Atti Accademia Nazionale dei Lincei

Classe Scienze Fisiche Matematiche Naturali

Rendiconti

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Tyrrhenian: a Pliocene deep sea

Atti della Accademia Nazionale dei Lincei. Classe di Scienze Fisiche, Matematiche e Naturali. Rendiconti, Serie 8, Vol. **50** (1971), n.5, p. 580–592.

Accademia Nazionale dei Lincei

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Geologia. — *Tyrrhenian: a Pliocene deep sea.* Nota di RAIMONDO SELLI e AUGUSTO FABBRI, presentata (*) dal Corrisp. R. SELLI.

RIASSUNTO. — Profili sismici a riflessione hanno permesso di determinare in tutta l'area tirrenica due distinti cicli sedimentari e tettonici, che giacciono su un basamento pre-miocenico. Normalmente, essi sono separati da due nette superfici di discontinuità. La trasgressione basale del ciclo sedimentario inferiore appartiene verosimilmente al Miocene inferiore, il tetto dell'intervallo sicuramente al Pliocene inf. (o inizio Pliocene medio). I dati forniti dai dragaggi provano che l'età del ciclo sedimentario più recente si estende dalla parte alta del Pliocene medio all'Attuale; la sua discontinuità basale corrisponde ad una estesa trasgressione del Pliocene medio, ben nota anche in tutta la Penisola italiana ed in Sicilia. I nuovi dati dimostrano che durante il Pliocene medio l'area tirrenica era in gran parte emersa e somigliava ad un arcipelago con numerose ed ampie isole separate da bracci di mare. A partire dal Pliocene medio, cioè da circa 4 milioni di anni fa, ha avuto luogo un colossale sprofondamento di tutta l'area tirrenica con una velocità media di 1,1 mm per anno. L'attuale bacino tirrenico è quindi di età pliocenica e forse costituisce il più recente mare profondo del mondo.

INTRODUCTION

The Tyrrhenian Sea lies in the center of the Mediterranean filling a triangular 3,6 km deep depression. It is bordered by the Italian Peninsula, Sicily, Sardinia and Corsica.

All past hypotheses outlining structural and geological evolution of the area were based mainly on geological evidence from surrounding lands and on unsupported speculations about the structure of the seafloor. The hypothesis of a foundering of the Tyrrhenian area during the Neogene, has been widely accepted since the last century (Forsyth Major, 1883) and is still accepted today. It accounts for the migration of Neogene and Pleistocene terrestrial Mammals to Mediterranean islands, for the archaic endemisms in today's flora and fauna of Sardinia and Corsica, for the western source of clastics in Tertiary Flyshes of the Apennines, and for the origin of metamorphic and granitic pebbles in several Neogene deposits of the Italian Peninsula. Other workers speculated that the geological features of surrounding lands: mountain chains, faults, basins etc. extend and multiply on the Tyrrhenian seafloor.

A direct knowledge of the marine geology of the Tyrrhenian Sea is essential for better understanding of the Mediterranean Tertiary orogeny, par-

(*) Nella seduta dell'8 maggio 1971.

ticularly that of the Apennines. This was the objective of two cruises run during 1970 by the Laboratorio di Geologia Marina in Bologna aboard the R. V. Bannock of the Consiglio Nazionale delle Ricerche.

This paper presents the highlights of the preliminary analysis of the results obtained.

Physiographic setting

The physiography of the Tyrrhenian Sea is well known today from the numerous and detailed bathymetric maps (Istituto Idrografico della Marina Italiana, 1967 and 1969; Morelli and others, 1970). Fig. 1 shows the seven morphological units which can be distinguished (Selli, 1970 b): *a*) continental

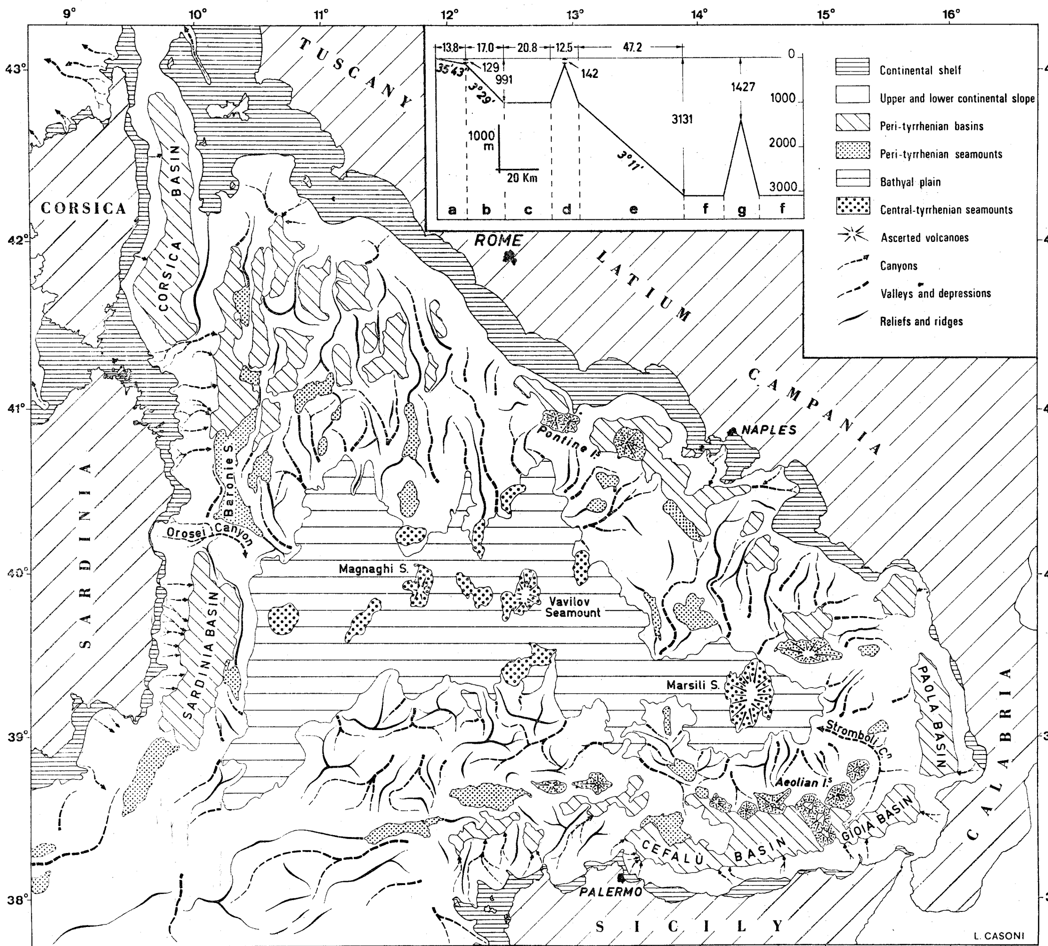

Fig. 1. – Morphological scheme of the Tyrrhenian Sea. Insert: generalized profile across the central and southern Tyrrhenian Sea with average widths (in km), depths (in m) and dips of main morphological units: *a*) continental shelf, *b*) upper continental slope, *c*) peri-Tyrrhenian basins, *d*) peri-Tyrrhenian seamounts, *e*) lower continental slope, *f*) bathyal plain, *g*) central-Tyrrhenian seamounts. From Selli (1970 b) simplified.

shelf, *b*) upper continental slope, *c*) peri–Tyrrhenian basins, *d*) peri-Tyrrhenian seamounts, *e*) lower continental slope, *f*) bathyal plain, *g*) central-Tyrrhenian seamounts.

The average depth of the shelf-break is 128 m. The continental slope is interrupted by a discontinuous, but distinct belt of large sedimentary peri-Tyrrhenian basins. Seaward, such basins are often bordered by seamounts and ridges or insular volcanoes, i.e. Pontine Islands, Stromboli and Aeolian Islands. Acting as dams, they help to retain the terrigenous sediments, carried through canyons cutting the upper slope.

The Tyrrhenian bathyal plain differs from an oceanic abyssal plain because of its gently concave shape, the high sedimentation rate and the intermediate type of the underlying crust (Fahlquist and Hersey, 1969). It rather resembles the oceanic continental rise. For this reason the term *bathyal* is going to be adopted here in preference to the generally used *abyssal*.

The central-Tyrrhenian seamounts are elongated features oriented about N to S or N–10–E to S–10–W, rising up to 2900 m height from the bathyal plain or from its borders; several of them are fissural basaltic volcanoes. Their orientation contrasts sharply with the concentric arrangement of the first five units.

A generalized profile (fig. 1, insert) across the Tyrrhenian Sea south of the 41° N parallel shows the average depths, widths and dips of the seven morphological units.

Seismic results

During the first Tyrrhenian cruise (July 1970), a continuous seismic reflection survey was carried out in four most-promising areas: Gioia Basin, Sardinia Basin and two areas of the bathyal plain (fig. 2 A). The seismic profiles obtained using a Teledyne 24 kilojoules sparker show three main acoustic units (fig. 3). These are now listed from the seabottom downward:

Unit A, displays many undisturbed, sharp and continuous near-horizontal reflections which can be followed over great distances. Occasionally, extensive and thick submarine slumps are present. The unit is well developed and underlies the bathyal plain, the peri-Tyrrhenian basins and even the shelf. Its greatest thickness is found in the middle of sedimentary areas, where it attains 1200 msec (two-way time), or about 1100 meters assuming an average velocity of 1800 m/sec. Unit A becomes gradually thinner toward the basin borders and thins rapidly against the seamount flanks or the continental slope, where the rocky substratum outcrops. The base of unit A appears to be conformable or near-conformable with the underlying unit B in the deepest areas of the sedimentary basins. In their shallower parts and at the flanks, unit A overlies nonconformably the units B or C.

Unit B is characterized by reflections progressively less continuous and regular downward. However, its base is marked by a strong three-cycle

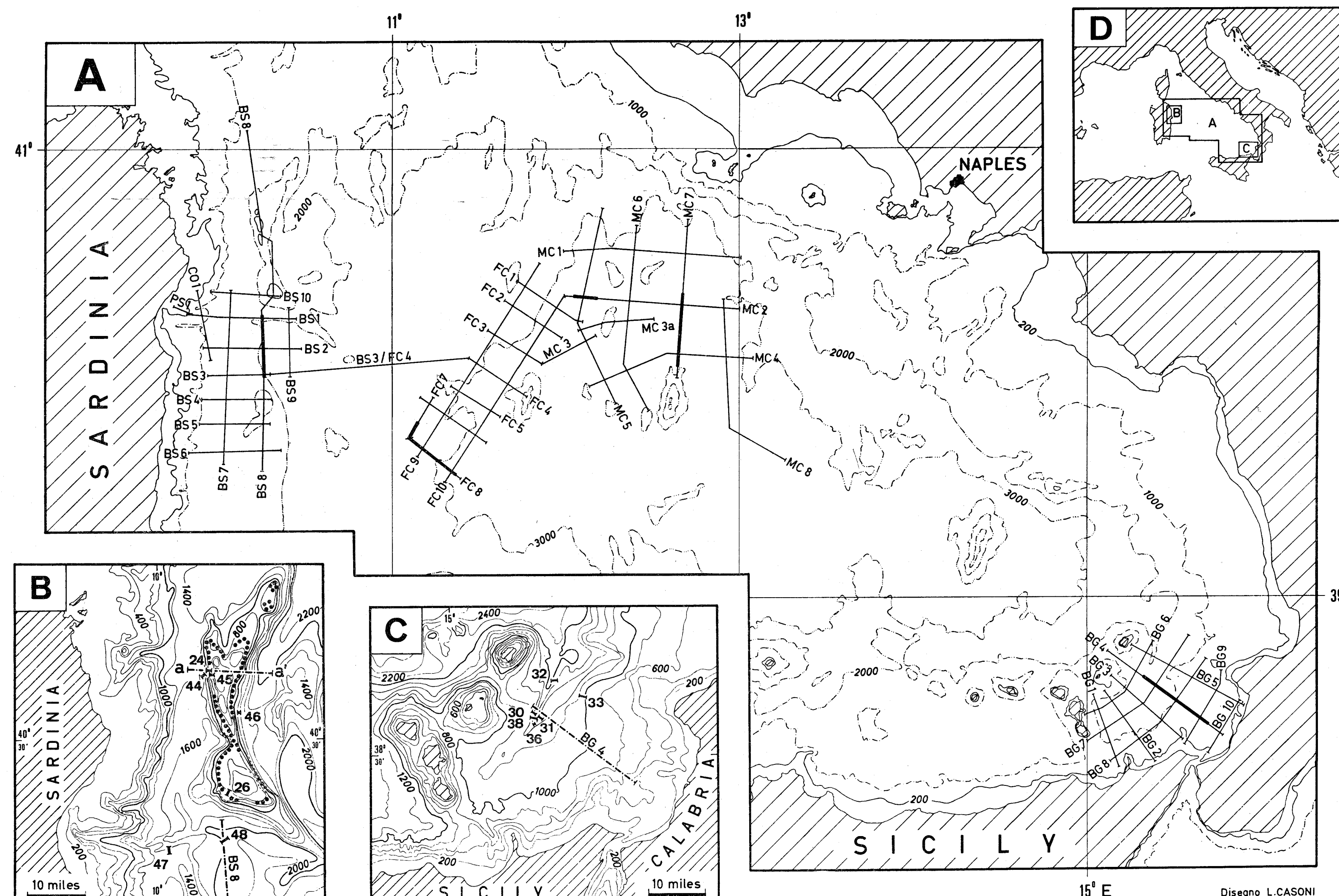

Fig. 2. – Location maps of continuous seismic reflection profiles and dredge hauls. (A) General location of seismic survey; heavy lines indicate the profiles reproduced in figs. 3 and 4. (B) Dredging locations (heavier numbers) at Baronie Seamount and Orosei Canyon; heavy points indicate the step or terrace around the Baronie Seamount; *a–a'* bathymetric profile of fig. 4–V. (C) Dredging locations at Stromboli Canyon. (D) Index map.

reflection. The unit is affected by a number of folds and faults increasing downwards. Its thickness varies from 0 to 900 msec (two-way time) that is about 0 to 900 m, assuming an average velocity of 2000 m/sec. A number of sub-units can be locally distinguished within the unit B (see *Stromboli Canyon*, below).

Unit C usually lacks clearly defined continuous reflections. It represents the acoustic substratum of the Tyrrhenian Sea.

Unit C probably represents the basement, while units B and A were found by us to represent two separate sedimentary and tectonic cycles in the sedimentary cover.

Geological results

A dredging program was carried out during our second Tyrrhenian cruise (September-October 1970) at the Stromboli Canyon, the Orosei Canyon and the Baronie Seamount to identify and date the seismic units.

The results of dredging are summarized below.

Stromboli Canyon.

It is a long deep furrow in the Gioia Basin whose flanks cut the seismic unit A and the upper half of unit B. Fig. 2 C shows locations of dredges. The seismic profile BG 4 crossing the canyon at its deepest point, shows a regular sediment sequence on the Calabrian side and severe faulting on the Aeolian side (figs. 3–I and 4–I).

White or yellowish marls, very rich in almost exclusively planctonic Foraminifera, were dredged at the lowermost parts of the both flanks, that is in the upper unit B. The microfauna is characterized by *Globorotalia puncticulata*, *Globorotalia puncticulata padana*, *Globorotalia margaritae*; therefore it belongs to *Globorotalia margaritae* zone (*puncticulata* subzone) (Cati and others, 1968), i.e. the middle part of Lower Pliocene (1). Other samples of the same rock contain the zonal indicators and numerous Foraminifera of the *Globorotalia bononiensis* subzone and the *Globorotalia aemiliana* zone, i.e. the uppermost Lower Pliocene and the lowermost part of Middle Pliocene. Lithological and micropaleontological character of the marls corresponds to that of the "trubi" Formation of Sicily and southern Calabria.

Blue marly clays, sandy clays and yellow clayey sands have been dredged from the middle and upper flanks of the Stromboli Canyon. All samples are

(1) We subdivide the Pliocene into three parts and, referring to the standard biozonation proposed by Cati and others 1968, i.e.:

Lower Pliocene (= *Globorotalia margaritae* zone)
Middle Pliocene (= *Globorotalia aemiliana* zone + *Gl. crassaformis* zone)
Upper Pliocene (= *Globorotalia inflata* zone).

This subdivision of Pliocene has been previously proposed by Ruggieri and Selli, 1950.

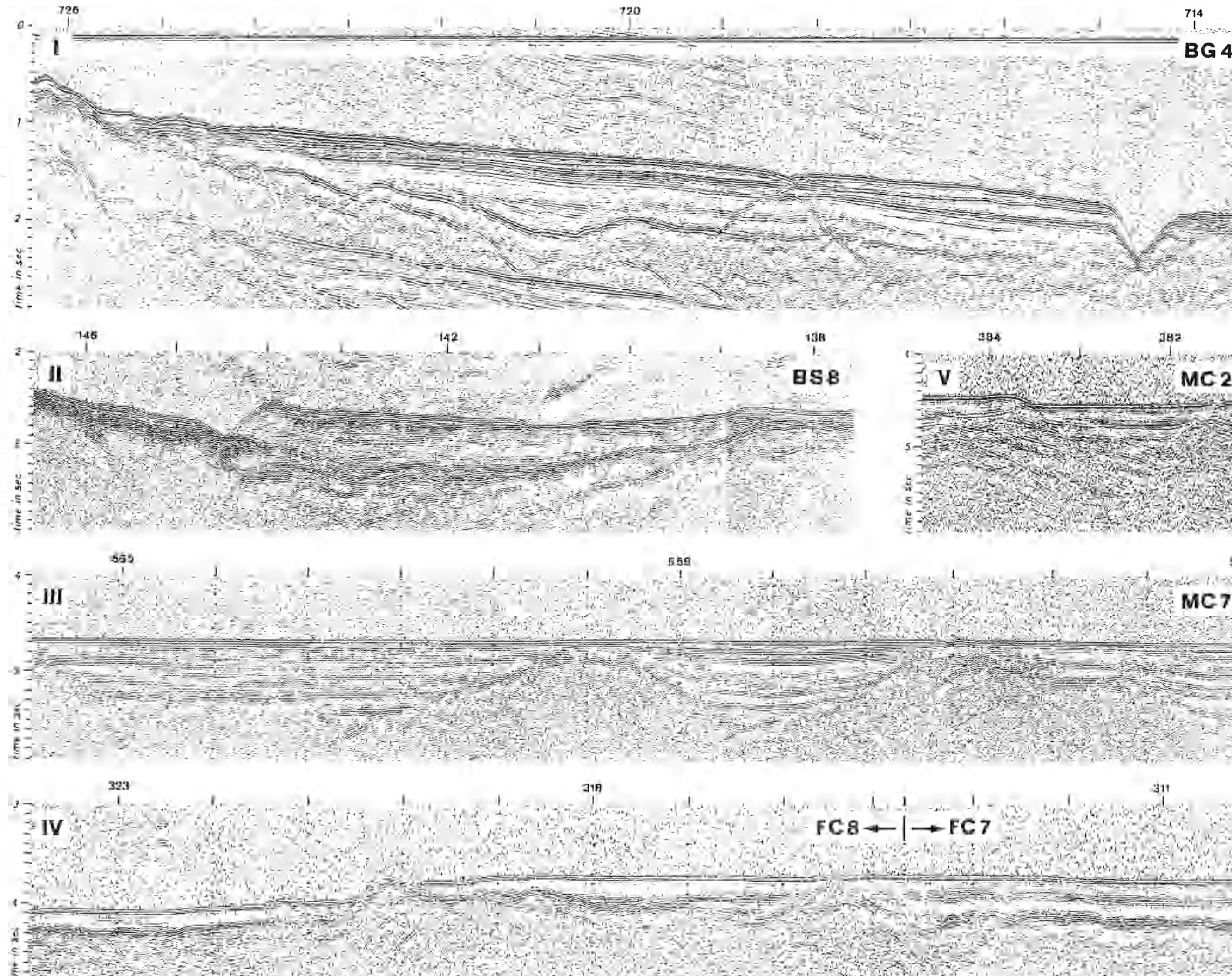

Fig. 3. – Typical continuous seismic reflection profiles across Tyrrhenian area (location on fig. 2). Ordinate: two-way travel time in seconds. Interpretation, scale and bearing shown in fig. 4.

rich in Foraminifera and contain microfaunas of *Globorotalia crassaformis* zone, *Gl. inflata* zone, *Globigerina pachyderma* zone (Colalongo, 1968; D'Onofrio, 1968), which belong to the uppermost part of Middle Pliocene, to Upper Pliocene and to the Lower Pleistocene.

The " trubi " Formation corresponds to the upper part of seismic unit B, the blue clays to the seismic unit A; between the two units lies a nonconformity *x–x* (fig. 4–I) and its age is Middle Pliocene, as in Sicily.

Deeper seismic units, not cut by the Stromboli Canyon, cannot be identified directly. However, they are correlatable with formations outcropping further east in Calabria by their attitude (dip, thickness, tectonic character) and their seismic response. Referring to the figs. 3–I and 4–I, the unit C can be identified as the crystalline basement; the strong three-cycle reflection *z–z*, at the base of unit B, may be the Lower Miocene transgression (Selli, 1957). The sub-unit B_1 will thus belong to the Lower and Middle Miocene; the strong reflection *y–y* to the Lower Messinian " gessoso-solfifera " Formation (Selli, 1954 and 1964); the sub-unit B_2 to the Middle and Upper Messinian and its upper half, as mentioned above, to the Lower Pliocene and to the lowermost part of the Middle Pliocene. Such interpretation is in a satisfactory agreement with all geologic data known from the neighbouring land i.e. Calabria and Sicily.

Orosei Canyon.

It extends from the shelf-break to the border of the bathyal plain, cutting deeply across the whole sequence of seismic unit A in the Sardinia Basin. At basin's flanks unit A lies nonconformably on a very regular upper part of the unit B; toward the basin's bottom they become conformable. The nonconformity crops out at the very bottom of the canyon (figs. 3–II and 4–II).

Here, at a depth of 2200 m, close to the seismic profile BS 8 (fig. 2 B) the dredge 48 brought up conglomerate rock. The elements are well rounded pebbles (up to 15 cm diameter), mainly of vesicular basalts and of some gray and yellow sandstones and clayey marls of Lower Pliocene (*Globorotalia puncticulata* zone with zonal indicator). The matrix is abundant; it is coarse, arenaceous or fine conglomeratic, with basaltic, quartzitic arenaceous, tuffaceous and other elements up to 2–3 cm in size. It is poorly cemented. The matrix includes littoral and shallow water Molluscs: *Lunatia catena* f. *helicina*, *Amyclina semistriata* f. *dertonensis*, *Vexillum plicatula*, *Ringicula auriculata*, *Flabellipecten flabelliformis*, from which can be inferred its Middle or Upper Pliocene age (Colantoni, 1970).

Another argillaceous-marly sample, dredged at contact with the conglomerate, contains a rich Foraminifera fauna with *Globigerina decoraperta*, *G. druryi*, *G. falconensis*, *Globigerinoides obliquus* (*Globigerina pachyderma* and *Globorotalia inflata* are absent), *Siphotextularia affinis*, *Stainforthia concava* etc. It pertains to the upper part of the *Globorotalia crassaformis* zone, i.e.

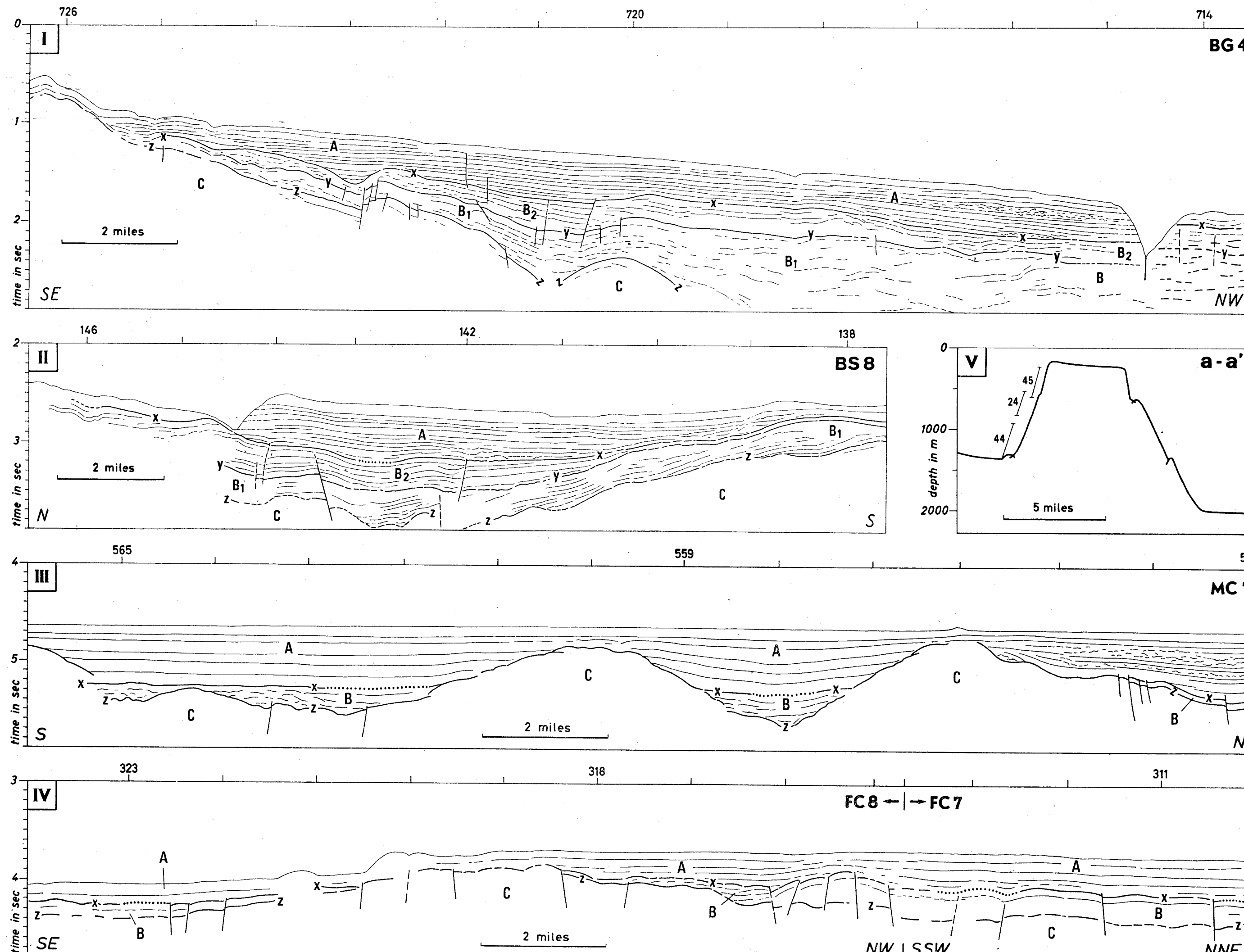

Fig. 4. – Geological interpretation of the continuous seismic reflection profiles of fig. 3.

A) continuous sequence from uppermost Middle Pliocene to the Present (seismic unit A); *x–x*) Middle Pliocene nonconformity and transgression, becoming a conformity (dotted line); *B*) Miocene, Lower Pliocene and lowermost Middle Pliocene sequence (seismic unit B); *B_2*) Upper Messinian, Lower Pliocene and lowermost Middle Pliocene sequence (seismic subunit B_2); *y–y*) likely top of gypsum (« gessoso-solfifera » Formation of Lower Messinian); *B_1*) Lower and Middle Miocene (?) sequence (seismic sub-unit B_1); *z–z*) likely Lower Miocene nonconformity and transgression; *C*) premiocene basement (seismic unit C). The seismic profiles cross the Gioia Basin and Stromboli Canyon (I), Sardinia Basin and Orosei Canyon (II), western (III) and eastern (IV) bathyal plain. Bathymetric profile across the Baronie Seamount (V) shows dredging ranges.

uppermost part of Middle Pliocene. Therefore this is the age of the conglomerate and also the age of the transgression.

The sedimentary sequence sampled continues with bluish and greenish, marly and sandy clays up to the edge of the canyon. The samples recovered by the dredge 48 contain *Globorotalia inflata*, *Gl. oscitans*, *Globigerina dutertrei*, *Fursenkoina tenuis*; therefore they belong to the *Globorotalia inflata* zone, i.e. Upper Pliocene.

The same rock has been dredged at station 47 (fig. 2 B), but it contains: *Globigerina pachyderma* (sinistral), *Globorotalia truncatulinoides*, *Hyalinea baltica*. Therefore the age is the preglacial Pleistocene (Selli, 1967).

In conclusion: the Middle Pliocene transgressive conglomerate outcrops near the bottom of Orosei Canyon. It is overlaid by a continous stratigraphic sequence of the upper part of Middle Pliocene, Upper Pliocene and Pleistocene. The Foraminifera assemblages also indicate a progressive increase of the water depth starting from the shallow water environment of a transgressive conglomerate.

The estimate of the age of deeper seismic horizons not outcropping at the Orosei Canyon is more difficult than in the Stromboli Canyon, as it is impossible to correlate them to Sardinian stratigraphic sequences. Tentatively, the seismic unit C should correspond to the Paleozoic metamorphic and granitic basement. The horizons and sub-units y–y, B_1, z–z, B_2 (fig. 4–II) can thus be ascribed (as in the Stromboli Canyon) to the Lower Miocene basal transgressive deposits, to the Lower and Middle Miocene beds (well known in Sardinia), to the Lower Messinian " Formazione gessoso-solfifera " and, finally, to the Middle Messinian-Lower Pliocene sequence (both units almost absent in Sardinia).

Baronie Seamount.

Three seismic profiles across the seamount did not yield reflections. Evidently, the acoustic basement (or the seismic unit C), crops out and is only topped by a very thin sedimentary cover.

A number of echo-sounding profiles made during our 1968 and 1969 cruises show that the flanks of the seamount are incised by a step, or an irregular narrow terrace, at the depths between 550 m and 740 m (figs. 2 B and 4–V).

Dredgings 24, 26, 46 were made on this step and biogenic calcarenites with abundant sand and pebbles were recovered. Pebbles are quartzitic, quartz-arenitic, granitic and metamorphic, all well rounded, ranging in size up to 15 cm. The biogenic content is very abundant although rich in broken and reworked fossils; it indicates a littoral and shallow water environment. The more recent, biostratigraphically significant species are frequent, well preserved and can be ascribed to the *Globorotalia aemiliana* zone, i.e. Middle Pliocene (Colalongo, D'Onofrio and Sartoni, 1970).

Numerous blocks of slightly tectonized and strongly cemented conglomerate have been recovered (dredge 45) from the cliff overhanging the terrace, at depths between 500 m and 237 m. The pebbles, generally well rounded, are of micaschists, granite, quartzites, etc. Blocks and fragments of red sandstone, red granule gravel and white orthoquartzite were also dredged. All these rocks are identical or quite similar to those of so called " Verrucano Formation " of Sardinia (Autunian = Lower Permian) and Tuscany (Permo-Trias).

From this data we infer that the terrace around the Baronie Seamount corresponds probably to an ancient beach of Middle Pliocene age, when the upper 400–500 m of the seamount emerged from the sea. The waves on the beach reworked pebbles and rock-fragments of " Verrucano " fallen from the island's cliffs. Later, a foundering of 550 m to 740 m must have occurred.

More evidence of the seamount sinking comes from dredges 24 and 45 (fig. 2 B). A Quaternary mollusc fauna characteristic of very cold water was recovered between 525 m and 600 m of depth, indicating that rapid sinking took place mainly during the glacial Pleistocene (Colantoni, Padovani and Tampieri, 1970). Indeed, taking into account that *Arctica islandica*, found here, lives today at a maximum depth of 120–150 m, that the mollusc fauna is very well preserved and further, assuming a eustatic sea lowering of 130 m during glacial times, it can be inferred that a minimum foundering of the seamount by 245 m (i.e. 525–150–130) took place after Riss or Würm glaciations.

Bathyal plain.

In the deepest areas, exceeding 3400–3500 m, the thickness of the seismic unit A is greatest (up to 100 msec two-way time i.e. about 900 m, assuming an average velocity of 1800 m/sec). It displays numerous clear continuous and undistorted reflecting horizons (fig. 3–III). At the depths lesser than 3400 m, the unit A attains a maximum thickness of 600 m (or 700 msec); in places it is only 200–300 m or even thinner. Although in this case the reflecting horizons are also near-horizontal and regular, they are often acoustically transparent (fig. 3–IV). In all cases the unit base is marked by the previously mentioned strong three-cycle reflection, and normally by a sharp nonconformity (figs. 4–III and 4–IV).

In the deepest parts of buried depressions, or where the bedding planes are near-horizontal, the seismic unit B appears to be conformable with the overlying unit A. On the flanks of those depressions it is nonconformable or locally absent. Usually the unit B is thinner than A, does not exceed 400 msec two-way time (200 m in thickness), and is everywhere separated by a nonconformity from the underlying unit C.

In several areas of the bathyal plain the unit C yields reflections good enough to indicate a sedimentary and not massive substratum; everywhere else it is acoustically non-responsive.

Unfortunately, no rock samples have been collected so far from the bathyal plain or from the surrounding features. However, correlation between the Sardinia Basin and the bathyal plain by means of profile BS 3/FC 4 suggests the following conclusions. The unit A is Plio–Pleistocene in age; the nonconformity at the base of unit A probably corresponds to the Middle Pliocene transgression. The unit B may be ascribed mainly to Miocene and its basal nonconformity to Lower Miocene. The unit C, the acoustic basement, appears to be heterogeneous; in several areas of bathyal plain, especially in the west it is metamorphic, as demonstrated recently (Heezen, Gray, Segre and Zarudski, 1971). In some central and eastern areas its upper part is bedded and probably sedimentary (Paleogene or Mesozoic) as shown by seismic reflections (fig. 3–V).

Discussion and conclusions

The most pertinent data and its interpretation are briefly summarized here:

1) In the central and southern Tyrrhenian Sea, especially in the bathyal plain and in the peri-Tyrrhenian basins, three main seismic units designated A, B, C, are found in the continuous seismic profiles. These units are usually separated by two nonconformities.

2) The dredge samples show in the Stromboli and Orosei Canyons and the Baronie Seamount, that the age of unit A is from the uppermost Middle Pliocene to the Present. Its basal nonconformity is of Middle Pliocene age and marked by a littoral conglomerate outcropping at the Orosei Canyon.

3) The basal nonconformity of unit A normally overlies the unit B and, in places, the unit C. It is very well defined on the flanks of the peri-Tyrrhenian basins and on the sides of buried uplifts found beneath the bathyal plain. On the other hand, in the deepest parts of the peri-Tyrrhenian basins and of the buried depressions of the bathyal plain, unit A appears to lie conformably or near-conformably on unit B. Therefore, in these areas a continuous sedimentation probably took place between the two units.

4) This wide-spread nonconformity corresponds exactly in age, as well as attitude, to the extensive regional Pliocene transgression, well known in Italy and Sicily along the Tyrrhenian coasts (Tuscany, Latium, at scattered places in Southern Italy and Sicily), but chiefly in the Apennine foretrough (extending uninterruptedly from the Po Basin to central Sicily). On land, the age of the nonconformity is generally the uppermost Lower Pliocene or Middle Pliocene; after it there follows a post-tectonic Plio-Pleistocene continuous sedimentary sequence. The Apennine orogeny ended before this nonconformity was produced.

5) From the new data reported here, we infer that during the Middle Pliocene the Tyrrhenian area had emerged to a large extent, resembling an archipelago of numerous and large islands (not unlike the present Aegean Sea) separated by water channels or sounds.

6) Starting at the Middle Pliocene a tremendous foundering of the Tyrrhenian area took place. The surface, corresponding to the ancient sea level, was lowered to about 740 m of depth at the Baronie Seamount, to 2,200 m in the Orosei Canyon, to 1,800 m in the Stromboli Canyon (all depths supported by the rock samples) and finally to 4,500 m in the deepest part of the bathyal plain. Assuming the more recent absolute ages (Berggren, 1969; Selli, 1970 a), the beginning of the Middle Pliocene occurred 4.7 or 3.9 million years ago; therefore the average rate of foundering was about 1 to 1.1 mm/year. Thus we conclude that the present *Tyrrhenian Sea is of Pliocene age.*

7) In the Mediterranean area, a comparable subsidence rate is known only in the Po Plain (Selli, 1962) where, incidentally, it is entirely compensated by the sedimentation rate. In the Tyrrhenian area on the other hand the latter has been minimal, relative to the subsidence e.g., where the Pliocene nonconformity lies today at a depth of 4,500 m, the post-tectonic sediments deposited during the Plio–Pleistocene amount to no more than 900 m.

8) During this collapse, the Tyrrhenian crust underwent a general extension in E–W direction accompanied by normal concentric faulting on the continental slope and by vertical N–S faults in the present bathyal plain. This interpretation is supported by much physiographic and geophysical evidence. Along the concentric faults the anatectic or hybrid, rarely basaltic, magmas rose causing the circum-tyrrhenian volcanism (Tuscany, Latium, Pontine Islands, Campania, Stromboli and Aeolian Islands). Along the second (N–S) set of faults basaltic magmas ascended from the mantle (Marsili, Vavilov, Magnaghi etc. Seamountains). According to the recent radiometric dating almost all of these volcanoes are younger than 4.5 to 5 million years, mostly only 1 million years.

9) The upper half of the seismic unit B is of Lower Pliocene to lowermost Middle Pliocene age, as proven by dredging in the Stromboli Canyon; the lower part of the B sequence may well be correlated with Sicily and Calabria sequences. Therefore its base should correspond to the transgression of the Lower Miocene, well known in Southern Italy (Selli, 1957), Sicily and Sardinia. Before this time a very extensive part of the Tyrrhenian area may have emerged. Between the Lower Miocene and the Middle Pliocene the Apennine orogeny took place, accompanied by enormous gravity nappes of the sedimentary cover. Probably the comparative thinness of the unit B and its discontinuous presence in the bathyal plain may be due more to the tectonic denudation than to the subaerial erosion.

10) Finally, data available today on the pre-Miocene basement, or our seismic unit C, is scarce. Metamorphic rocks (Heezen, Gray, Segre and Zarudski, 1971) and Paleozoic rocks (Baronie Seamount) have been dredged; probably younger sedimentary rocks are present as well.

11) With the three geological revolutions, i.e. Lower Miocene transgression, Apennine orogeny and Middle Pliocene transgression, and with the subsequent foundering, another environmental change took place in the Tyrrhenian area. It was the so-called " crisis of salinity " of Upper Miocene

age (Messinian). It gave rise to the extensive evaporitic sediments of the Italian Peninsula, North Africa, Middle East, Crete, Ionian Islands and in the floor of the western and southern Mediterranean (Selli, 1954 and 1964).

Acknowledgements — For the unstinting assistance at the sea the Authors are highly indebted to Drs. P. Colantoni, L. Tomadin, F. Francavilla, F. Marabini and A. Poluzzi and Messrs C. Brazzorotto, P. Ferretti, A. Magagnoli, G. Zini and P. Zucchini of the Laboratorio di Geologia Marina of Bologna and to Mr G. Zvelich.

We also thank Drs. S. D'Onofrio and M. L. Colalongo for checking our micropaleontological datings and Dr. E. F. K. Zarudzki for helpful discussions and reviewing the English version of the manuscript and Messrs G. Camarinos and L. Casoni for illustrations.

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