocene. At each cycle, the manifestations have been divided into two main groups according to the geostructural character of the various volcanic chemistries. Volcanics broadly indicating extensional processes in the crust (alkali-olivine and tholeiitic) have been distinguished from volcanics somewhat related to subduction and close to compressional belt fronts (calc-alkaline and ?shoshonitic). The location of high-potassic volcanics is still controversial in this respect. Examining the temporal sequence obtained in this way, we have indications about the history and

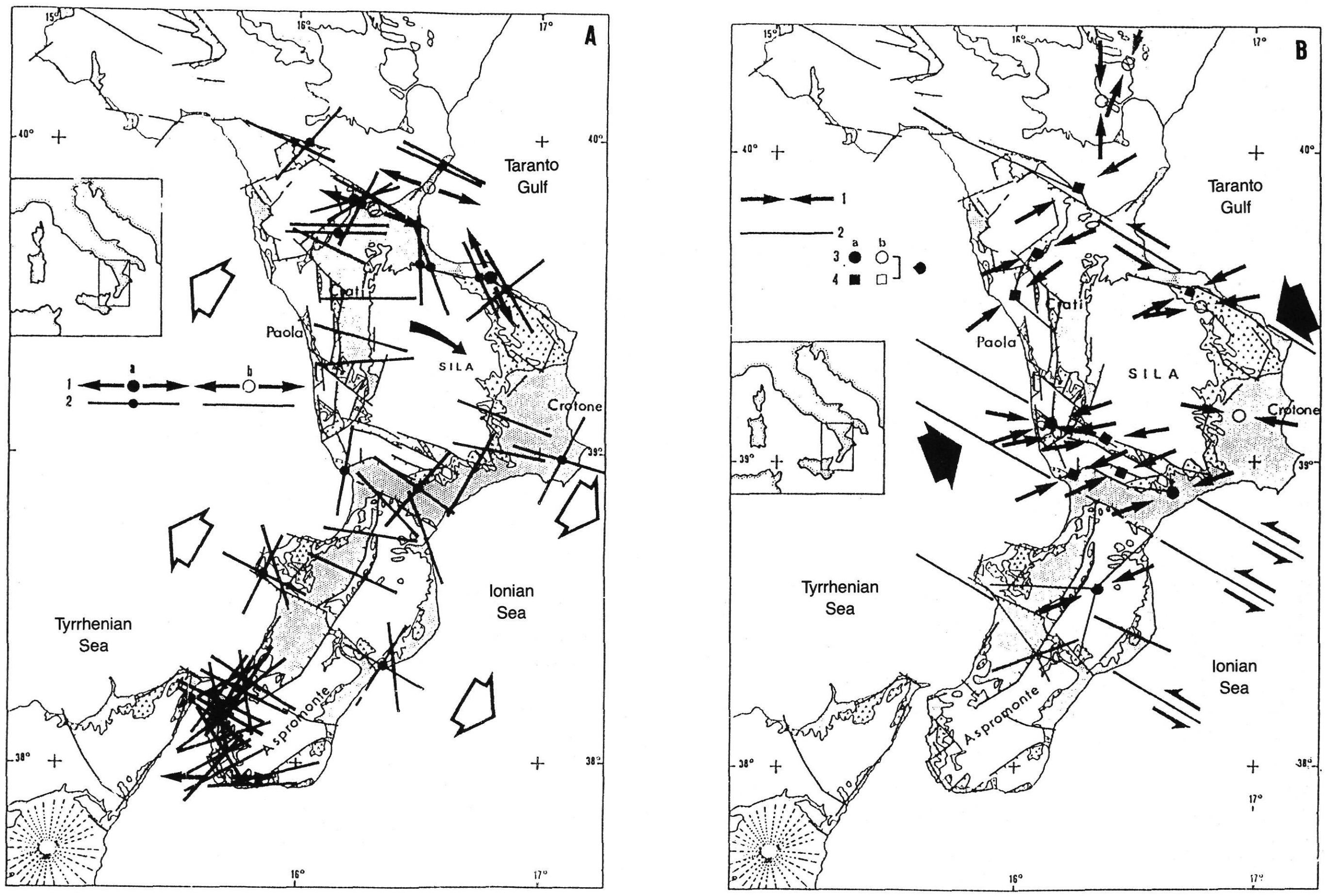


Figure 25. Extension in: A. Pliocene and Quaternary formations. B. Compression in Tortonian, Messinian, early Pliocene, and their substrata in the Calabrian arc. 1. Computed; 2. Constructed; 3. Station in early Pliocene formation; 4. Station in basement; A. measurement by Moussat et al., 1985; B. measurement in literature. After Moussat et al. (1985).

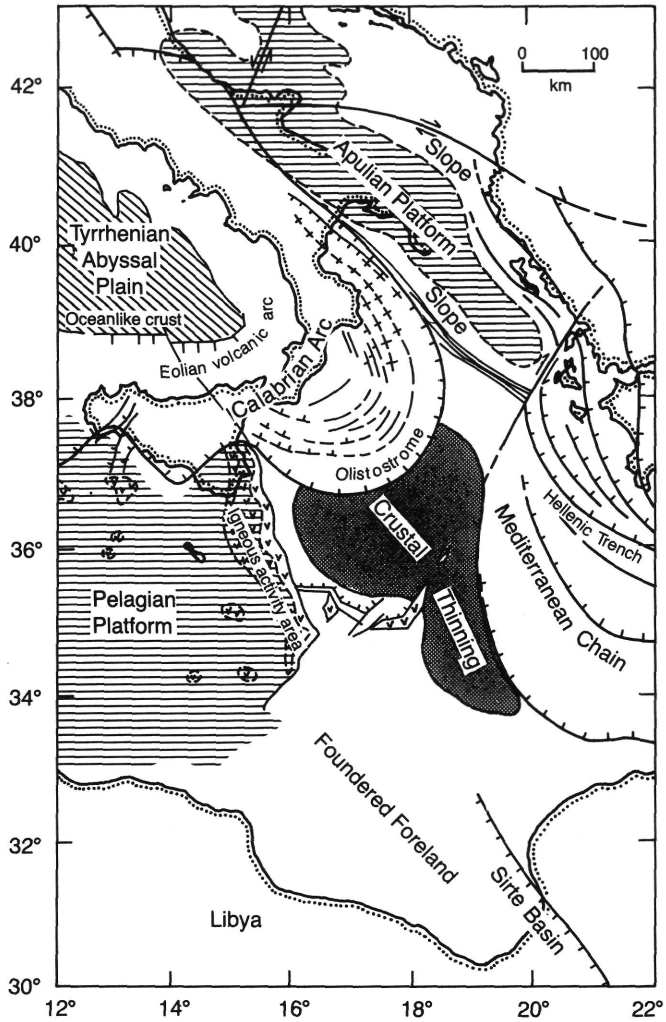


Figure 26. Tectonic sketch of the Ionian Sea. After Finetti (1982).

geometry of opening of the Tyrrhenian basin. We observe a progressive eastward displacement and a progressive deformation, also possibly caused by stress changes, of an arcuate row of subduction-related volcanics with parallel enlargement of the zone occupied by extension-related volcanics.

CONCLUSIONS

1. The Tyrrhenian area is inserted among structural domains that differ from each other in structure and age of deformations. They are: (A) Alpine units, deformed in pre-Oligocene times, and now present with their foreland in the Corsica-Sardinia block. (B) Internal Apenninic units, characterized by Miocene deformations related to the opening of the western Mediterranean basin and to the rotation of the Corsica-Sardinia block. Some segments of Alpine units (Calabria-Peloritani, internal Ligurian units, etc.) were also incorporated into this younger deformation system. (C) The Calabrian arc and the external Apennines and Sicily (including the foredeeps) result from late Miocene to present-day deformations. Some segments of previously deformed belts were also involved in these late events; present-day compression is mainly directed N120°E in Calabria.

2. The foreland zones are represented by three different segments: (A) The Adriatic-Apulian carbonate platform with a normal crustal thickness; (B) The Ionian abyssal plain possibly with a thin and old crust; (C) The Hyblean-Pelagian platform, an emerged to very shallow-water area with slightly thinned crust.

3. A very rapid crustal thinning was produced in the Tyrrhenian area in the Neogene at the expense of a previously thickened crust. This picture seems quite different from that of the western Mediterranean basin, whose stretching affected continental crust of almost normal thickness.

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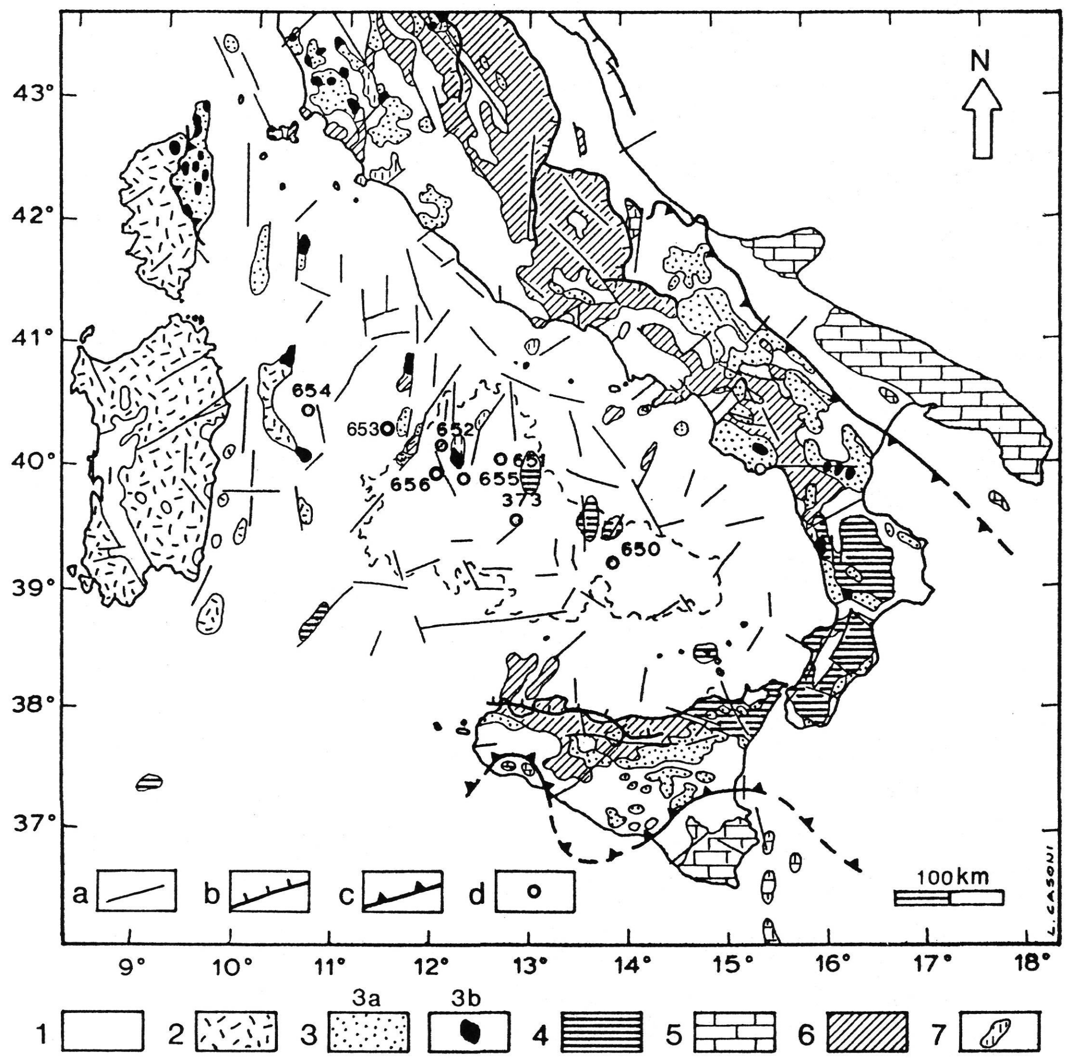

Figure 27. Main structural units around the Tyrrhenian Sea and possible equivalents inside the basin. 1. Late and postorogenic Units and post-upper Tortonian igneous rocks. European units: 2. Corsica-Sardinia Alpine foreland. Internal units: 3a Mesozoic to Tertiary pelagic sequences including 3b ophiolites of the Alpine cycle; 4. Crystalline massifs (Calabride and Kabilide). African units: 5. Apulian-African foreland; 6. Continental margin deformed by the Alpine-Apenninic orogenesis; 7. "Basal series": metamorphic basement and rocks affected by Miocene greenschist metamorphism. a. Normal, vertical, and strike slip faults; b. Main thrust fronts; c. External front of Apennines and Sicily; d. DSDP and ODP Sites. After Sartori (1986).

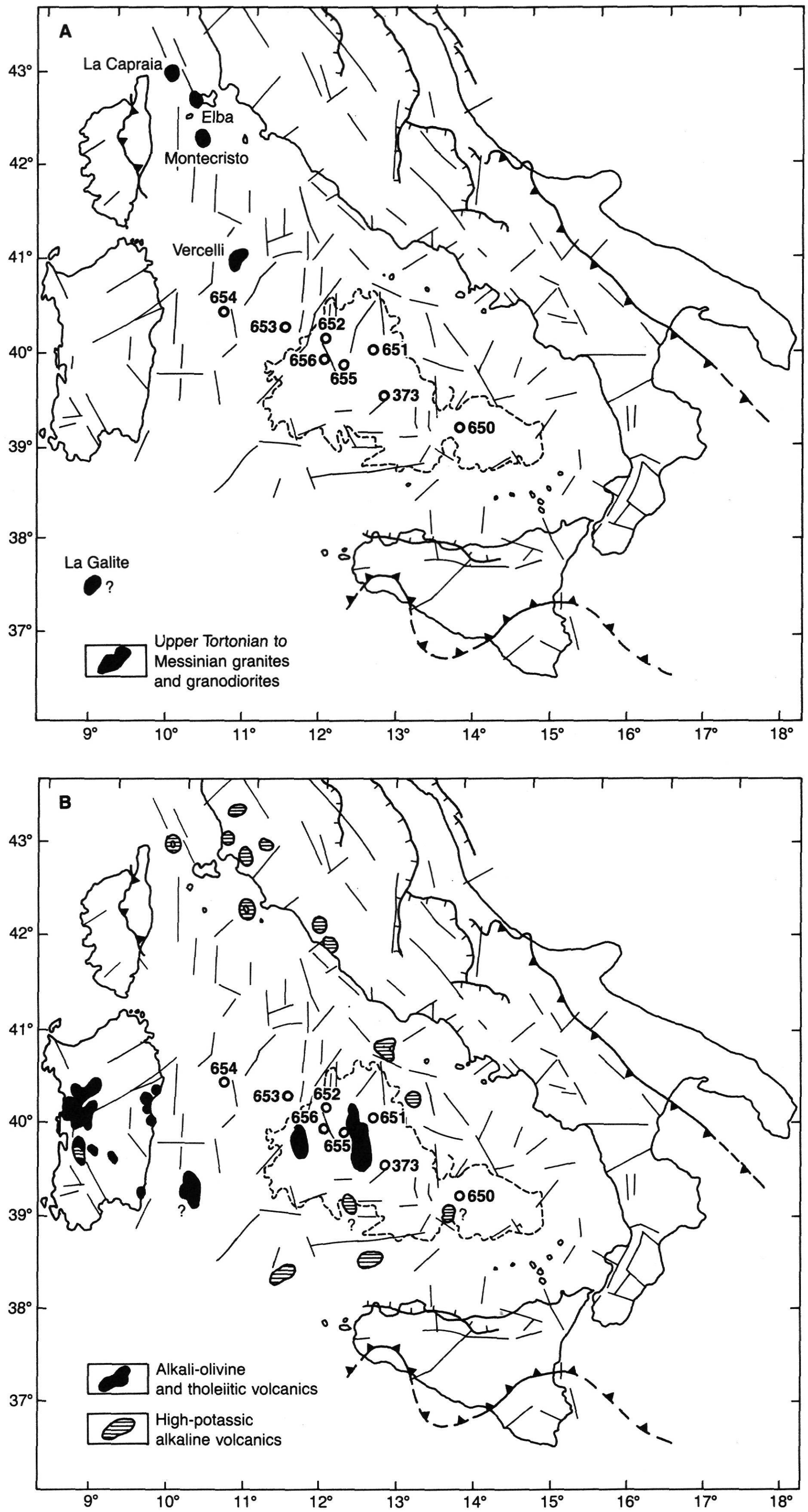

Figure 28. A. Upper Tortonian to Messinian (9–7 Ma) magmatic cycle: granites and granodiorites. B. Pliocene magmatic cycle in and around the Tyrrhenian Sea. After Sartori (1986).

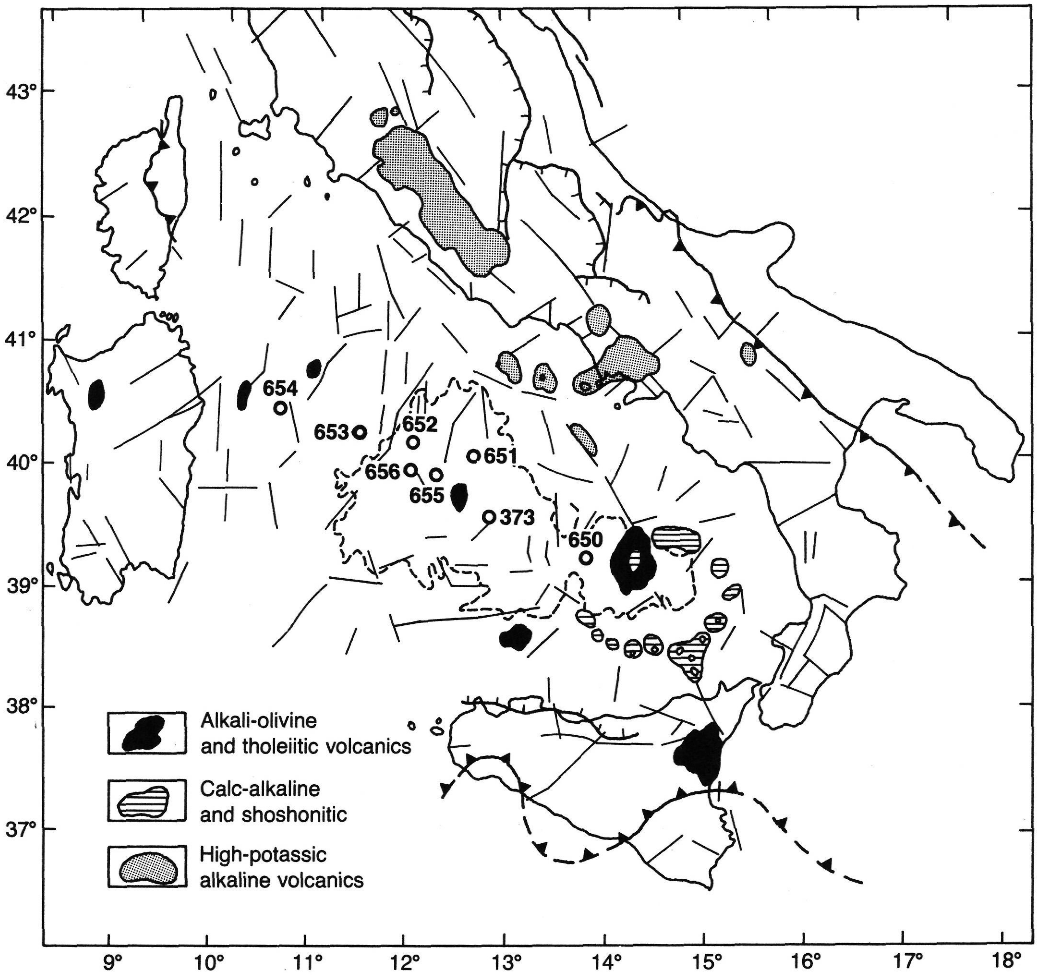

Figure 29. Pleistocene volcanism in and around the Tyrrhenian Sea. After Sartori (1986).