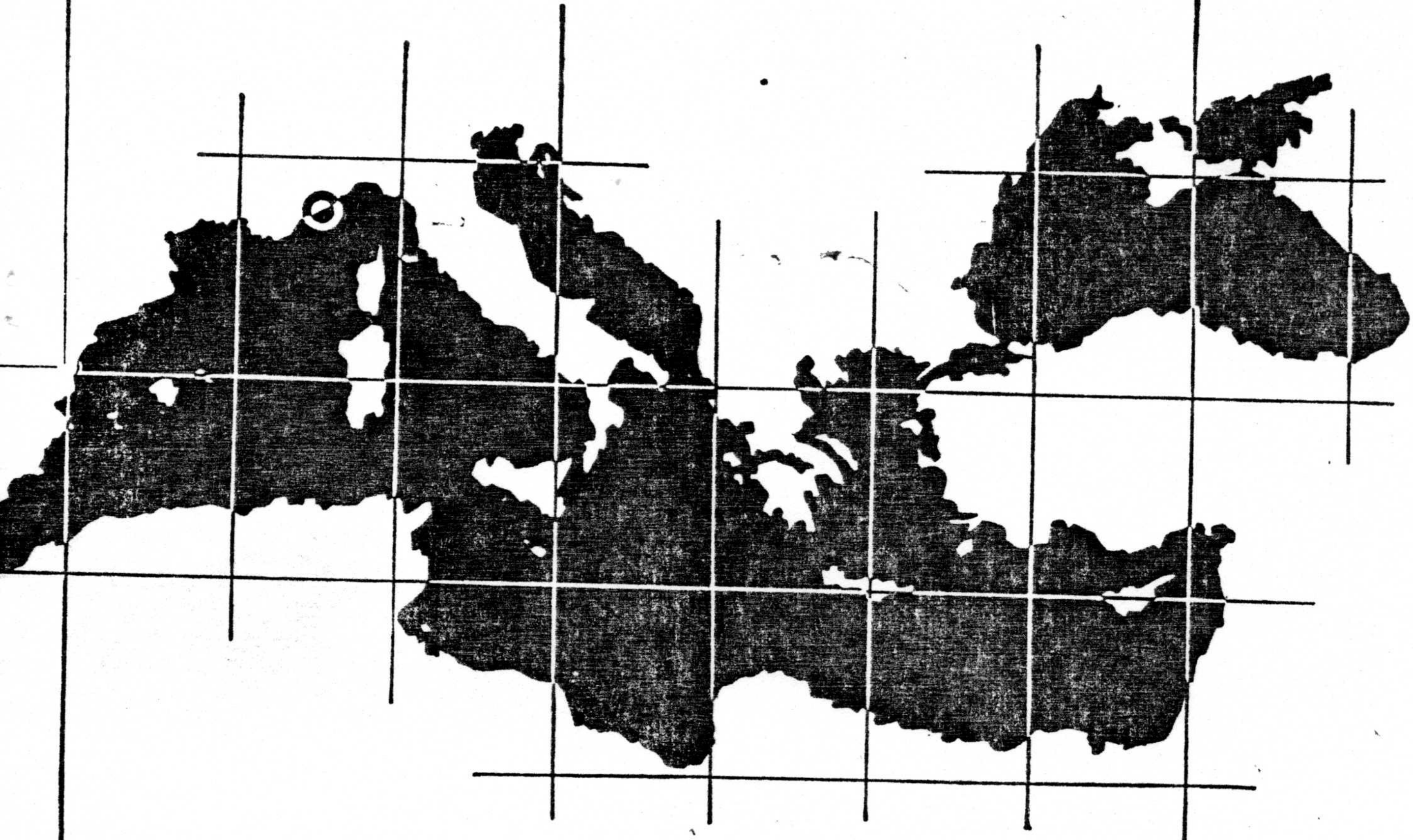
COMMISSION INTERNATIONALE POUR
L'EXPLORATION SCIENTIFIQUE
DE LA MER MÉDITERRANÉE
MONACO



RAPPORTS ET PROCES-VERBAUX DES REUNIONS

PUBLIÉ SOUS LA DIRECTION DE J.-Y. COUSTEAU
SECRÉTARIAT GÉNÉRAL: 16. Bd DE SUISSE, Pté de MONACO

VOLUME 27
FASCICULE 8
1981

GÉOLOGIE ET GÉOPHYSIQUE MARINES

STRUCTURE AND EVOLUTION OF THE TYRRHENIAN BASIN

G. Calcagnile[1], A. Fabbri[2], F. Farsi[3], P. Gallignani[2], C. Gasparini[4], G. Iannaccone[5], E. Mantovani[3], G.F. Panza[1], R. Sartori[2], P. Scandone[6] and R. Scarpa[5]

1. Istituto di Geologia e Geofisica dell'Università, Bari.
2. Istituto di Geologia Marina del C.N.R., Bologna.
3. Osservatorio Geofisico, Siena.
4. Istituto Nazionale di Geofisica, Roma.
5. Osservatorio Vesuviano, Ercolano (Na).
6. Istituto di Geologia e Paleontologia dell'Università, Pisa.

Numerous and often controversial hypotheses on the origin and evolution of the Tyrrhenian basin have been put forward, but no univocal and fully satisfactory explanation has been obtained as yet. In this short note, the basic geological and geophysical information available on the Tyrrhenian Sea and the surrounding land masses will be summarized (Fig.1) and the different proposed interpretations will be discussed.

The physiography of the Tyrrhenian sea-floor has been extensively investigated and quite detailed bathymetric and morphologic maps are available (Morelli 1970, Finetti and Morelli 1973, Savelli and Wezel 1979). The marginal parts of the Tyrrhenian Sea are characterized by narrow and elongated Neogene-Quaternary basins (peri-Tyrrhenian basins) which trend roughly parallel to the surrounding land masses and are often bordered by ridge-shaped seamounts. The central part of the Sea is a bathyal plain more than 3,500 meters deep from which several volcanic and non volcanic seamounts rise up.

The western margin of the Tyrrhenian Sea trends N-S and is made by the eastern edge of the Corsica-Sardinia "block", currently interpreted as a counterclockwise rotated or a drifted micro

---

P.F. GEODINAMICA, Pubbl.n°370

plate which during uppermost Oligocene-lowermost Miocene opened the space corresponding to the present Western Mediterranean basin (Boccaletti and Guazzone 1972, Alvarez 1972, De Jong et al. 1973, Westphal et al. 1973, Auzende et al. 1973, Bayer et al. 1973).

Most of the Authors agree that Corsica and Sardinia belong to a segment of the European continental margin which during Paleogene and lowermost Miocene played the role of the Alpine nappe foreland. A piece of the Alpine chain is preserved in north-eastern Corsica, where a pile of nappes having western vergence is well exposed. These units have their equivalents in the Western Alps (upper Penninic nappes), in the Northern Apennines (Ligurian nappes), in the Southern Apennines and in the Calabrian Arc (upper Penninic and Ligurian nappes). A continuation of the Alpine chain to the south of Corsica is suggested by the presence of thrust sheets in eastern Sardinia (Chabrier 1970, Cherchi, personal communication) as well as by findings of metamorphites with lawsonite and blue amphibole on the Cialdi seamount and of non-metamorphic ophiolites on the north Baronie Ridge (Wezel et al. 1977, Bacini sedimentari 1979).

The Corsica-Sardinia continental margin is, at present, dissected by vertical faults having mainly N-S strike. Two basins develop along this margin: the Corsica basin and the Sardinia one, the latter subdivided into several minor physiographic units (Ichnusa, Ogliastra, Baronie, Olbia basins). In the Corsica basin a thick sedimentary sequence has been recognized by reflection seismic profiles, which consists of pre-evaporitic deposits (about 3,000 meters), a thin layer of Messinian evaporites and a pile of Plio-Quaternary sediments (up to 1,000 meters)(Aleria 1979). A comparable succession is present in the Sardinia basin, showing however less pre-evaporitic sediments and a greater thickness of the evaporites which include here a lower salt layer and an upper gypsum layer (Borsetti et al. 1979).

The southern margin of the Tyrrhenian Sea, having E-W trend, is constituted by the eastern segment of the south-verging Neogene Maghrebian chain which in Sicily mainly consists of decollement sedimentary nappes. In the Peloritani mountains, the latter are overlain by basement nappes, generally not affected by Alpine

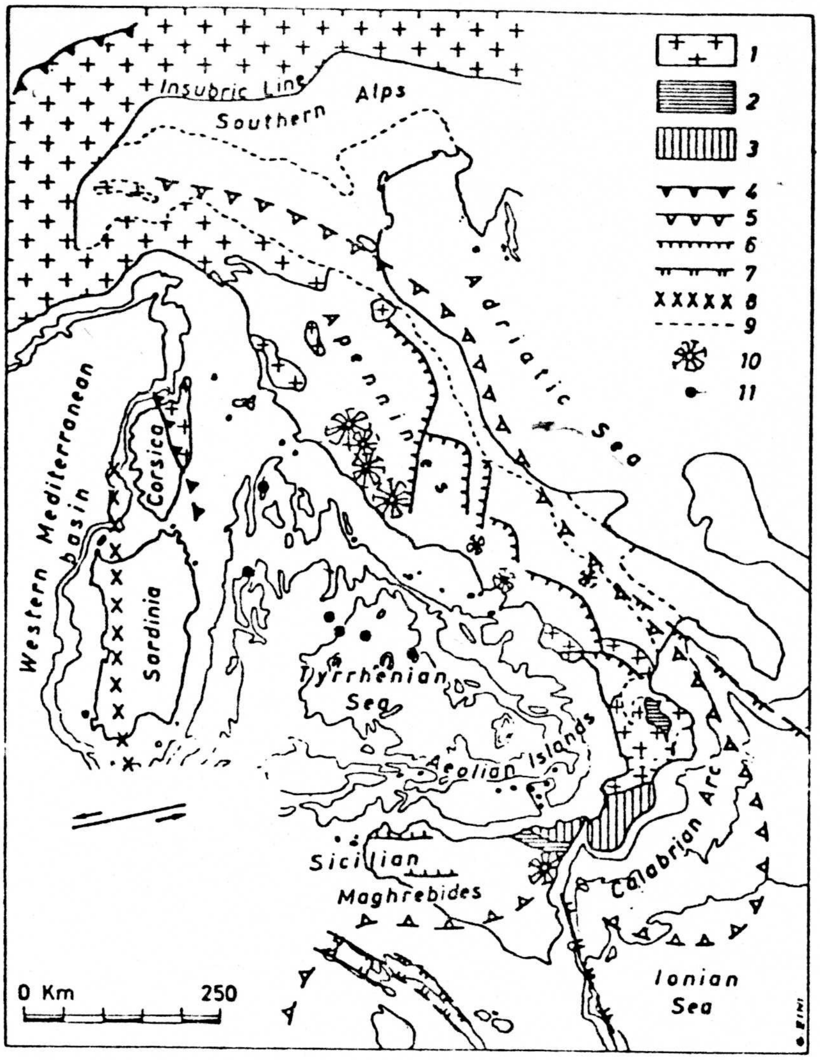


Figure 1. - Structural sketch of the circum-Tyrrhenian area. 1. Paleogene and Neogene Europe-verging Alpine chain; 2. "Insubric" Africa-verging basement nappes; 3. Upper crystalline units of Aspromonte and Peloritani; 4. European front of the Alpine chain; 5. Neogene compression front of the Apennines and Sicilian Maghrebides. In the Ionian Sea: front of the Calabrian Ridge; 6. Neogene front of the carbonate units in the Apennines and Sicily; 7. Apulia escarpment, Malta escarpment and Pantelleria Graben; 8. Oligocene-Miocene calc-alkaline arc of western Sardinia; 9. Limits of postorogenic deposits; 10. Main uppermost Tertiary-Quaternary volcanoes on land; 11. Location of samples possibly indicating elements of the Alpine chain.

metamorphism, which had been piled up during Paleogene and were then transported in toto over the southern domains during the lower Miocene.

The slope to the north of Sicily looks more irregular than the eastern margin of Corsica-Sardinia, as it is complicated by several volcanic and non-volcanic seamounts enclosing small basins (Trapani, Erice, Ustica, Cefalù, and Orlando basins). The sedimentary sequence is less complete than in the Corsica-Sardinia basins, as pre-evaporitic deposits have seldom been recorded in the reflection seismic profiles, and the Messinian evaporites are generally represented by only a thin and discontinuous layer. The Plio-Quaternary sediments reach a thickness of about 1,500 meters (Bacini Sedimentari 1980).

The south-eastern margin of the Tyrrhenian Sea is bordered by the faulted inner side of the Calabrian Arc. The structure of this belt, mainly made of crystalline units, is very complex and not yet wholly understood (Amodio Morelli et al. 1976). The metamorphic nappes of Northern Calabria, which overlie the highest units of the Neogene Adria-vergent Apennine chain, have been attributed to the Paleogene Alpine chain. The overthrust of the Europe-verging Alpine chain over the Apenninic domains dates back to the lower Miocene (Burdigalian). The Apenninic units crop out in some tectonic windows as far south as the Catanzaro fault zone. Southwards, they disappear plunging beneath the Alpine nappes, so that their connection with the Maghrebian units is not exposed. The Alpine nappes, in turn, are tectonically buried, in the Serre mountains, by the crystalline higher units of Aspromonte and Peloritani, whose provenance is supposed to be European. The picture is even more complicated by the presence of "Insubric" Africa-verging Paleogene elements which form a discontinuous belt from Northern Calabria (Sila) to Eastern Sicily (crystalline lower units in the Peloritani mountains).

Also along the Calabrian Arc Plio-Quaternary basins (Gioia, Paola, and Sapri basins) are developed. The Gioia basin is characterized by a strong subsidence before the salinity crisis, and a sequence of pre-evaporitic deposits about 2,500 meters thick has been recorded in the reflection seismic profiles (Fabbri et al., in press). The maximal post-evaporitic subsidence has been reached in the Paola basin, where a succession more than 4,000 meters thick has been recognized (Finetti and Morelli 1973).

At the south-eastern corner of the Tyrrhenian basin the Aeolian islands emerge, sketching an incomplete ring around the Marsili seamount, together with the other calc-alkaline submarine volcanoes (Glauco, Sisifo, Enarete, Eolo, Lametino, Palinuro) (Selli et al. 1979, Colantoni et al., in press). Dredgings from Marsili revealed the presence of tholeiitic basalts near the base and of products with calc-alkaline affinity (shoshonites) on the top (Selli et al. 1979).

The north-eastern margin of the Tyrrhenian basin is constituted by the inner faulted side of the Apenninic chain. At the northern apex of the Tyrrhenian Sea the Europe-verging Alpine chain and the Adria-verging Apenninic chain face each other. The former partially overthrusts the latter. In this area an anatectic magmatic activity is developed, ranging in age from midlle Miocene until Quaternary; a time-space migration of this activity from the wast to the east has been ascertained. Post-orogenic deposits are poorly developed in this area.

The Tyrrhenian bathyal plain may be subdivided into two sectors, separated by the Tyrrhenian central fault (see Fabbri et al. in this volume) which crosses the basin with strike changing from N-S in the northern part to NE-SW in the southern one. Sedimentary sequences comparable to those filling the Sardinia and Corsica basins, with thick pre-evaporitic deposits (Cornaglia Terrace) and thin (some hundreds of meters) Plio-Quaternary sediments have been recognized west of the Central Fault. This part of the Tyrrhenian basin is probably founded on a thinned continental crust. In the eastern Tyrrhenian Sea the basins north of the Magnaghi and Vavilov volcanoes are characterized by a thick upper Miocene? -Quaternary sequence with no clear evidence of Messinian evaporites. The latter are more developed southwards, where they overlie directly the basement or cover stratigraphically a poorly penetrated sedimentary sequence having seismic characteristics different from the pre-evaporitic deposits in the western sector.

Dredgings along the Tyrrhenian central fault revealed lithologies comparable to the Sardinian and Tuscan sequences (Fabbri et al., in progress). Samples of granite, metamorphites, gabbros and their sedimentary cover have been collected from the Flavio Gioia and De Marchi seamounts. Some of these lithotypes show analogies with the Alpine sequences of North-eastern Corsica and Northern Calabria (Dal Piaz et al.,in progress). Location of possible Alpine fragments in the Tyrrhenian area is shown in Figure 1.

Important results came from the DSDP Site 373A, which penetrated the magnetic basement of the central bathyal plain, made up of tholeiitic basalts. The deepest penetrated lavas are here slightly older than the Messinian evaporites (7.3 My) (Hsü, Montadert et al. 1976).

The whole Tyrrhenian area is characterized by strong positive Bouguer anomalies, with maximum values measured in the bathyal plain (Morelli 1970). Deep seismic soundings revealed a crust less than 15 kms thick (Finetti and Morelli 1973). The heat flow measurements show a great variability, without apparent correlations with shallow structures. The average value in the central bathyal plain is around 2 HFU (Foucher, personal communication), whereas an average value higher than 3 HFU is reached in the south-eastern part of the basin (Della Vedova and Pellis 1979).

The deep structure of the Tyrrhenian and circum-Tyrrhenian area has been investigated by analysis of teleseism as well as of intermediate and deep local earthquakes. The analysis of Raleigh-wave velocity dispersion from teleseism (Berry and Knopoff 1967, Baldi et al. 1979, Calcagnile and Panza 1979, Calcagnile et al. 1979, Mantovani et al. 1980) and of group velocity dispersion from earthquakes in the Mediterranean area (Mantovani et al. 1980) has provided information on the velocity-depth behaviour of S-waves in the crust and upper mantle. In order to apply the cross path technique, the area was initially subdivided into ten regions on the basis of the dispersion characteristics and of the lithological-geophysical features. By trial and error it was finally possible to define the six main regions shown in Fig.2. The lithospheric typologies, as derived from the interpretation of the dispersion curves for each region, are reported in the caption of this figure. It is worth mentioning that in region 1 a crustal velocity layer is not required and that the crust-mantle transition is not sharp. In region 2 a mild crustal low-velocity layer may be present, although not required, and still the crust-mantle transition seems quite smooth. Furthermore, beneath parts

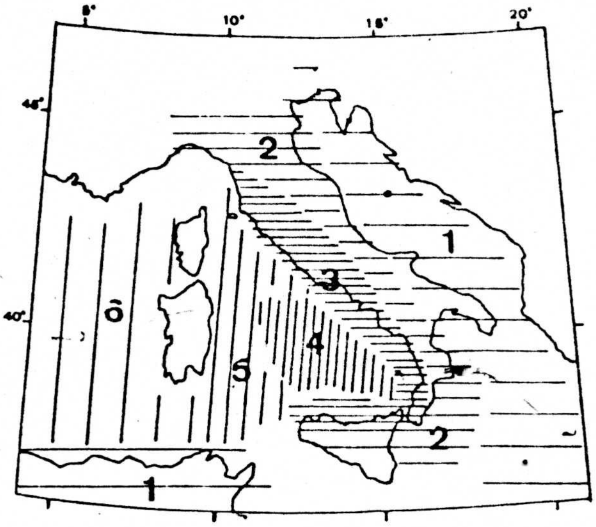


Figure 2.- Lithosphere-astenosphere properties.

1. Crustal thicknesses (h_{cr}) about 30-35 km; lithospheric thickness (h_{lith}) about 90-110 km; average S-wave velocity in the LID (v_{LID}) about 4.50-4.65 km/sec; average S-wave velocity in the upper astenosphere (v_{ast}) about 4.2-4.4 km/sec.

2. h_{cr} about 30-37 km; h_{LID} about 60-80 km; v_{LID} about 4.20-4.40 km/sec; v_{ast} about 4.4-4.5 km/sec.

3. h_{cr} is not easily definable, but it may be of about 20-25 km if a very low velocity (4.05-4.20 km/sec) is assigned to the upper mantle; h_{lith} about 50-70 km; v_{ast} about 4.4-4.6 km/sec.

4. h_{cr} about 10-15 km; h_{lith} about 20-30 km; v_{LID} about 4.20-4.35 km/sec; v_{ast} about 4.0-4.3 km/sec.

5. h_{cr} about 15-20 km; h_{lith} about 40-60 km; v_{LID} about 4.20-4.35 km/sec; v_{ast} about 4.3-4.5 km/sec.

6. h_{cr} about 10-15 km; h_{lith} about 30-50 km; v_{LID} about 4.20-4.35 km/sec; v_{ast} about 4.1-4.3 km/sec.

---

of regions 2 and 3 it was possible to locate high velocity material, starting at a depth of about 70 km and extending for at least 100 km, which could be interpreted as a lithospheric root.

The analysis of the Tyrrhenian deep and intermediate seismicity has been performed through hypocenter relocation and evaluation of all available fault-plane solutions. The structure sketched by the intermediate and deep hypocenters is almost continuous to a depth of 480 km in the southern part of the Calabrian Arc, whereas a seismicity gap above 200 km is present in the northern part of the arc. Most of the seismic energy has been released in the 230-340 km depth range, and the decrease of earthquake number and energy aboveand below this depth interval occurs in low velocity zones of body waves, as inferred from Raleigh wave dispersion measurements (Panza and Calcagnile 1980) and from inversion of P-wave traveltimes (Mseddi 1976). The Tyrrhenian Benioff zone presents a concave shape and an arc-like structure plunging in a NW direction, with an almost vertical dip to a depth of 230 km, a dip of 50° in the 230-340 km depth interval and a low dip angle down to the depth of 480 km. Relocation through Joint Hypocenter Determination (JHD) has improved by a factor of 2 the RMS value of the residuals, with a reduction of the hypocenter scattering in the Benioff zone from 100 to about 50 km.

55 most reliable fault-plane solutions inferred from P-wave first motions indicate a complex stress pattern occurring in the Calabrian Arc and surrounding regions (Fig.3). Focal mechanisms of earthquakes occurring in the 230-340 km depth interval indicate a predominance of down-dip compression. Intermediate earthquakes located between the Calabrian Arc and the Aeolian islands show instead both down-slip extension and normal faulting with T-axes in a horizontal plane, parallel to the strike of the Calabrian Arc. This last stress pattern may be interpreted as due to the unusual strong curvature of the arc. The deep earthquakes located at the northern and southern borders of the arc indicate strike-slip motion, in good agreement with the fault-plane solutions of shallow earthquakes. The strike-slip motion may be interpreted as a consequence of a deformed Benioff zone, consistent with its concave shape. The crustal earthquakes indicate predominance of normal faulting and transcurrent motion. The stress pattern observed along the Calabrian Arc is consistent with the neotectonic analysis, which indicates a lateral stretching and segmentation of the shallow part of the arc.

We said that numerous and often controversial hypotheses on the origin and evolution of the Tyrrhenian Sea have been proposed. Leaving out the idea - at present obsolete - that the Tyrrhenian .

Figure 3.- Schematic stress pattern of the Calabrian Arc and surrounding regions. Open and closed symbols represent stress and strike slip of preferred fault orientation for deep-intermediate and for shallow earthquakes respectively. The size of symbols is proportional to the number and reliability of fault plane solutions.

---

basin may represent a remnant of the ancient Tethys, there is a general agreement that the basin is a young foundered area with oceanic characteristics. The main disagreement among the authors concerns the dynamic model. Four models will be discussed here.

1) Oceanization and foundering of a continental stable belt (Van Bemmelen 1969, Morelli 1970, Selli and Fabbri 1971, Selli 1974). This model, with some minor variants (Wezel 1978, Savelli and Wezel 1979) does not give satisfactory explanation of the magmatic activity (e.g. contemporaneity of the anatectic activity in the northern Tyrrhenian Sea and tholeiitic volcanism in the central bathyal plain; presence of the calc-alkaline Aeolian islands in the south-western corner of the basin), nor of the deep focus earthquakes in the Southern Tyrrhenian Sea and of the split of the Alpine chain whose remnants are today preserved in Corsica and in Calabria on the opposite sides of the basin. This last problem is bypassed by Wezel (1978) who hypothesizes, without any evidences, two branches of the Alpine chain bordering the Tyrrhenian Sea.

2) Back-arc basin (Boccaletti and Guazzone 1972, Barberi et al. 1973). This is the most popular and accepted model, which apparently fits a lot of geological and geophysical data. However, no time relation seems to exist between the assumed arc-trench migration (which started before Messinian) and the present calc-alkaline arc. Moreover, no explanation of the contemporaneous anatectic and tholeiitic magmatism in the Northern and Sothern Tyrrhenian Sea respectively is given. In addition, the planimetric extent of the arc is very small compared with the considerable depth of the Benioff zone, and it does not seem comparable with the dimensions of the typical Pacific arcs.

3) Fragmentation and dispersal of microplates (Alvarez et al. 1974). According to this model the Calabrian Arc is a microplate derived from the eastern edge of Sardinia; the Tyrrhenian Sea was formed in the wake of the Calabrian massif as it moved south-eastwards reaching its present location in recent times. The deep seismicity of the Southern Tyrrhenian Sea is interpreted as showing an ESE-directed overriding of a small Calabrian plate over the oceanic crust of the eastern Mediterranean-Ionian Sea. The main argument against this model is the timing in the proposed kinematics. We know, in fact, that the Calabrian Alpine nappes were welded to the highest Apenninic units already during Langhian, that is before the proposed time of fragmentation and south-eastward migration of the Calabria microplate.

4) Sinistral megashear and anticlockwise rotation of the Apennines (Scandone 1978). Following this model the fragmentation and splitting of the Alpine chain, as well as the opening of the Tyrrhenian basin, were generated by a middle-upper Miocene rifting in the Alpine belt east of Corsica-Sardinia, followed by an anticlockwise rotation of the Apennines and simultaneous eastward lateral displacement of the Tunisian-Sicilian Maghrebides. The displacement was probably accompanied in the Tyrrhenian area by several synthetic transcurrent faults, the most important being probably represented by the Central Tyrrhenian fault. Sinistral megashears in the Mediterranean area were already proposed by Carey (see, e.g. Carey 1976, Figs. 91-92). According to this model the present Benioff zone of the Southern Tyrrhenian Sea is a remnant of a large slab, chiefly consisting of African continent

tal lithosphere, subducted during the Europe-Africa collision. The original geometry of this slab was strongly deformed by the opening of the Western Mediterranean basin and subsequently of the Tyrrhenian Sea. The latter did not open, therefore, in a back-arc position (the arc at this time was located along the western margin of the Sardinia "block"), but developed further east of the volcanic arc, within the deformed belt of the Alpine chain. The western portion of the basin may be related either to the early Tyrrhenian extensional phases, as suggested by the sedimentary sequence which includes a thick pre-evaporitic succession and by the elastic properties in the crust and upper mantle, or to the development of Western Mediterranean.

The last model seems consistent with the available geological, volcanological and geophysical informations, but induces some new first-order problems. First of all the sinistral transcurrent fault postulated between Sardinia and Sicily is at present a "deus ex machina" which, moreover, induces serious kinematic implications to the west, in the direction of Gibraltar. Another problem is represented by the simultaneous spreading in the Tyrrhenian Sea and compression along the Apenninic front, which, vice versa, could be more easily explained by an arc-migration mechanism.

In conclusion, we consider the origin and evolution of the Tyrrhenian Sea a problem not yet solved, and new geological and geophisical researches have been programmed for the next years. An useful input is expected from the aeromagnetic survey recently carried out by AGIP Mineraria, which will be available in 1981.

References

Aleria, 1979, C.R.Acad.Sci.Paris, 288, 20, 1521-1524.
Alvarez W., 1972, Nature Phys.Sci., 235, 103-105.
Alvarez W. et al., 1974, Nature, 248, 308-314.
Amodio Morelli L. et al., 1976, Boll.Soc.Geol.Ital., 17, 1-60.
Auzende J.M. et al., 1973, J.Geol.Soc.London, 129, 607-620.
Bacini Sedimentari, 1979, Atti Conv.Sc.Naz.P.F.Oceanografia, 2, 713-727.
Bacini Sedimentari, 1980, L'Ateneo Parmense, Acta Nat., 16, 1, 3-18.
Baldi P. et al., 1979, Boll.Geof.Teor.Appl., 21, 82, 94-104.
Barberi F. et al., 1973, J.Geophys.Res., 78, 5221-5232.

Bayer R. et al., 1973, Earth Planet.Sci.Lett., 19, 168-176.

Berry M.J. and Knopoff L., 1967, J.Geophys.Res., 72, 3613.

Boccaletti M. and Guazzone G., 1972, Mem.Soc.Geol.Ital., 11, 201-216.

Borsetti A.M. et al., 1978, Atti Conv.Sc.Naz.P.F.Oceanografia, 2, 769-784.

Calcagnile G. and Panza G.F., 1979, J.Geophys.Res., 45, 319-327.

Calcagnile G. et al., 1979, Tectonophysics, 56, 51-63.

Carey S.W., 1976, The expanding Earth. Developments in Geotectonics, 10, Elsevier Sc.Publ.Co.

Chabrier G., 1970, C.R.Acad.Sci.France, 271, 1251-1255.

Colantoni P. et al, Marine Geology (in press).

De Jong K.A. et al., 1973, Nature, 243, 281-283.

Della Vedova B. and Pellis G., 1979, Atti Conv.Sc.Naz.P.F.Oceanografia, 2, 693-712.

Fabbri A. et al., Geologica Romana (in press).

Finetti I. and Morelli C., 1973, Boll.Geof.Teor.Appl., 15, 263-340.

HsüK.J., Montadert L. et al., 1978, Initial Reports of DSDP, 42, 1.

Mantovani E. et al. 1979, Atti Semin."Integrazione dei risultati della sismica attiva e passiva", P.F.Geodinamica.

Mantovani E. et al., 1980, Ann.Geofisica.

Morelli C., 1970, Boll. Geof.Teor.Appl., 12, 275-305.

Mseddi R., 1976, Ph.D.Thesis, Univ.P. et M.Curie, Paris.

Panza G.F. and Calcagnile G., 1980, Paleog.,Paleocl.,Paleoec., 29, 3-14.

Savelli D. and Wezel F.C., 1979, Atti Conv.Sc.Naz.P.F.Oceanografia, 2, 729-738.

Scandone P., 1978, Boll.Soc.Geol.Ital., 95.

Selli R., 1974, Rend.Sem.Fac.Sci.Univ.Cagliari, Suppl. 43, 327-349.

Selli R. and Fabbri A., 1971, Rend.Acc.Lincei, 50, 5, 104-116.

Selli R. et al., 1979, Rapp.Comm.Int.Mer Médit., 25/26, 2a, 61-62.

Van Bemmelen R.W., 1969, Geol.Mijnb., 26, 13-52.

Westphal M. et al., 1973, Earth Planet.Sci.Lett., 18, 137-140.

Wezel F.C., 1978, Rend.Soc.Geol.Ital., 1.

Wezel F.C. et al., 1977, L'Ateneo Parmense, Acta Nat., 13, Suppl.1, 71-92.