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The magnetic anomalies of the Mediterranean Sea (IBCM-M)

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Abstract. The results of marine magnetic measurements and the research done to obtain the magnetic anomalies of the Mediterranean sea are here summarized. Integrated with the available data from deep reflection seismics, deep refraction seismics, and heat flow they contribute to a better understanding of the geology and geodynamics of the Mediterranean. A few examples are given. *Regional,* mainly negative magnetic anomalies in the Eastern Mediterranean, a remnant of Paleo-Tethys, give an inverse magnetization to the old oceanic crust, deeply buried under thick sediments (10-12 km); they are mainly bipolar in the Western Mediterranean and Central Mediterranean, and caused by magmatic bodies in, or over, a recent thin crust mostly fractured by extension (Oligocene in the former to very Recent in the latter). *Very strong* magnetic anomalies due to the ophiolites define the southern continuation of the Africa-Europe contact in the Ligurian-northern Tyrrhenian sea, or in the arcs of the Eastern Mediterranean, or in the main fault systems (Malta Escarpment). *Local* magnetic anomalies connected with extensional tectonics in the thinned continental margin W of Sardinia, in the Sicily Strait and in the Aegean sea. *Spread* magnetic anomalies are connected with Miocene to Pliocene rifting in the Tyrrhenian and Ionian seas.

1. Introduction

1.1. The Mediterranean Sea and the Alpine System

Plate Tectonics show that in the Jurassic and Cretaceous, sea floor spreading opened the Central Atlantic and Central and Western Tethys. Further opening of the Southern Atlantic and the motion of Africa towards Eurasia produced the continent-continent collision which genera-

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ted the Alpine System: the motor is attributed to convection currents in the upper mantle.

After the 1st opening phase (Paleo-Alpine), Adria separated from Africa; a 2nd orogenic phase (Eo-Alpine: 70-60 Ma) produced compressions, further reduced the width of the Alpine System and increased the elevations. The prevailing motor is the same and the forces mainly horizontal. The Western Mediterranean and the Central Mediterranean did not exist, and the Eastern Mediterranean closed due to rifting of the Arabian Plate.

Approximately 40 My ago in the Western Mediterranean, heating in the upper mantle produced elevations, centrifugal tensions, rifting and radial discharging of upper crustal material, thus producing the present Neo-Alpine chains and the opening of the Western Mediterranean. Starting from the west, the sequence of events was as reported in Table 1.

Table 1 - Sequence of the events.

Alboran	Oligocene	~35 Ma
Provençal and Ligure	U. Oligocene - L. Miocene	~30-19 Ma
Sardo-Corsica translation and gulf of Lions opening	L. Miocene	~24-21 Ma
Sardo-Corsica rotation	Miocene	~21-19 Ma
Tyrrhenian	U. Miocene - Present	~10-0 Ma

The subsequent cooling of the mantle produced rapid subsidence and formation of the present Mediterranean Basins. This mantle activity in the Western Mediterranean and Central Mediterranean progressed from west to east, starting in the Oligocene, and is still active on the northeastern and southeastern Tyrrhenian borders.

Determination of the thicknesses and ages of the basins are one of the main results of the OGS-CNR Deep Reflection Flexotir Seismic (hereafter NVR) Marine Surveys (MS) 1969-1973 with the r/v Marsili. This was the first systematic seismic survey in the Mediterranean (22,100 km; Finetti and Morelli, 1973; Fig. 1).

Using these data, those of a similar survey by IFREMER, and data kindly placed at our disposal by different institutions and private companies, the Plio-Quaternary maps of the International Bathymetric Chart of the Mediterranean (IBCM-P/Q) at 1:1,000,000 and 1:5,000,000 were published.

An initial look at the Plio-Quaternary maps suggests immediately some ideas: the thickness of the Plio-Quaternary sediments is a few kilometers, except in front of the large rivers (Nile Cone, Po Plain, Rhone Fan, Ebro Delta and Danube Delta) or in the marginal basins: Valença, Alboran, North African, Calabrian arc, Sicily, Iskenderun Gulf, Anatolya Gulf.

Further important results obtained from NVR surveys are as follows.

1) The thickness (2-3 km) and continuity of shallow-water (deltaic) deposits of Plio-Quater-nary age in most of the present Mediterranean indicate a subsidence of at least that amount;
2) There is a thick evaporitic layer of Messinian age in most of the present deeps, with an irregular top and a regular base; under a thick sedimentary cover this layer becomes buoyant and consequently produces salt domes. The evaporitic layers thin and disappear progressively

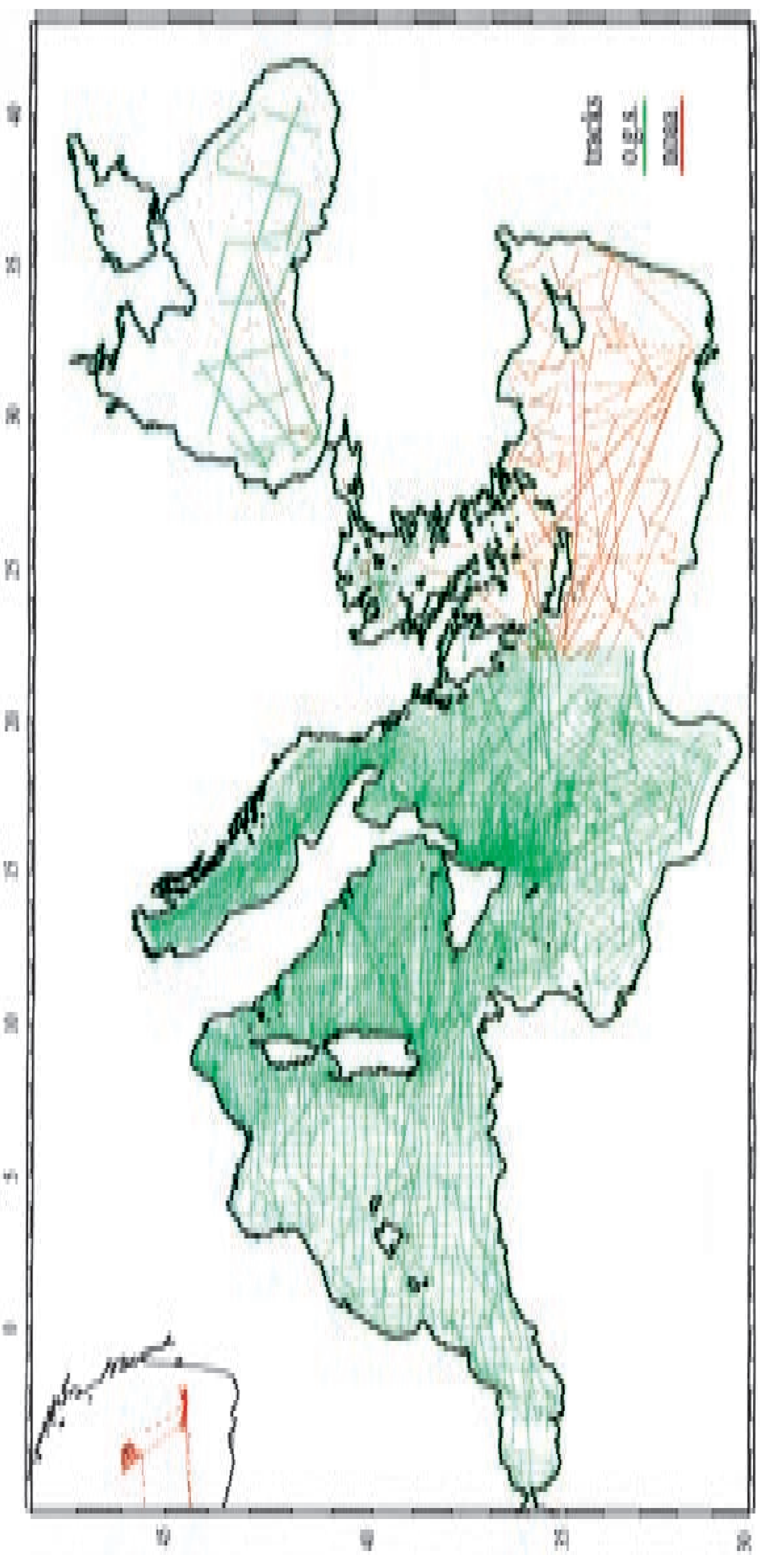

Fig. 1 - The tracks for the sea magnetic measurements utilized for the computation of the magnetic anomalies.

against the continental margin; they were deposited in shallow environments that subsided regularly;

3) Pre-Messinian sediments are also present almost everywhere, and their thickness can reach several kilometers;
4) The structure of the main Upper Tertiary basins in the Mediterranean has been outlined;
5) The importance of the post-Miocene tectonics is evidenced. They consist mainly of vertical motions (mostly subsidence), clearly indicated by vertical faults with throws often exceeding 5 km, including the North African slope, Ligurian and Provence margin, Emile Baudot fracture zone, Malta Escarpment, and others. As a consequence, the hypothesis that the present form of the actual Western Mediterranean is pre-Messinian herewith loses much of its value;
6) There are older active island arc type systems (Gibraltar, Cyprus) and presently active island arcs (Calabrian, Hellenic). On their convex side, the thick sedimentary cover slid outwards away from the interior of the arcs, so as to form extensive olistostrome fronts; basins constitute a marginal sea type on the concave side of these same island arcs;
7) Continental margins are mostly passive with the exception of those associated with islands arcs.

Since the magnetic anomalies are caused mainly by the variation in topography and composition of the magnetic basement[(*)], they allow the sediment thickness to be followed in the Mediterranean. They are also useful for determining the presence of volcanic structures and of intrusives and effusives magmatites, and the existence of magnetic lineations.

1.2. The magnetic measurements

The marine measurements of the Earth's magnetic field intensity presented in the map IBCM-M (10 sheets, scale 1:1,000,000) were obtained in parallel with the bathymetric and gravimetric OGS measurements during the 1961-1972 surveys, for a total of 329,500 km. Details of these surveys have been outlined in Morelli and Val'chuk (1988).

The 1961-1965 surveys, for a total of 112,000 km, were performed on the Saclantcent Research Vessels "Aragonese" and "Maria Paolina", and the results published by Allan and Morelli (1971), with 36 maps at the scale 1:750,000, equidistance 100 nT. They cover the Western, and part of the Eastern Mediterranean.

The measurements were continued from 1966 to 1972 by the CNR ship "Bannock", covering the Western, Central and Eastern Mediterranean as far as 19.5° E (Gantar et al., 1968). The Saclantcent and OGS ship positionings benefited from the Loran C Mediterranean system. The accuracies were checked during the bathymetric and gravimetric measurements on the

[(*)] By magnetic basement it is generally intended the deepest level that can be evidenced with magnetometry, and below which the presence of sedimentary rocks should be generally excluded. Sometimes depth differences can be found between the magnetic, geologic and seismic basements, nevertheless the magnetic marker is always an important element for evidencing the structural behaviour and the nature of the deep substratum, often difficult to recognise with other geophysical methods.

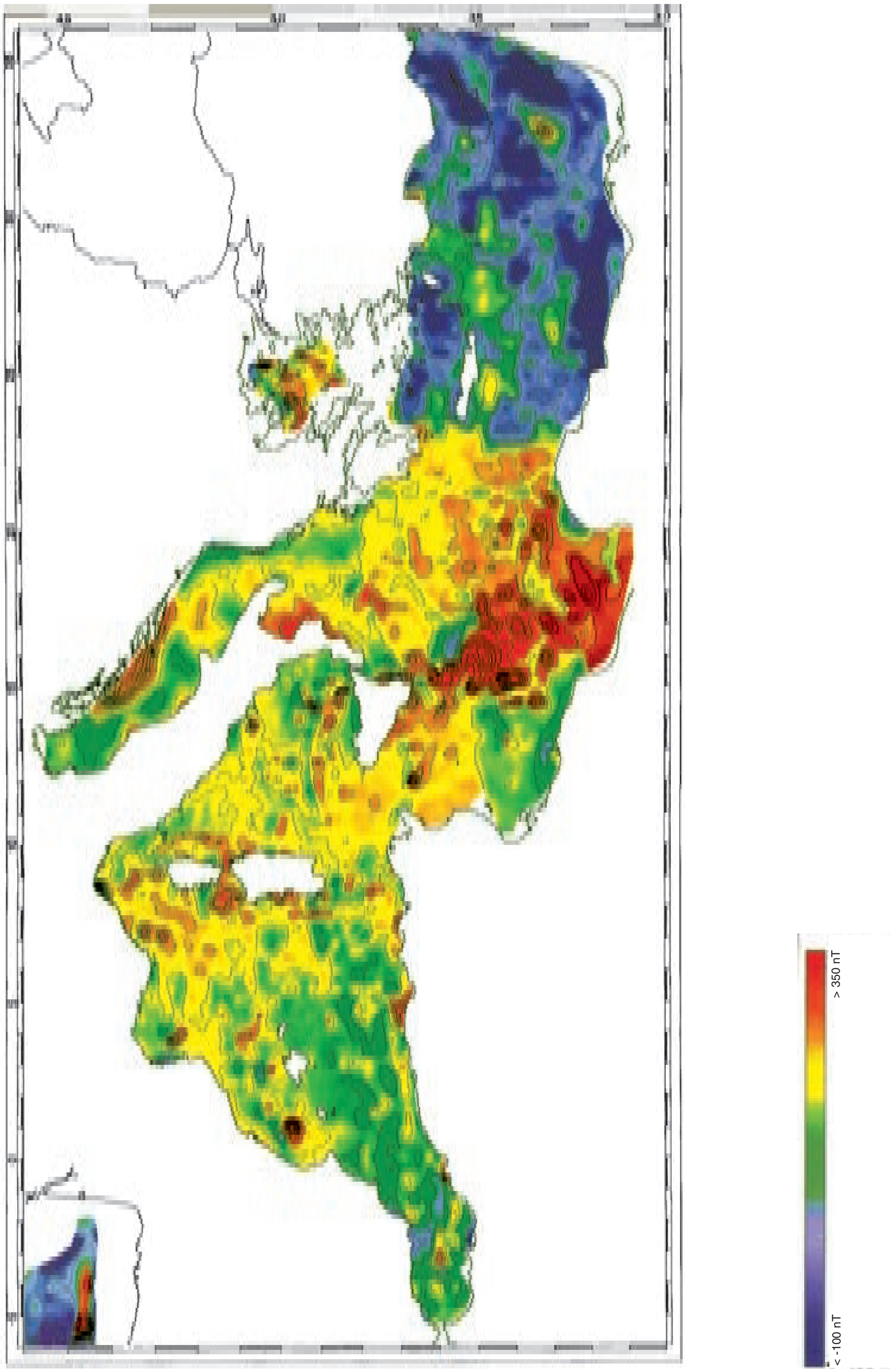

Fig. 2 - A sketch of the magnetic anomalies at 50 nT intervals.

track crossings, and were from ±100 m in the central areas to ±600 m in marginal areas: sufficient for the magnetic accuracy discussed below. The Levantine sea was surveyed by the British RRS "Shackleton" and "Discovery", between 1971 and 1974, for the Department of Geodesy and Geophysics, Cambridge (UK), using satellite navigation and dead reckoning (220,000 km; Woodside and Williams, 1977; Wright et al., 1975). They were utilized for the preparation of IBCM-M as a part of the data kindly delivered by the National Geophysical Data Center, NOAA, Boulder, Colorado.

The results of the OGS surveys, with the bathymetric and gravimetric maps, were published in Morelli et al. (1975a, 1975b, 1975c).

The magnetic anomaly maps at the scale 1:750,000 for the Adriatic Sea, with equidistance of 20 nT, were published by Morelli et al. (1969), the map for the Tyrrhenian sea, at the scale 1:750,000; with equidistance 100 nT, was published by Morelli (1970). The magnetic anomalies map for the Mediterranean Sea to 23° E was recently published by Makris et al. (1994; scale 1:5,000,000; equidistance 25 nT).

1.3. The magnetic data

The magnetic data used for the preparation of IBCM-M were obtained with a towed proton magnetometer. The precessional frequency of the proton magnetometer was measured to an accuracy of 1/100,000, which corresponds to ±0.5 nT. The various effects which can degrade the accuracy of the field measurements have been described by Allan (1969). The most important is temporal variations in the field.

The magnetic field charts were reduced to the epoch 1965.5 by applying secular variation corrections obtained from the magnetic observatory at L'Aquila, Italy. The diurnal variation corrections also were calculated from the recorded hourly values of the horizontal and vertical components at L'Aquila. The corrected field values are considered to be accurate to within 10 nT.

The OGS tracks for the magnetic measurements to 26.5°E are the same as those for the bathymetry and gravity (Fig. 1). From the data measured on the OGS tracks, one value every mile was extracted (110,000 values) to form the original database. From these observed values (properly reduced) the magnetic anomalies were computed and drawn.

The magnetic field intensity values were converted to anomalies after subtraction of the 1965.5 International Geomagnetic Reference Field. About 55,000 data points were used to produce, by means of a second order polynomial interpolation, a regular grid with 3 km spacing in Mercator projection. Each grid point was computed using not more than 3000 field data within a radius of 75 km. The anomaly contours are represented on the 1:1,000,000 sheets with isolines at 50 nT (Fig. 2). For the Biscaglia Gulf and Eastern Mediterranean (east of about 24°E) data recorded by NOAA between 1970 and 1985 were used. In this case the data for each cruise were corrected with the IGRF relevant to the measurement epoch. The approximately 38,000 anomaly data points were merged into the global data set and interpolated using the above mentioned criteria. We chose not to apply any artificial mean field to the corrected data so as to allow recovery of the original measured total field. For the Black Sea, about 24,000 data recorded by OGS and 25,000 by NOAA were used and processed using the above mentioned method.

To complete the information, it should be added that, with a mean track spacing of 15'×20', the detection of small, local anomalies, cannot be guaranteed. To understand their value after interpolation, the OGS tracks are indicated on the reverse side of the 1:1,000,000 sheets by dotted lines, whereas the NOAA tracks by crossed lines.

In the Mediterranean the maps reveal the strong magnetic anomalies connected with the fault systems of the continental slopes, and anomalies spaced throughout the area. No magnetic lineations (in the plate tectonic sense) could be deduced with certainty.

The top of the magnetic basement can be modified by tectonism, and the magnetic susceptibility k can vary due to composition, origin or physical conditions. In this paper, all the magnetic anomalies are expressed in nT (I.S.: 1nT = 1γ, c.g.s. system); all the magnetic susceptibilities k in I.S. units $\times 10^{-6}$.

The associated magnetic anomalies are generally wide, and of regional character. Regional anomalies can be also due to extended fluxes of magma, or intrusions of bodies with different magnetic susceptibility. The local magnetic anomalies are normally generated by faults in distensional tectonics, or by infrasedimentary magnetic intrusions, and are often bipolar (i.e., caused by magnetic induction).

In the interpretation of magnetic data the constraints are normally obtained from seismics, as in gravity.

2. Discussion of the magnetic anomalies with reference to Mediterranean tectonics

The magnetic anomalies are normally caused by variations (composition, extension or topography) of the magnetic strata in the oceanic crust (layers 2 and 3, generally regional anomalies); or by infrasedimentary magmatic intrusions and/or submarine volcanism (local anomalies). Both causes being tectonism-dependent, and since the tectonics of the Mediterranean are different in the various areas and complexes, we will summarize in the course of the presentation the main tectonic features.

The geophysical interpretations are mainly constrained by deep seismic marine surveys, especially deep seismic refraction soundings (DSS; Fig. 3) and reflection soundings NVR (Fig. 4), mainly performed by OGS in the years 1968-72 (Finetti and Morelli, 1973; Mulder; 1973). Fig. 4 is also presented to show that the MS 1970's Flexotir results are still comparable with the more modern CROP 1990's Air-Gun.

From geological knowledge it is known that the Mediterranean originated as a consequence of African and European plate convergence, and that the Western Mediterranean is all contained within the Alpine belt, whereas the Eastern Mediterranean is all outside (to the south of) the Alpine belt. We can therefore separate the presentation of the two regions, and also discuss separately the transition between the two, i.e., the Central Mediterranean.

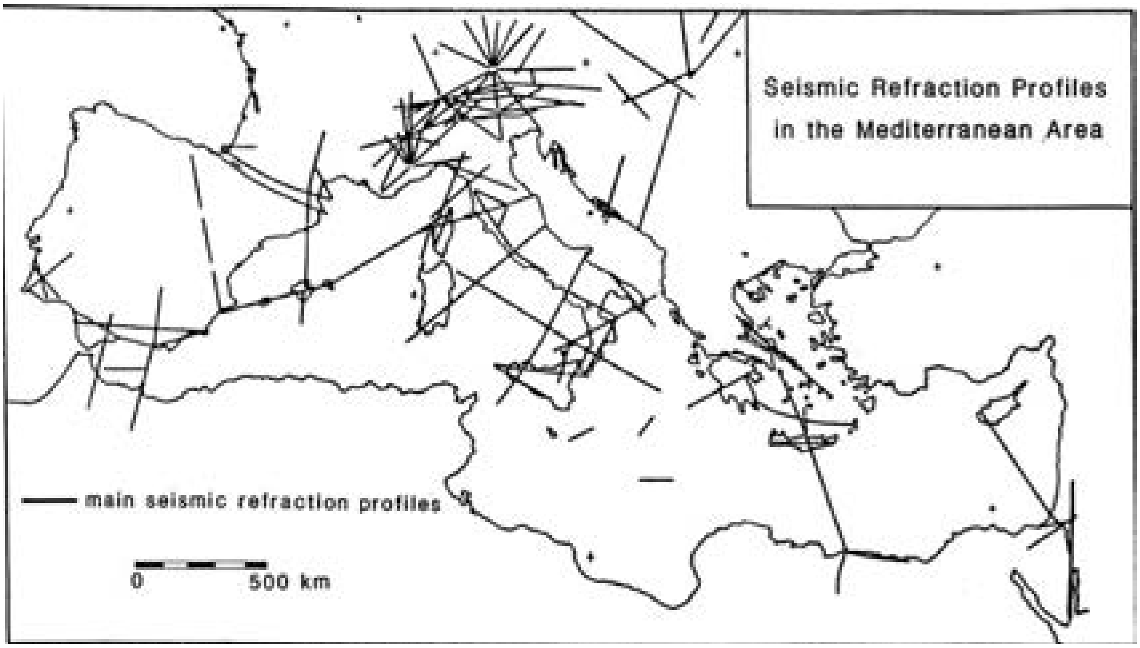

Fig. 3 - The Deep Seismic Refraction Profiles (DSS).

2.1. The Western Mediterranean

The Western Mediterranean is characterized by a practically flat bathyal plain (-2500 ÷ -2800 m) covered mostly by undisturbed sediments, with scarse magnetic anomalies. Since it is a tectonized micro-ocean, the role of the continental margins is dominant. Due to the young age of most of the basins and their deformations, the continental shelves are generally narrow and the slopes steep, characterized by vertical or subvertical faults indicating a very rapid subsidence (~5000 m). Most of the local, mainly bipolar magnetic anomalies, are located on these strongly tectonized continental margins and slopes.

THE MARGINS. The Western Algerian margin is particularly narrow, and the slope consists of steps limited by normal faults. The Provençal margin is also very steep, and cut by deep canyons, as in the South Balearic margin, which widens ~200 km into the sea. The intermediate zone of the margin is the well known Emil Baudot fracture zone, running NE-SW, again with steep slopes to the east.

All around the Western Mediterranean the margins are cut by canyons, normally narrow and perpendicular to the coast, very often reaching the deepest parts. Of particular interest are the two parallel canyons in the northern part of the Gulf of Genoa, which are the continuations of rivers, and of which only the eastern-most one reaches the bathyal plain. In effect, most of the margins of the Western Mediterranean are very similar to passive or Atlantic-type continental margins.

The Algerian abyssal plain is the site of salt tectonics; this can be observed throughout the deep Western Mediterranean.

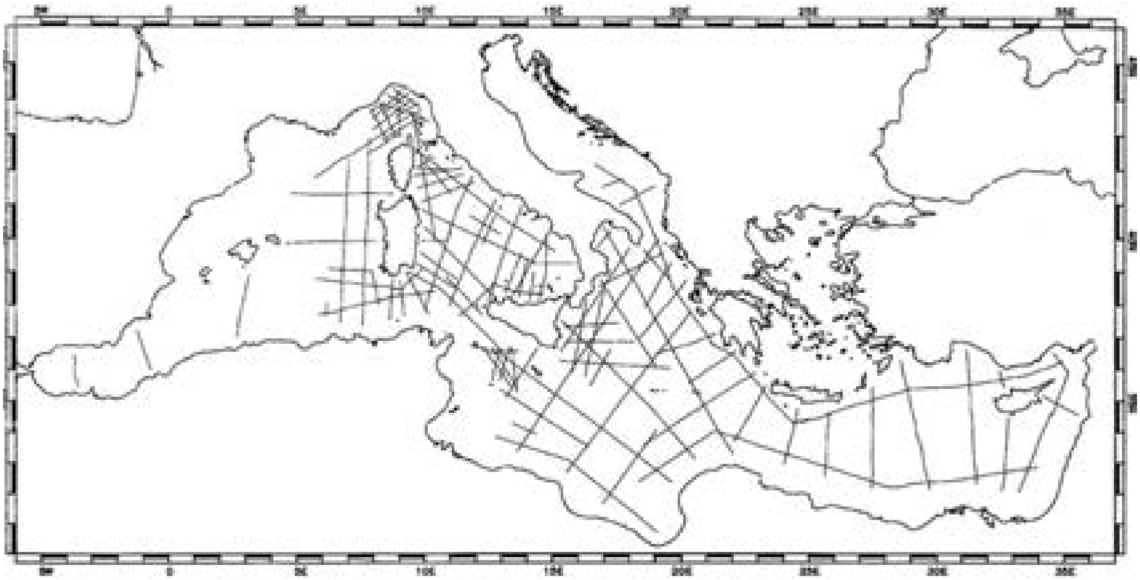

Fig. 4 - The Deep Seismic Reflection Profiles (NVR) in the Mediterranean sea by OGS (MS) and other institutions.

THE BASINS. The Western Mediterranean basins were formed within the Alpine belt, by collapse of the crust, after updoming and centrifugal discharge of the upper crust. That is to say, they are essentially connected to vertical movements.

The bathyal plain crust is mainly oceanic, 6-8 km thick. Indeed Hirn et al. (1977) found in the Provençal Basin a Moho depth of 11 km and an uppermost mantle velocity of 7.7 km/s. But De Voogd et al. (1991), in the preliminary interpretation of the French part of the ECORS-CROP profile from the Gulf of Lions to Sardinia, concluded that "typical" oceanic crust cannot be readily recognized along this transect, though the oceanic nature of the central basin is not questioned. The relief characteristics of a spreading ridge are not observed, though features of uncertain nature are imaged within the basement at the northwestern end of the CROP line.

The acoustic basement is everywhere visible by NVR under the sedimentary cover of variable thickness, and shows two significant structural orientations: NE-SW and NW-SE. These directions appear in the outline of the margins, the volcanic alignments and in some magnetic anomalies.

The depth of the top of the layer responsible for the magnetic anomalies in the deep basin is 8 to 9 km (Le Borgne et al., 1971), which is the depth of the top of oceanic layer 2 (5.5 - 5.8 km/s) indicated by DSS. These results confirm that the crustal structure in the deep basin corresponds to that of an oceanic crust.

The character of the rifting areas in the Alboran sea (spread volcanism, with connected magnetic anomalies) and in the Valençia basin (dominated by a large volcano) is different. The Alboran sea is floored by a thin continental crust, no more than 18 km in thickness, covered by more than 6 km of sediments.

The same values are valid for the Spanish margin and the Balearic Islands, which are stretched continental crust of approximately 16 to 18 km thickness, covered by 6 km of sediments, thickening in near continental basins.

The Alboran basin contains two basins deeper than 1,000 m separated by a NE-SW trending Alboran Ridge or "Alboran rise", which is a lineament probably made up of non-volcanic material, as indicated by sea magnetism.

The bathymetric map indicates also several conical mounts and banks: several of these are clearly associated with magnetic anomalies. On the other hand, others are not visible on the magnetic map. Some are certainly buried in nearby linear anomalies of large amplitude; some may have escaped observation because of the spacing of profiles; and some may simply be made of volcanic material that has low remanent or induced magnetisation, or that has been altered.

A belt of magnetic anomalies associated with an outcrop of ultramafic and associated metamorphic rocks coincides in part with the two well known crustal gravity high zones along the Moroccan and Spanish margin. The magnetic anomalies are also associated (not coincident), as above mentioned, with the Alboran rise and the Oran and Almeira-Cartagena continental margins; but there are no clear lineations characteristic of an oceanic crust.

The only certain interpretation is that the seamounts give rise to the magnetic anomalies, located on the break of the continental slope: they are volcanic intrusions through the systems of vertical faults marking the continental margins. But again they can be explained both as being associated with the initial rifting apart of continental blocks (plate tectonics) or with the vertical movements that generated the actual deep basins (oceanization).

The evaporitic layer discovered by NVR on the eastern side of the Alboran Basin extends over most of the Mediterranean Sea (Finetti and Morelli, 1973; Mulder, 1973).

On the eastern side of the Algero-Provençal basin the magnetic anomalies are practically aligned along a meridian strip which is the southwards continuation of the magnetic anomalies characterizing the western Corsica-Sardinia margin. They are probably caused, as for most of the magnetic anomalies outside the bathyal parts of the Mediterranean Sea, by magmatic intrusions through tensional faults, mostly at marginal contact areas affected by subsidence.

A submarine volcano is clearly visible on the bathymetric and magnetic maps on the African continental slope. Another ("Quirino") has been outlined by NVR on the south-western Sardinia slope.

The western margin of Sardinia has subsided, stretched and tilted, and expands much more than previously thought towards the bathyal plain (Fig. 5). The magnetic anomalies therefore confirm one of the major results already obtained from MS data: the continental basement extends far offshore from the Balearics and the Corsica-Sardinia block. Oceanic crust, therefore, is present only in the centralmost part of the basin, the rest being a transitional type of continental crust. In view of the strong and extensive Bouguer anomaly, support is given to the hypothesis favouring distension and rifting, with consequent collapse of the basin and formation of a near-flat bottom occupying its deepest part (see bathymetry).

2.2. The Central Mediterranean

The Central Mediterranean is the area that not only geographically, but also geologically and

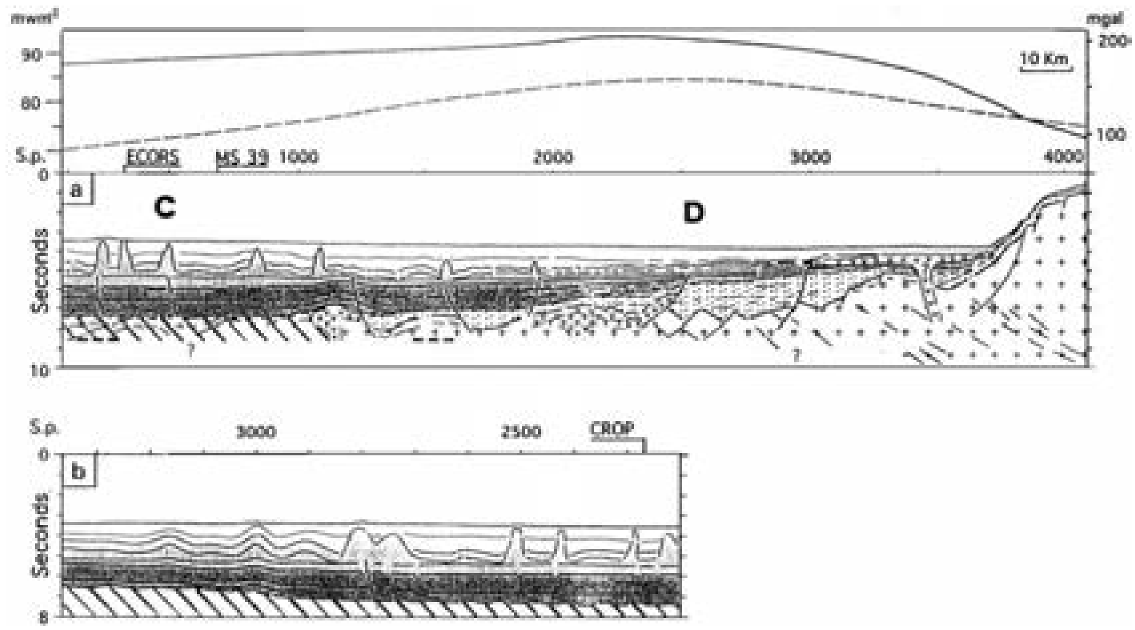

Fig. 5 - Interpretation (a) of the seismic reflection profile CROP-Mare1 from the Gulf of Lions to West Sardinia and (b) of a part of the profile MS-39 (from Morelli et al., 1993). C) External zone of the Sardinia margin. D) "Terrace". The heavy line is the Bouguer gravity anomaly, the dashed line the heat flow (not corrected).

geophysically, separates the Western Mediterranean from the Eastern Mediterranean. It is also important because it contains:
- the youngest area of the Mediterranean (SE Tyrrhenian), where tectonism is in action;
- the most important areas of volcanism and geothermal exploitation;
- areas where the boundaries between different plates can be recognized, and their actions and effects (e.g., Africa-Europe collision all around the western Tyrrhenian and Northern Italy) understood;
- relicts of active tectonics in crustal extension areas (Tyrrhenian) or compression areas (Apennines foredeeps).

All the above mentioned evolutionary aspects are responsible for deformations in the Earth's magnetic field, i.e., for the magnetic anomalies.

The Central Mediterranean is mostly contained between the Corsica-Sardinia block to the west and the Cyrenaica-Peloponnesus region to the east. It comprises the northeastern part of the Ligurian sea, the Tyrrhenian sea, the Pelagian sea, the Western Ionian and the Adriatic sea. The dominant continental block is the Adriatic micro-plate.

But from the geophysical and tectonical point of view, as we will see, the situation is as follows:
- the western Ligurian sea is the continuation of the Balearic-Provençal Basin, with practically the same characteristics;
- the Tyrrhenian sea is the present eastwards continuation of the back-arc activity which formed the Western Mediterranean;

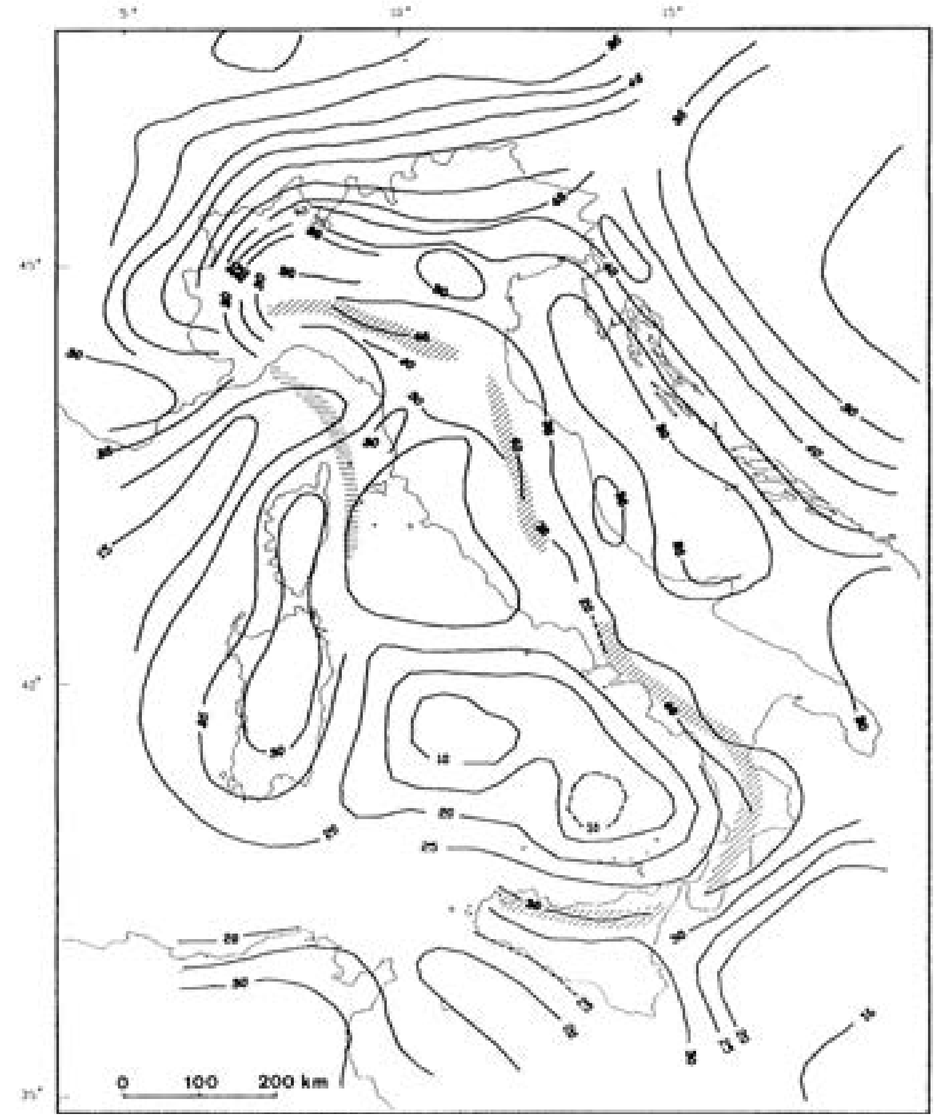

Fig. 6 - Moho isobaths (in km) for the different crustal types evidenced by DSS (from Nicolich and Dal Piaz, 1988): normal (continental): Adriatic, Sardo-Corso; thick: Alps; thinned: Tyrrhenian; rifted: southeastern Tyrrhenian, Sicily Strait.

- the Ionian sea is the western limit of the Eastern Mediterranean;
- the crustal seismic, gravimetric and heat-flow data confirm crustal thinning in the Tyrrhenian and Ionian bathyal plains, as well as in the Sicily Strait.

Knowledge of the above mentioned picture is also a pre-requisite for understanding the meaning of the magnetic anomalies. These can again be separated into regional and local ones, according to their spatial wavelengths.

REGIONAL MAGNETIC ANOMALIES. To understand the geographical distribution, origin and character of the regional magnetic anomalies, the structural model of Italy and surrounding sea is very useful. Fig. 6 represents the Moho isobaths in the Central Mediterranean area, as obtained from DSS and ocean bottom seismographs (OBS) profiles. The following features are indicated.

The Adriatic plate. A thick craton, with the maximum thickness (35-40 km) oriented NNW-SSE; against which (foreland) the tectonic activities of western and eastern origins collided.

The emerged foreland areas of Italy are generally taken as being the Hyblean Plateau (Sicily) and Apulia. These two areas are characterized by thick, Mesozoic-Tertiary, carbonate sequences, with widespread volcanic episodes ranging from the Triassic to the Pleistocene.

From the magnetic point of view, these areas are characterized by regional anomalies of long wavelengths (60-100 km) and amplitudes ranging from 40 to 200 nT, which can be associated with the structural heighs of a basement of variable basicity (k = 0.010-0.025; Arisi-Rota and Fichera, 1987).

Anomalies of this type can be found in the following localities:

1) the Hyblean Plateau, where the existence of a basic substratum (k = 0.025) has been revealed at a depth of between 4 and 7 km below sea level (b.s.l.);
2) the Apulian offshore region, south and east of the Salentina Peninsula, with ENE-WSW and WNW-ESE trends, respectively. The basement is located at a depth of 11-12 km b.s.l.;
3) along the coast from Pescara to Ancona, where the basement is 7.5 to 9 km deep b.s.l.

*The European plate***.** This is subducted under the Adriatic plate from the north and west, but on the contrary, from east overlaps the Adriatic.

The Tyrrhenian-Apenninic crust is characterized by collapse due to normal faults, which have led to thinning and localized tearing of the crust, thus permitting the effusion of basaltic and/or calc-alkaline magmas.

The Tyrrhenian-Apenninic crust is the remnant of a continental crust which was elevated, and the upper crust discharged radially, northeast-wards and east-wards over the Apennines, south-wards over Sicily and Tunisia. A complete section of the lower crust was discharged southeast-wards (the "Serre" over Calabria). Then finally (in the Quaternary) it rapidly subsided (by 4-5 km).

The two areas can be considered separately, the Northern Tyrrhenian-Apennines and the Southern Tyrrhenian-Calabrian Arcs which result from geodynamic differentiated evolution and are tied to different compositions of the lower plate: an oceanic lithosphere to the south and a continental one to the north; the first submitted to a subduction and the second to a delamination.

The eastern part of the Ligurian sea is the southward continuation of the Alpine domain. The medium-high frequency magnetic anomalies, with approximately 100 nT maximum intensity, associated with highly magnetized bodies (2000-3000 m deep), show a main north-south trend connecting Alpine Corsica with the offshore sector of the Chiavari zone.

Locardi and Nicolich (1988) attributed the tectonic evolution of the Tyrrhenian area to two asthenolites, separated by the 41st parallel (Fig. 7).

Very accurate geochemical and petrological studies have been performed by Serri et al. (1993). They noticed that the Neogene-Quaternary magmatism of the northern Apenninic arc

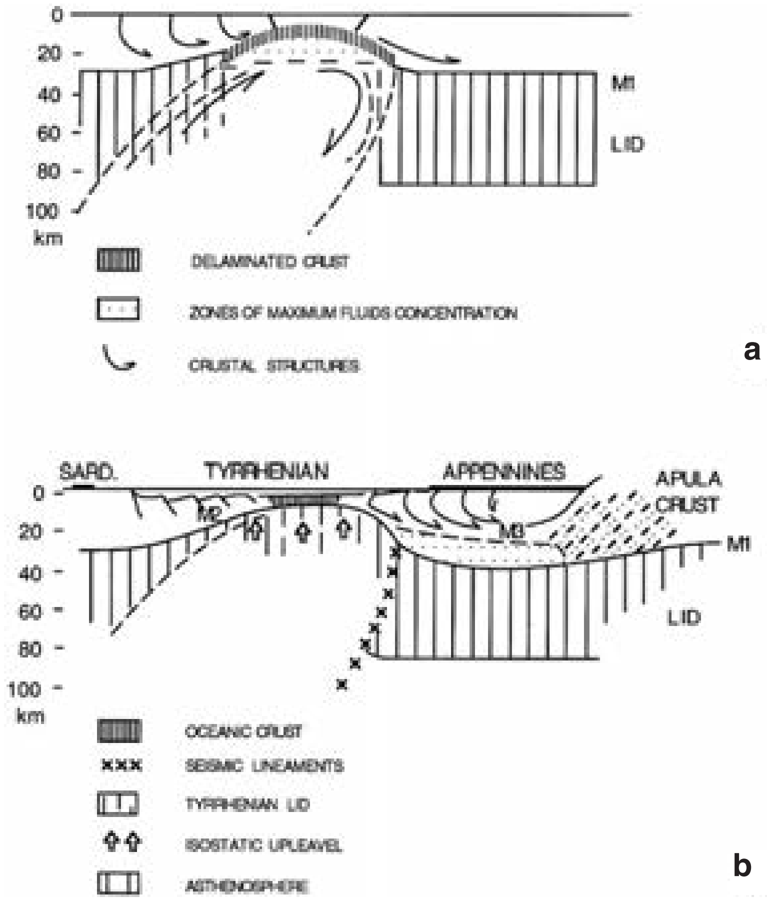

Fig. 7 - Evolutionary scheme for the LID in the southern Tyrrhenian area: a) ascending diapir; b) collapse of the top of the diapir (from Locardi and Nicolich, 1988).

took place in four phases, separated in space and time, which become progressively younger from west to east: Phase I, ~14 Ma; Phase II, 7.3-6.0 Ma; Phase III, 5.1-2.2 Ma; Phase IV, 1.3-0.1 Ma (Fig. 8). This magmatism is the result of activation of three physically separate sources: (1) the Adriatic continental crust, extracted from the mantle in the late Proterozoic; (2) a strongly refractory, recently *k*-enriched harzburgitic mantle located in the mechanical boundary layer of the lithosphere; and (3) a recently metasomatized mantle, interpreted as an ephemerally *k*-enriched asthenosphere.

The Adriatic continental crust is considered the dominant source of the acid plutonic and volcanic rocks of the Tuscan region. The acid magmatism is mostly found inside an ellipsoidal area (about 150×300 km) centered on Giglio Island, defined as the Tuscan Crustal Dome. Within this area, mantle-derived magmas unaffected by important crustal contamination processes and mixing with crustal anatectic melts have not so far been found.

The geochemical and isotopic features of the components that metasomatized the mantle sources of the northern Apenninic arc magmatism can be explained by a geodynamic process

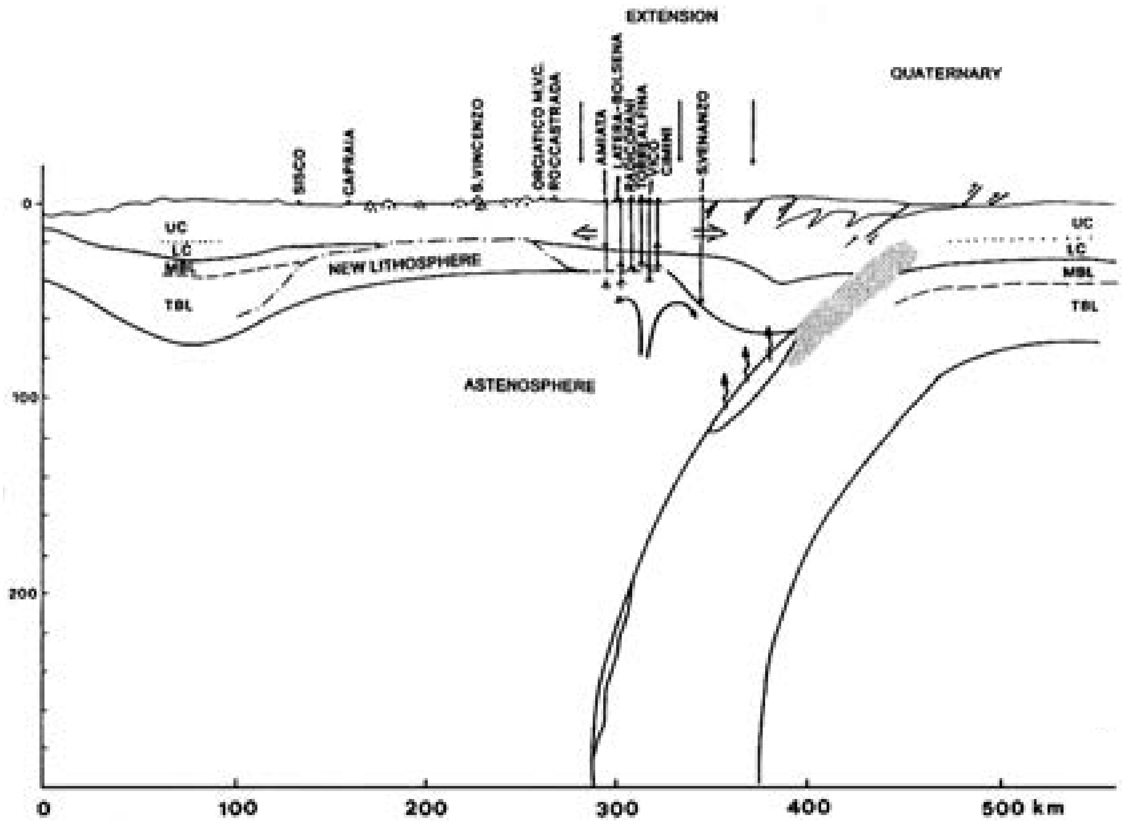

Fig. 8 - Interpreted section (from Serri et al., 1993) for the Quaternary during the fourth magmatic Phase (1.3 - 0.1 Ma). UC = upper crust, rigid; LC = lower crust, ductile; MBL = mechanical boundary layer, brittle; TBL = thermal boundary layer, ductile.

which causes a large amount of crustal materials to be incorporated within the upper mantle. The delamination and subduction of the Adriatic continental lithosphere, related to the still ongoing northern Apennine continental collision, provide a viable mechanism to explain the genesis and eastward discontinuous migration of the magmatism in central Italy. The subduction of delaminated lithospheric mantle with lower crustal slivers would have exposed uppermost mantle (Adriatic mechanical boundary layer) and crustal units previously imbricated in the Apennine chain to the heating advected by the upwelling of a recently and ephemerally *k*-enriched asthenospheric mantle wedge and by the underplating of magmas derived from it. The diapiric uprising of a hot, crustally-contaminated asthenosphere occurs in the wake left above the sinking of the Adriatic delaminated/subducting continental lithosphere (Fig. 8). The delamination/subduction process of the Adriatic lithosphere probably started in the Early-Middle Miocene, but earlier than 15-14 Ma, as indicated by the age and petrologic characteristics of the first magmatic episode of the northern Apennine orogenesis.

The rifting zones. The recently subsided area in the Tyrrhenian sea is circumscribed by a line that joins the Aeolian and Pontines Islands, the 41st parallel and the Quirra seamount and Ustica

Islands.

The Tyrrhenian sea is probably the most peculiar basin of the whole Mediterranean. Despite its relatively small size (270,000 km^2), its depth exceeds 3,600 m. It is a micro-ocean with a stretched crust, locally oceanic, edged by two active orogenic systems: the Apennine to the NE and the Calabria-Sicily arc southward. The large submarine volcanic massifs reach more than 2,000 m above the deep plains floor, and a still active volcanic arc (Aeolian islands) crosses the southern rise. These features result mainly from the very young age of this sea, late Miocene to Present, and are imprinted in the very diffused local and regional magnetic anomalies.

The first rifting occured along the Sardinia margin during the Mid- to Late Miocene, and the magnetic anomalies generated can be recognized in the long meridian strip eastwards to Sardinia.

Southeastwards, the deep basins of Vavilov and Marsili were oceanized during the Pliocene and Pleistocene by a stretching mechanism possibly more complicate than the back arc model. The Tyrrhenian sea is indeed a distensive basin recently created in an compressive environment (Africa-Europa convergence). Numerous characters show that this process is of back-arc-like type, behind the subduction of the Ionian Sea under the Calabrian arc. However, it is important to emphasize the role of direct crustal motions in this morphostructural genesis, as for example, the curtailed eastward rotation of Sardinia, and the displacement and present day orogenesis of the Apenninic chain.

From the magnetic point of view, the subsided area is characterized by medium-wavelength, high-amplitude anomalies (30 km wavelength and greater than 30 nT) that are associated with a basic substratum k (0.020 - 0.045). This substratum cannot be correlated with the crystalline basement of the continent, although they are interconnected by a gradual, dovetailing, magnetization transition.

To the south of the 41st parallel the magnetic anomalies are distributed in an inhomogeneous manner and follow approximately an E-W direction (South-Tyrrhenian Line) or follow sub-circular configurations (Southeastern Tyrrhenian). The regional magnetic field is characterized by short wavelength anomalies having amplitudes ranging from a few hundred to 1200 nT. This occurs in the largest of the Tyrrhenian bathyal plain seamounts. The Vavilov seamount - located between the Magnaghi and Marsili seamounts - produces an anomaly which has inverted polarity (amplitude 190 nT). Unfortunately, the intense magnetization of these calc-alkaline and tholeitic volcanoes, which erupted along the lithospheric fractures, masks the actual trend of the basic substratum, and also partially masks the weaker anomalies (80-100 nT) produced by the relic remains of the acid, crystalline, continental basement outcropping from the floor of the Tyrrhenian Sea: Farfalla, Issel, Flavio Gioia, Cassinis, Vercelli, Baronie and Cornaglia seamounts.

LOCAL MAGNETIC ANOMALIES. The local magnetic anomalies are normally correlated with areas of recent extension, rifting, collapse and connected effusions of alcaline and/or calc-alcaline magmas. The most important area with such characteristics is the thin stretched crust which occupies the Tyrrhenian sea and the Tyrrhenian region west of the Apennine chain (Fig. 6). The widespread volcanism creates diffused magnetic anomalies throughout the area, not only in the

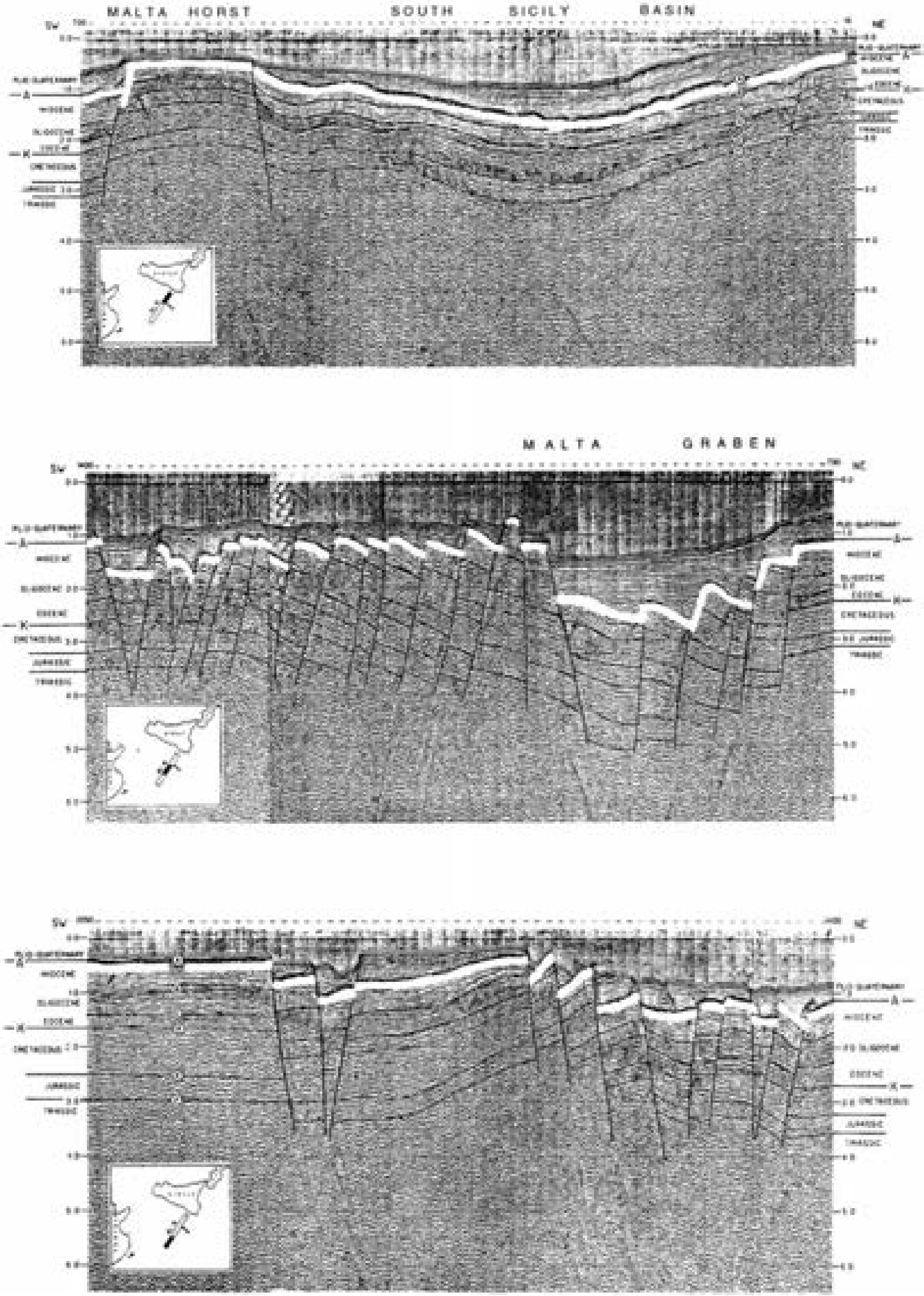

Fig. 9 - Example of a seismic reflection line (MS-19) in the Strait of Sicily, calibrated from the known Ragusa area on-shore and offshore drill-holes (from Finetti and Morelli, 1973).

basement but also infrasedimentary. The anomalies are of medium frequency (30 km) and amplitude (> 200 nT) and are correlated with a high susceptibility basement. The anomalies are young to very young, and their migration with time from west to east has been known for decades and allows a reconstruction of the Central Mediterranean tectonic activity's evolution.

ALIGNMENTS OF LOCAL MAGNETIC ANOMALIES. The local magnetic anomalies are often aligned, and in fact define several structures:
- the continuation of the contact between the European and the Adriatic margins southeast-wards along Western Liguria and the Eastern Ligurian Sea, and then southwards along the east-Corsica margin;
- the 41st N parallel from Bonifacio Strait to Vesuvius, and its continuations in the high-amplitude volcanicity of the Olbia lineament and eastwards in the Volturno River lineament. The "41st N Parallel Discontinuity" marks the northern limit of the recent Tyrrhenian depression;
- the E-W Southern Tyrrhenian line;
- the N-S fracture zone from the Aeolian Islands to Etna to the eastern coast of Sicily.

The strong magnetic anomalies connected with the large Marsili and Vavilov volcanoes are also N-S aligned; as is a weaker volcanites band from Marsili to Argentario, parallel to the Campania-Latium volcanoes.

Local magnetic anomalies can also be recognized in the rifting areas of the Ligurian Sea, of the Sicily Strait (Pantelleria, Linosa and Malta Grabens; Fig. 9) and in the peri-Apenninic onshore area.

The significant alignment of the anomalies, reaching from the Hyblean Plateau through Apulia, Marche and up to the Po Plain, reveals their extremely homogeneous characteristics. This leads to the plausible hypothesis that they could belong to the same geological domain, which is most typically represented by a basement with differentiated basicity.

In particular, the magnetic anomalies in the Ionian sea offshore from Sicily and Calabria, which from the magnetic point of view connect Calabria and Sicily, could be caused by Mesozoic volcanites.

A 500 km long profile from southeast Corsica to Calabria using OBS in 1979 indicates an irregular Moho with depths ranging from 8 to > 20 km. It deepens towards Sardinia, more gently towards Calabria, and there is a sudden interruption with a sloping refractor west to the Marsili Seamount (Fig. 10; Steinmetz et al., 1983).

Crustal thinning is a consequence of the general east-west distension to which the Tyrrhenian region has been subjected, accompanied by the formation of normal faults in a concentric pattern along the continental slope, and by vertical north-south faults in the present bathyal plain. Quaternary basalt-flow volcanism is related to this distensive tectonics (Etna, Ustica, and other seamounts in the Tyrrhenian bathyal plain).

Elongated sedimentary basins occur on and around Tyrrhenian Sea continental margins. These basins, formed by basement highs oriented parallel to the coast, have trapped sediments flowing downslope toward deeper sectors. The most important basins lie between Corsica and Elba, where stratigraphic studies have been carried out carefully by DRS shallow seismic surveys. An insular arc structure, high heat flow in the southeastern sector, gravity and magnetic

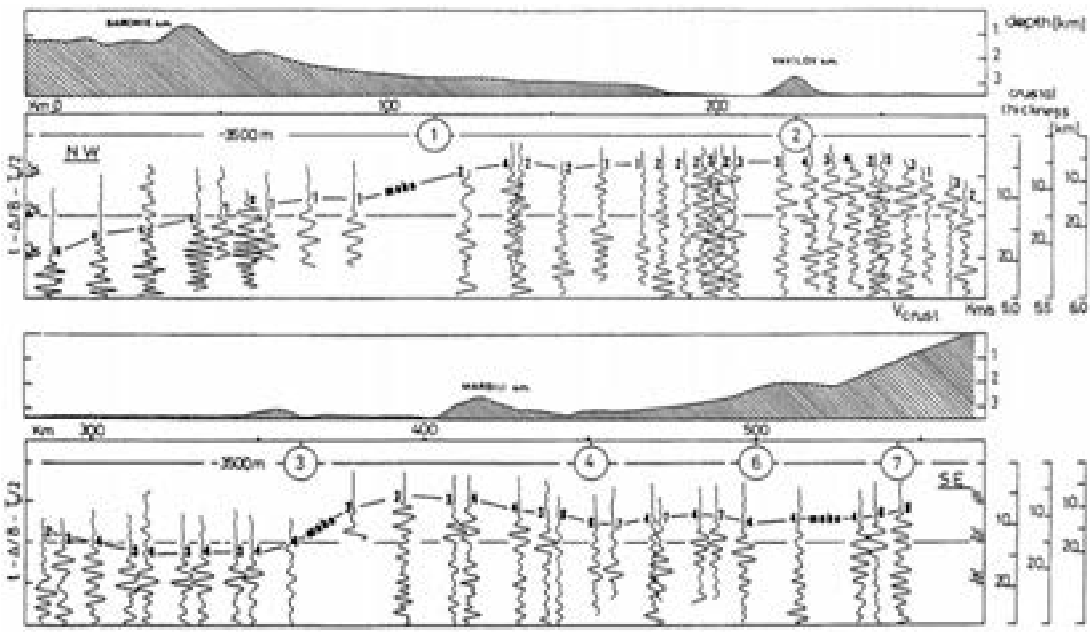

Fig. 10 - Cross-section of the Moho on a DSS profile from N. Sardinia to SE Tyrrhenian (Steinmetz et al., 1983). The crustal thickness corresponds to the different values of mean crustal velocity indicated (this may range from 5 km/s in the central basin to 6 km beneath Sardinia).

anomalies, a very thin crust, and the mantle structure (hotter, less rigid) suggest that the southeastern Tyrrhenian Sea is a typical marginal sea, beneath which the lithosphere is characterized by intermediate and deep earthquakes.

The Calabrian Arc, often compared to a circum-Pacific subduction zone, extends from the Molise Basin (where Apennine overthrusts lie on the Apulia continental block), to Sicily (where a similar setting is noted between the northern nappes and the Sicilian-Tunisian-platform), and then through the Calabria nappes and the Messina cone north of the Ionian abyssal plain. This arc was active throughout the Miocene: several nappes were emplaced, along with numerous olistoliths and olistostromes, in foredeep basins that were progressively deformed towards the external zone. Deformation and external gravity sliding occurred during the Pliocene and even the Quaternary. Behind the external zone (Calabria) the opening of, or tension within, the Tyrhenian Sea gave rise to extensive volcanism that is clearly revealed by bathymetry and recorded by magnetic anomalies The Tyrrhenian basin deep crust could therefore be a typical transition crust. A similar crust would be the product of an upper mantle uplift, with the previous sialic material sliding radially, and a subsequent sinking of the same upper mantle, whose elastic properties are lower than normal ("soft mantle"). The thin "oceanic layer" would be basalt, covering the mass of the previous geotumor.

Because the mantle rock and its basaltic derivative are both heavier than the granitoid rock of the continents, they assumed a level (-4 km) corresponding to the general oceanic mean depth; the few hundreds of metres of recent, soft sediment reduced the depth to the current one (-3600 m).

Geological and geophysical investigations indicate that the older unconsolidated sediments, the consolidated ones and the crystalline layer have been spread radially over the Italian peninsula and Sicily (Fig. 11). The so called "Tyrrhenide" therefore existed, and was at least partially of continental type. The evolution of the Tyrrhenian geotumor, probably as a consequence of the reversal of the process or motion in the mantle which deepened before (and after) the basin and made the thick accumulation of sediments possible, proceeded in time horizontally from the interior against the eastern and southern borders of the present sea area, where it is very young (2-5 Ma) and is even currently active (volcanicity, seismicity).

This could be considered therefore an example of the transition from a continental crust (or, better, a crust very like a continent formed from a sinking ocean basin) to an oceanic. So the actual Calabrian Island Arc would be an example of formation of new continental crust, at least partly at the expense of the ancient Tyrrhenian sedimentary and sialic covers, the tectonic actions deriving from the active upwelling of a soft mantle; and the Tyrrhenian Bathyal Sea is a marginal sea which formed in the SE Tyrrhenian corner, at or behind the Calabrian Arc, as the arc migrated outwards.

This complicated evolution could explain the inhomogeneous distribution of volcanites in the central-Tyrrhenian area: their presence is revealed by some magnetic alignments, with mean trends E-W and WSW-ENE, of complex geological interpretation (e.g., the "41st parallel line" or the "Southern Tyrrhenian line"), to which has been attributed the function of preferential conduits of the Tyrrhenian magmas. In the area between the alignments, the volcanites develop according to the NW-SE (eastern Tyrrhenian) and the WNW-ESE trend (Central Tyrrhenian).

The south-eastern Tyrrhenian reveals a sub-circular distribution of volcanic bodies around seamounts Marsili and Palinuro, suggesting the existence of a particular area inside the Southern Tyrrhenian.

THE OTHER RIFTING ZONES. The Sicily Strait area, between the Pantelleria, Linosa and Malta troughs, constitutes a prominent rift zone which started in the Late Quaternary.

The magnetic panorama shows short-wavelength, high-amplitude anomalies, which are mainly due to basic volcanic dykes at a shallow depth beneath the sea floor (0 - 2000 m). The substratum of this intercratonic rift area, which is deeper than 8 km b.s.l., could be associated with the southern-Tyrrhenian substrata that have medium-high susceptibilities.

Remarkably enough, the Malta-Gozo Horst, which forms the southern rim of the Malta Trough, is a basement high (7-8 km b.s.l.) and shows differentiation of basicity (k = 0.01).

The continental crustal connection between Sicily and Tunisia across the Sicily Strait has been perfectly evidenced by the MS-profiles (Fig. 9; Finetti and Morelli, 1973), with the continuity of the sedimentary series (down to the Triassic), broken by many sub-vertical faults (some of which with magma-rises responsible for the local magnetic anomalies) and forming horsts and graben.

The Sicily Strait comprises primarily the Pelagian Plateau, a thick carbonate platform underlain by normal continental crust that is locally reduced to a thickness of approximately 20 km around the volcanic area southwest of Sicily. The eastern edge of the plateau is defined by the Malta Escarpment. To the south, the plateau is separated from the African Platform by the Tripoli Basin.

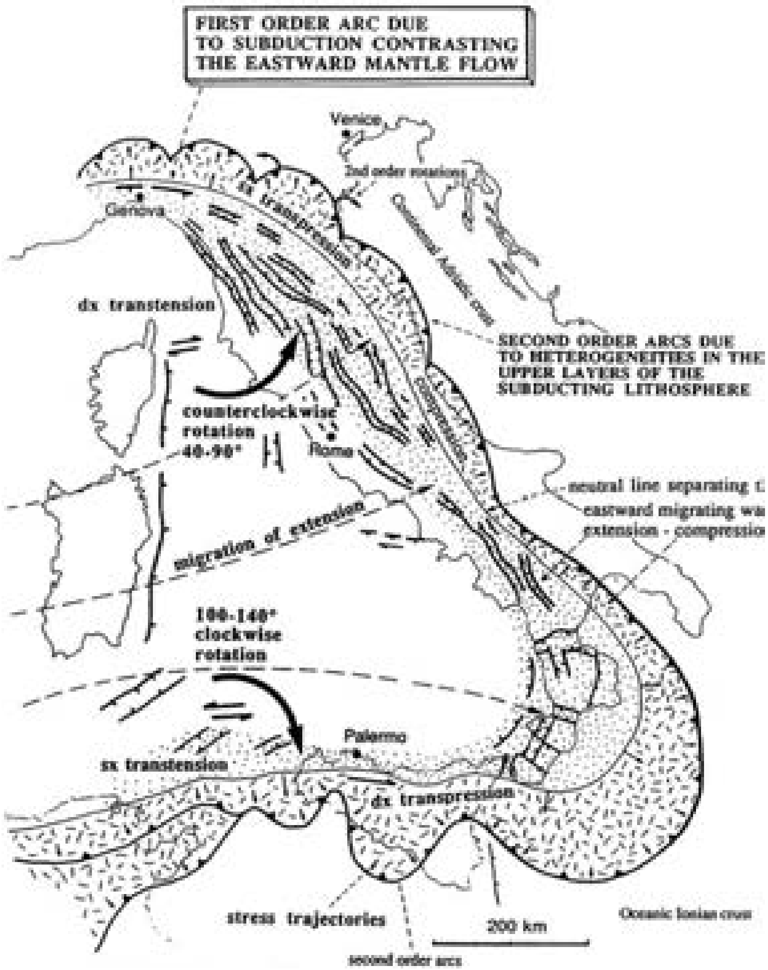

Fig. 11 - Kinematic model by Doglioni (1991) to show how the migration and rotation of stress patterns have fashioned the present shape and state of the Tyrrhenian sea tectonic system.

The Sicily Strait can thus be viewed as an area in which magmatic activity has involved the sialic crust, but with lesser intensity than in other areas of the Western Mediterranean, such as the Balearic and Tyrrhenian abyssal plains. Magmatic activity reached the seafloor surface as a consequence of post orogenic distension phases that produced offsets, including troughs within the Sicily Strait region. Magma intrusions reached the seafloor surface and various subbottom levels by means of faults related to distension phases. Some intrusions produced eruptions recorded in historic times. Volcanic structures have also been mapped by the magnetic and seismic surveys.

The Pelagian sea is a vast faulted and slighly warped shelf which extends the Saharan craton. The deep fracturation of the block began in Cretaceous times in the southern zone. In the northern zone, as mentioned, it started in the late Miocene, and continued into the Pleistocene, associated with magmatism.

In the Sardinia Channel no trace of compression is recorded in the sedimentary cover;

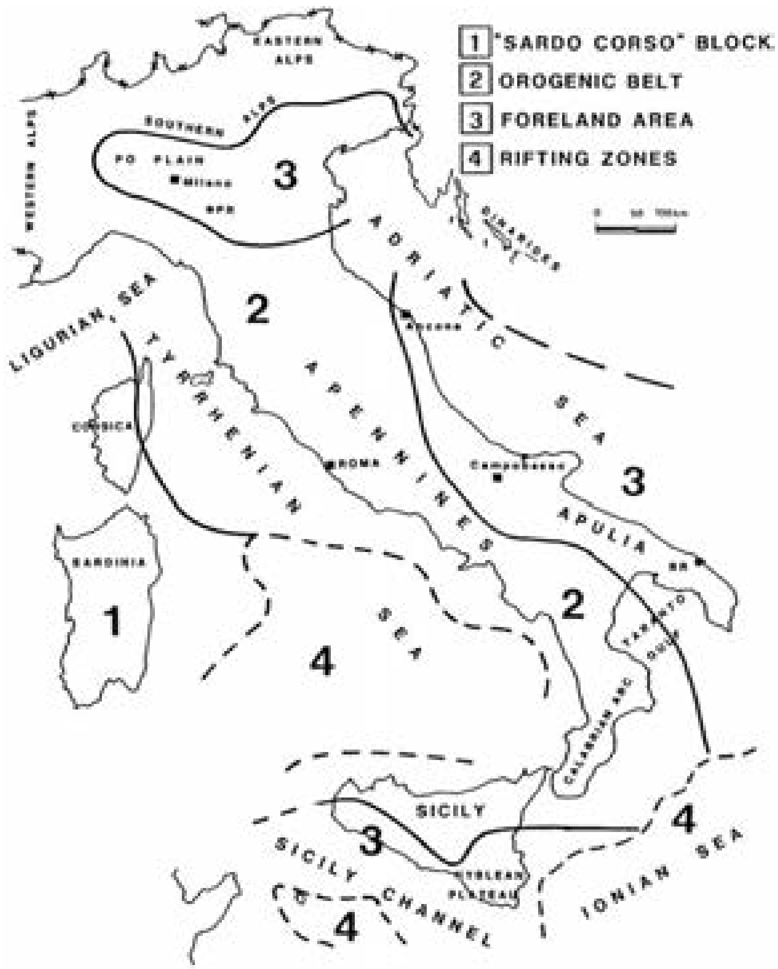

Fig. 12 - The "geomagnetic provinces" of Italy and surrounding seas, evidenced from the aero-magnetic anomalies integrated with other geophysical data (from Arisi Rota and Fichera, 1987).

moreover, basement faults are associated with Pliocene subsidence (Auzende, 1971). There is a bathymetric depression in the central part of the channel, but the basement does not show magnetic anomalies nor any obvious difference between the European and African Paleozoic series. The boundary between European Sardinia and African Tunisia is only suggested by the channel. On the other hand, the Malta Escarpment, the eastern edge of the Pelagian Plateau, represents a recently formed continental slope.

THE ADRIATIC SEA. A magnetic anomaly map for the Adriatic sea, scale 1:750,000, equidistance 20 nT, was published by Morelli et al. (1969).

The Adriatic sea, which is connected to the Ionian sea by the channel of Otranto, is mainly epicontinental. The main part is less than 200 m deep, except for a small trough (Jabuka Pits) and the South-Adriatic basin where the depth attains 1200 m. It is 900 km long, and is part of the Apulian plate. Its basement and the thick sedimentary cover have been squeezed by the Africa-

Europe collision. On the NE side, it is overthrust by the Dinarides with compressive and transtensive mechanisms. On the SW side, the Apennines oversthrust the Adriatic basin and cause deformation of the Apulian plate itself. After Messinian emersion, subhorizontal Pliocene sediments were lain on a strongly faulted substratum.

The effects of the Triassic volcanism are imprinted in the Northern Adriatic magnetic anomalies. A few local magnetic anomalies in the Central and Southern Adriatic (<160 nT) are connected with volcanite and plutonite outcrops on the sea bottom. The very strong regional magnetic anomalies (>320 nT) in front of the Dalmatian coast is probably caused by variations in the basement (rise and/or increase in magnetic susceptibility).

AN INTEGRATED INTERPRETATION. An integrated interpretation of the aero-magnetic anomalies for the Italian and surrounding sea areas, using advanced techniques (interactive modelling) and other geophysical methodologies (mainly gravimetric and seismic), have defined the characteristics of the magnetic basement with reference to the geologic situation as follows (Fig. 12; Arisi Rota and Fichera, 1987):

1) The "Sardo-Corso" block, which represents the eastern boundary of stable Europe, is characterized by medium-wavelength, low-amplitude anomalies that originate in an outcropping basement (Hercynian granites, s.l.);
2) The "Orogenic belt", which constitutes the double Alps-Apennines system, is characterized by short-wavelength, low-amplitude anomalies, that are due to Paleozoic outcrops and/or buried, acid, crystalline basement. These anomalies are found to overlie long-wavelength, medium-amplitude regional anomalies that are related to a deep, Apenninic basement (central-northern Apennines);
3) The "Foreland area", which extends from Sicily (Hyblean Plateau) and Apulia northwards to Ancona and the Po Plain, is characterized by a crystalline basement which is typically "differentiated" in terms of basicity;
4) The "Rifting zone", which is represented by the part of the Tyrrhenian Sea lying south of the "41st Parallel discontinuity", the Ionian Abyssal Plain, and the Pantelleria and Linosa troughs in the Sicily Strait, presents extreme basicity differentiation in the crystalline basement, induced by geochemical processes connected to deep, geodynamic events. These phenomena do not permit correlation of the semi-oceanic basement of the rifting zone with the continental basement.

Using interactive modelling, a structural-tectonic picture of the basement of the various Italian "geo-magnetic provinces" was obtained. The main result was that the orogenic belt basement is undergoing intense tectonic compression and overlies the structural highs of the foreland area, which mainly show tensional events.

The values of magnetic susceptibility k published by Arisi Rota and Fichera (1987) were computed from the anomalies, and are not those measured in the laboratory. Values calculated from anomalies tend to exclude remanant magnetization oriented in directions not parallel to the present magnetic field, even in the opposite direction. In this case, the susceptibility is fictious, but is nevertheless able to satisfy the majority of the anomalies present in the studied area.

For regions of intense volcanism, a detailed sampling was done to obtain (in the laboratory) a total magnetization intensity (remanent plus induced) for the volcanites being examined.

Another important result is the strong variation of basement composition and depth, which changes abruptly from a few kilometers depth and a basic differentiated composition in the western (Tyrrhenian) area to 10-14 km depth and a crystalline, acid composition in the eastern (Apenninic) area. The separation (already known by geologists as the Pontremoli-Amiata-Civitavecchia line) is linear, 680 km long, and runs parallel to the actual coastline, approximately 20 km onshore, from the Ivrea zone in Piemonte to the 41st parallel.

The magnetic modelling of a profile from Corsica to Ancona shows an acid, crystalline basement lying below the northern part of the Tyrrhenian Sea, at a depth - controlled by recent tensional tectonics - that varies between 4 and 8 km b.s.l. A body having high suceptibility (0.02) is found to be present in this area, in the vicinity of Elba Island at a depth of 2.7 km b.s.l. This area is part of a strip which extends uninterruptedly for 300 km from south Corsica to the Ligurian Sea. This body probably belongs to the ophiolitic suture of the Ligurian- Piedmont Jurassic ocean, as evidenced by the particular kind of anomaly, the magnetic characteristics of this type of body, the lack of a high-temperature gradient and the fact that it lies in the crustal doubling between the Adriatic and European plates.

A magnetic horizon is also seen, starting at the Tuscan coastline and going northeast, which can be correlated with a tectonic wedge of the acid, crystalline basement (0.0006 - 0.004) that extensively overthrusts a deep basement lying at a depth of from 10 to 14 km b.s.l.

The presence of a basement involved in the overthrusts is also demonstrated by the data from many wells drilled in the Larderello and Mt. Amiata geothermal areas. The calculated susceptibility of the deep, Apenninic basement (0.004 - 0.01) indicates a gradually-increasing basicity, which can be related to a Moho that is unusually high for a continental area (Nicolich, 1981).

The acid, crystalline basement of the belt lies superimposed, most likely as a result of reverse faulting, upon the foreland basement near Ancona in the Marche area, where the depth of the foreland basement reaches 7-8 km b.s.l. and the susceptibility contrast is typical of foreland areas.

Of particular interest is the magnetic modelling on a profile from Sardinia to the southern part of the Tyrrhenian sea and to Apulia, crossing all four geomagnetic provinces above mentioned. The main results are:

1) The crystalline basement can be traced from Sardinia as it descends eastward, monoclinally, and probably making gradual, dovetailed contact with the highly-susceptible semi-oceanic basement of the Tyrrhenian rifting zone;
2) The intense anomalies caused by such seamounts as the Vavilov (with its reverse polarity) and the Marsili, in the Tyrrhenian domain, do not allow a correct quantitative interpretation of the substratum. In any case, this substratum should lie at a depth of between 4 and 7 km b.s.l.;
3) There is an additional transition zone under the Paola Basin, whereby the basement becomes of continental type. This basement was probably involved in the orogenic phenomena and shows a structural high at a depth of 8 km b.s.l. under the eastern coast of Calabria, with medium-high susceptibility (0.015);
4) There is evidence that the Bradanic Trough continues offshore, where it reaches its maximum calculated depth of more than 13 km b.s.l. Under the Adriatic Sea, the Apulian-Foreland base-

ment rises to a depth of 11 km b.s.l. and increases in basicity (0.025).

The results of magnetic modelling for the foreland geomagnetic province which extends from the Hyblean Plateau (Sicily), to Apulia and to the Adriatic offshore as far as the Po Plain, are in agreement with the gravimetric data and indicate that the transition from the orogenic belt to the foreland area takes place through compressive, tectonic phenomena involving the crystalline basement.

In the middle of the Adriatic Sea the highs of the basement with elevated susceptibility are at a depth of 7-10 km b.s.l.

We can now summarize as in Table 2 the magnetic characteristics for the geo-magnetic provinces outlined in Fig. 12, which in general corresponds to the types of crust presently known (Fig. 6).

Table 2 - Magnetic characteristics of the geo-magnetic provinces. m.a. stands for magnetic anomaly; RMA for regional magnetic anomaly; LMA for local magnetic anomaly.

Geo-magnetic provinces	**m.a. (nT)**		***k***
	RMA	**LMA**	
1. Sardo-Corsican block			
(European crust)	10-50	420	low (0.004)
2. Orogenic belt			
Tyrrh.-Apenn. transition crust(*)			medium-low (0.01-0.02)
Western Tuscany	low low		0.006-0.013
Southern Apennines	2000 (Vesuvius)	<500	0.06-0.12
3. Adriatic microplate (Foreland)	40-200		medium-high (0.01-0.02)
4. Rifting zones			
Southern Tyrrhenian and SicilyStrait	>1200	>200	0.02-0.12
Ionian Abyssal Plain	high		high (0.045)

In conclusion, the western Central Mediterranean, as all the Western Mediterranean, was formed within the Alpine belt after the continental-continental Cretaceous oceanic collision between Africa and Europe. Starting in the west from Oligocene times (Alboran ~35 Ma) and continuing until the present (south-eastern Tyrrhenian, < 2 Ma), the crust was thinned and rifted by the tensional stresses of warmer bodies (asthenoliths) in the upper mantle, caused by subduction of the downgoing plate.

More recently (Cassano, 1990) a new aeromagnetic map of the Western Mediterranean and Italy has been interpreted, and geomagnetic domains have been identified which are characterized by magnetic anomalies related to different structural settings of varying lithological and geodynamic significance.

Apart from the zones with little magnetic activity and a small number of magmatites associated with blocks or possible groups of such blocks, the areas of high magnetic activity were distinguished as follows:

1) the Alboran Sea with magmatites trending WSW-ENE and WNW-ESE;

(*) An acid, crystalline basement lies at 4-8 km under the northern part of the Tyrrhenian sea. Starting at the Tuscan coastline and going towards the northeast, a magnetic horizon (which can be correlated with a tectonic wedge of the acid, crystalline basement, 0.0006-0.0012) overthrusts a deep basement lying at a depth of 10-14 km, whose increasing basicity (0.004-0.01) can be related to a Moho at 25 km, unusually high for a continental area.

2) the Algerian-Balearic Basin, containing magmatites with varying trends;
3) the Gulf of Valencia, with mainly SW-NE trending magmatites;
4) the northern margin of the Balearic promontory, with NW-SE trending magmatites, extending to the latitude of southern Sardinia;
5) the Algerian-Sardinian Basin which appears trapezoidal in shape, with magmatites trending NW-SE and having symmetrical normal and reverse polarities; this is the only zone with oceanic characteristics;
6) 41st parallel zone characterized by magmatites erupted from E-W fractures in the Western Mediterranean These fractures rotate slightly in the Gulf of Asinara and continue into the Tyrrhenian Sea with trends which are less evident, but certainly organized with an E-W lineament as far as the Campania offshore area;
7) the magnetic trend of the Gulf of Lyons with magmatites trending NW-SE which appears to intersect the 41st parallel zone at the Gulf of Asinara. This band may continue into the Tyrrhenian and includes the magmatites of the western Sardinia offshore area, at least as far as the 'Central Fault';
8) the Ligurian Basin with magmatites trending mainly NE-SW. This zone ends when it intersect the Gulf of Lions zone;
9) the northern Tyrrhenian zone where the magmatites are prevalently Alpine ophiolites;
10) the southern Tyrrhenian zone which lies between the 'Central Fault' of the Calabria-Campania margin and the Sicilian margin. This is a zone of very high magnetic activity which is generally divided into directions 120° apart.

The main conclusion was that the outlined magnetic bodies only occasionally coincide with known tectonic elements. The evolutionary models proposed for the Tyrrhenian and Western Mediterranean seas are only partly supported by the magnetic zonation. Other new elements calling for a reconsideration of the origin and presumed oceanic nature of the two basins emerge:

1) North of Algiers there are lineaments which do not correspond to the NW-SE transform faults which in the literature are seen as responsible for the dislocation of the Algerian-Balearic Basin axis of acretion;
2) Some trends in the Western Mediterranean seem to continue into the Tyrrhenian Sea, such as the Marseilles-Bocche di Bonifacio line which is evident in Sardinia and offshore from Olbia and South of the Baronie mountains. This trend appears to dislocate the 41st Parallel Belt near north-western Sardinia;
3) The eastern continuation of the 41st Parallel Belt is very evident in the Tyrrhenian Sea, where it coincides with a great increase in magnetic activity and an abrupt deepening in the southern Tyrrhenian Basin, and onshore, to the east of the Volturno River, where it intersect discontinuities in the magnetic basement;
4) A further trend which seems to continue in the Tyrrhenian Sea is the SW-NE one in the eastern Algerian basin, which may correlate with the Central Fault trend;
5) The ODP drilling data confirm that in both the Tyrrhenian and Western Mediterranean Seas, volcanic materials are only found in particular zones (Vavilov, Marsili Basins and the Gulf of Valençia) always coinciding with magnetic anomalies, while drilling beyond the magnetic lines has not encountered any volcanic layers. It can be concluded that the fully oceanic cha-

racter of the two major Mediterranea basins has yet to be confirmed. The only area of fully oceanic character is that north of Skikda (SW of Sardinia).

2.3. The Eastern Mediterranean

The geological setting of the Eastern Mediterranean Basin is considerably different from that of the Western Mediterranean: it has formed largely on the more stable African margin lying to the south.

Gravity anomalies, a few DSS data, DRS results, the reduced magnetic anomalies in the deep basin, and heat flow data indicate that the deep abyssal plains of the Eastern Mediterranean formed on a thick sedimentary cover lying on a thin crust that probably includes pre-Mesozoic series. This crust is of intermediate or oceanic origin, thickens progressively southward toward the African continent, and becomes more disrupted and tilted from east to west.

The African plate is pushed to the north, and its northern border is being subjected to collision to the east and subduction to the west, so creating the Calabrian, Hellenic, Anatolian and Cyprean Arcs, with associated deep earthquakes, trenches and sediment infill. The Hellenic Arc is seismogenetically the most active one, and its trenches are the deepest of the Mediterranean Sea (> 5000 m).

The Ionian basin is surrounded by various types of margin: to the west, the Malta Escarpment is a major normal fault, smoother southward near the Lybian margin; to the north, the Calabrian margin, from the Messina Strait to the Gulf of Taranto, is a sedimentary accretion wedge overlying the subduction zone of the Ionian crust below Calabria. The widespread magnetic anomalies have a N-S trend, border the eastern coast of Sicily and constitute the magnetic expression of the Sicily-Malta escarpment separating the Ionian Basin from the Hyblean Plateau.

More eastward the Hellenic margin begins, formed by the front of the Hellenic arc and the foredeeps. The structures are complicated, being continuously tectonized by compression stresses.

The larger part of the Eastern (or Levantine) Basin is in a position of foredeep with respect to the Hellenic arc. It may be divided in two parts along the Eratosthenes seamount latitude: the northern part is tectonized, at the junction of plates, and the sedimentary cover is thick in places; the southern part is the African plate border, dominated by Nile sediments widely spread on both sides, the Herodotus abyssal plain, and the Israeli margin.

The eastermost Mediterranean is in the initial stage of continent-continent collision, the main effects of which are:

- the Quaternary uplift of Cyprus;
- the break-up and subduction of the Erathostenes seamount (Pool and Robertson, 1991), which is a continental fragment 24 km thick, covered by relatively thin Mesozoic sediments;
- the formation of the Anaximander seamount, which could be an allocthonous part of an accretional margin.

Between the Eratosthenes seamount and Israel, there is a crystalline upper-crust continental layer, which does not exist in the central part of the Levantine Basin, and beneath which the oceanic crust is approximately 6 km thick.

All this active tectonic area is characterized by magnetic anomalies which are of a local character:

- *positive* ones west of Crete, NW of, and on Cyprus, on the continental margin of Israel, and offshore Egypt between 27° E and 28° E; they correspond to volcanic intrusions; the same is true for the Malta Escarpment and its southward continuations, and the Medina seamounts;

- *negative* ones, spread especially over the nothern and eastern areas and mostly corresponding to small trenches or sedimentary basins.

Cyprus, accordingly to Makris et al. (1983), consists of normal continental crust (Mono depth at = 30-32 km) with about 4 km of obducted ophiolites, exposed in the Troodos Massif. To these ophiolites, of Cretaceous age, either infrasedimentary or thrusted over the continental and oceanic igneous basement, are attributed the dipole magnetic anomalies of the Cyprean Arc.

In the Cyprean Arc and the eastern part of the Hellenic Arc, the dipole anomalies often coincide with the bathymetric features and connected gravity highs and lows.

On the southern side, along the Cyrenaica coast, the steep slope is formed by faulted steps, which generate magnetic anomalies.

Regional magnetic anomalies can also be recognized in the area:

1) two big negative anomalies, one to the SW of the Herodotous Abyssal Plain, the other between the Eratosthenes seamount and Israel; they are attributed to an oceanic crust of inverse polarity, most probably of Early Jurassic age, which floors the deeper parts of the Levantine sea crust and the Eastern Mediterranean;
2) one big positive anomaly, centered south of Cyprus and corresponding to the Eratosthenes seamount (which in reality is a crustal structure 24 km thick).

In the rest of the Eastern Mediterranean the magnetic field is mostly regular. The absence of magnetic anomalies in the central part of the Ionian sea and the Eastern Mediterranean is, at least partly, attributed to the thick sediments (many km) which cover all the Eastern Mediterranean, and which become thicker on the Nile Cone (16 km), on the Calabrian cone and in the Hellenic Trench, on the Mediterranean Ridge and in the Eratosthenes Trench (15 km).

The Mediterranean Ridge is an accretionary compressive wedge of sediments accumulated on relicts of oceanic crust. The demonstration that the Mediterranean Ridge is not a ridge comes from Flexotir results, which prove beyond doubt that most of the area south of the Hellenic Trench has a thick (> 1000 m), widely and strongly deformed, evaporitic series followed by other pre-evaporite thick sediments. In the deepest parts of the basins the evaporites are approximately 1 km thick. They are generally undisturbed where the overlying Plio-Quaternary layer is thin; but they are deformed with salt domes where loaded with thick sediments.

This area is the continuation of the foundered and intensively fractured Cyrenaica platform: large fault systems separate the lowered sedimentary plateau from the North African Slope (Cyrenaica Trench). The magnetic anomalies on the area derive from this tectonic situation.

The deep Ionian Basin is bordered to the west by the already mentioned Calabrian Arc, with thick continental crust and thick sediments accreted by crustal shortening and subduction. The magnetic anomalies of the Ionian Abyssal Plain have high amplitude and are associated with a semi-oceanic basement located at a depth of 5-7 km b.s.l. and probably linked to the Middle

Fig. 13 - Location of the two-ship, deep seismic soundings in the Eastern Mediterranean basins (Pasiphae cruise; De Voogd et al., 1992).

Jurassic rifting that gave rise to the opening of the Ionian sea (Finetti, 1982). The faults opened the way for magma ascent and therefore for magnetic anomalies.

The presence of a continental crust in the Ionian Basin was postulated mainly on the evidence of the overall thickness of the crust (~ 20 km) deduced from the dispersion of seismic surface waves. The problem of the nature of the crust in the deeps of the Eastern Mediterranean (oceanic or stretched continental) was solved in 1988 by a two-ship refraction and oblique deep seismic survey on the Ionian, Sirte and Herodotus abyssal plains (Fig. 13; De Voogd et al., 1992).

The three basins have a relatively thin crust (8 to 11 km) overlain by a thick sedimentary cover, up to 10 km in the Herodotus abyssal plain. The Moho boundary (Pn = 8.4 - 8.5 km/s) and the main crustal units identified in the basins can be followed beneath the Calabrian prism to the west, and beneath the Mediterranean Ridge to the east. The Moho progressively deepens towards the Hellenic Arc, in agreement with the accretionary wedge model.

The crustal structure is of oceanic type for both the Ionian and Sirte basins, where typical oceanic layers 2 and 3 are recognized. The thin crust of the Herodotus Basin may be interpreted either as oceanic or thinned continental crust (about 10 km thick). The top of the crust of the Herodotus Basin is much deeper, thus the Herodotus Basin is probably significantly older than the Ionian basin, Triassic versus Early Cretaceous in age.

The Aegean sea is all on the European plate, and all on continental crust. The southern part is a marginal sea, on the concave side of the Hellenic arc; the crust has reduced thickness

(Bouguer: +170 mGal). The rest is a foundered continental area. The sedimentary basins are indicated by the negative gravity anomalies: they are fragmented and irregularly disseminated.

Two DSS profiles taken in the Aegean area (Makris, 1978) have shown that the crust is updipping from 32 km at North Evia to 26 km in the South Aegean Sea. The true velocities computed from the observations are 6.0 km/s for the crystalline basement and 7.7 km/s for the upper mantle.

The observations at Crete showed results similar to those of the Aegean section. The crust is also continental, increasing in thickness in the E-W direction from 30 to 34 km. The western part of the island, beginning at the western border of the Messara basin, is down-dipping to the west, where the nappes have their maximum thickness.

The Aegean sea is an uplifted continental crust thinned by stretching between two 40 km thick continental areas, the Hellenide and the Anatolian, covered partly by thick sediments. They exceed 8 to 10 km thickness in western Greece and are strongly deformed by compression.

The North Aegean crust has nearly 26 km thickness, and in pull-apart depressions up to 6 km of sediments are present. The Cretan sea is composed of 18-20 km thick stretched continental crust, including 3 km of Miocene and post- Miocene sediments.

The magnetic anomalies reflect the above mentioned tectonics.

The relatively high heat flow in the Aegean sea and the volcanoes are indications of an upper mantle softened due to convection processes induced by the downgoing Ionian slab.

The North Aegean basin especially is characterized by a succession of deep troughs, in continuity with the North-Anatolian strike-slip fault. In the central part of the North Aegean troughs, many short and discontinuous faults form small grabens. The central plateau is a mosaic of high blocks and small basins resulting from polyphased compressive and distensive tectonics since the Middle Miocene. N 40° and N 120° trending faults predominate, associated with some N-S grabens.

The Cretan Sea is limited on its southern side by the Hellenic Arc and on the north by the southern Cyclades and Dodecanese archipelagoes, with the main volcanoes of Milos, Santorin (Thira) and Astipalia. Morphostructural features and the network of faults suggest a radial extension. This extension is actually of back-arc type, as is proven by the presence of recently active explosive volcanoes. The floor did not reach the oceanic state, as in the Tyrrhenian Sea.

The large Iraklion basin forms the main part of this sea in distension. It is limited on the eastern side by two grabens, parallel to the arc.

The Black Sea is linked to the Aegean Sea distension area through the Dardanelles Straits.

The major distension is thought to have begun during the Middle Miocene, in relation to subduction of the African margin below the Aegean area. This general extension, acting as a back-arc basin, continued until the present. This mechanism is complicated by the westward movement of Anatolia, pushed by the Arabic plate.

The present morphology of the Black Sea is characterized mainly by narrow shelves. Only in the NW and W of the sea is there a zone of 200 km width in the north and 20-40 km width near the European part of Turkey. The slopes are rather steep, and the basin has a smooth, flat bottom 1.8-2.2 km deep.

The Black Sea is a large marginal sea located within a complex of folded chains of the Alpine

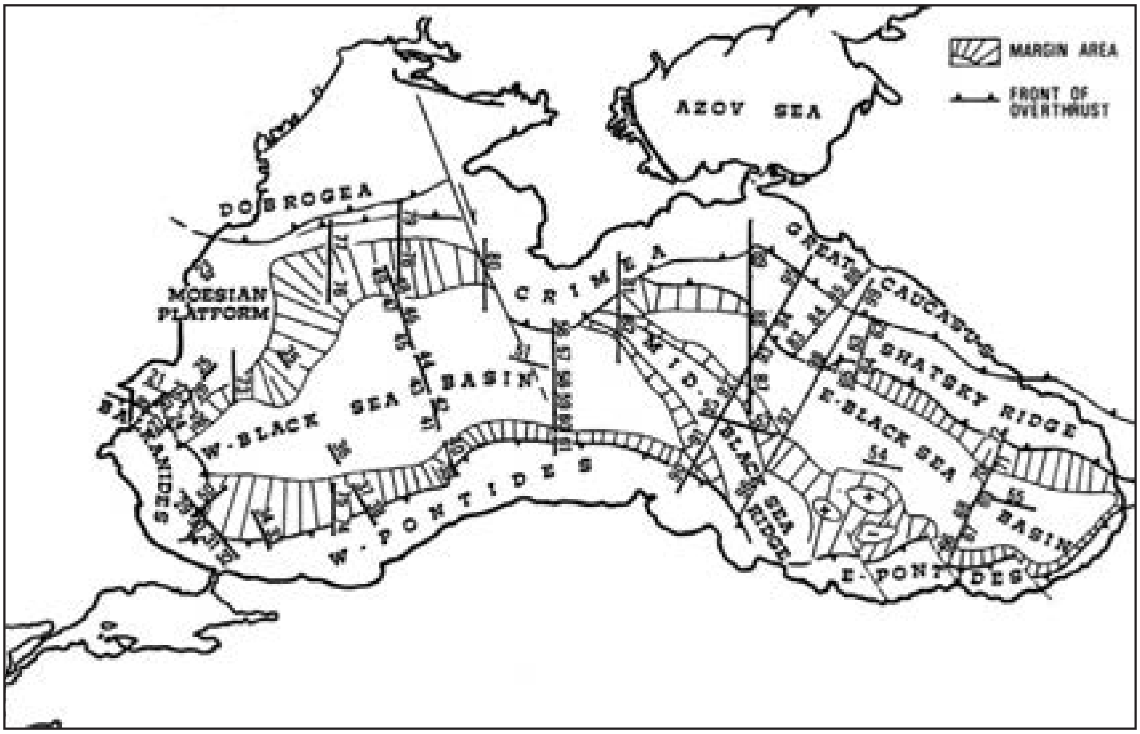

Fig. 14 - Black Sea: regional features reconstructed by seismics, position of the interpreted seismic lines and time structural sections shown in Finetti et al. (1988).

System, generated by tectonic events that affected the area during Mesozoic and Tertiary times.

The magnetic survey of the Black Sea was performed by OGS with CNR's r/v Bannock in 1975. A multichannel deep reflection seismic survey (3701 km) with the ship Explora was done by OGS in 1975, and the data exchanged with 3880 km from the USSR and 2420 km from Bulgaria (Fig. 14). A special monograph on geology and geophysics of the Black Sea was published in 1988 by OGS as a special issue of the "Bollettino di Geofisica Teorica ed Applicata" (vol. 30, n. 117-118). This discussion of the magnetic anomalies will be accompanied by geological and geophysical summary information from this monograph.

The article by Beloussov et al. (1988) summarizes the information on the structure and evolution of the Black Sea. The mountains to the south of the Black Sea basin belong to the structures of the Alpine Mediterranean Belt. The Black Sea tectonic basin has been warping intensively since the Cenozoic. The geophysical study, performed in connection with Bulgaria and Romania, consisted mainly of multi-channel deep seismic profiles. The seismic exploration identified huge amounts of sediment. The thickness of the Plio-Quaternary deposits is higher in the eastern part of the Black Sea basin, where the magnetic anomalies are also a consequence of the strong tectonism. In conclusion, the Black Sea is floored partly by stretched continental, and partly by oceanic crust with thick sediments on top.

The results clearly show that the Black Sea is formed by two deep basins separated by a regional ridge (the Mid-Black Sea ridge). In the deep Western Black Sea basin the seismostratigraphic reconstruction indicates that, on a substantially flat acoustic basement attributable to a basaltic layer, lies a very thick (over 14 km) strong reflecting sedimentary sequence, which started about 110 My ago (upper part of Lower Cretaceous) and continued until the present. In the Eastern Black Sea basin, the acoustic basement is not flat but is affected by tectonization and fault displacements, and is covered by a sedimentary succession which, very probably, commenced in the Middle Jurassic and continued until the present with a total thickness of about 13.5 km.

Observing and analysing the extension tectonics of the Black Sea margin and of the Mid-Black Sea ridge, it is possible to show that this region was affected by two main rift phases. The first, Middle Jurassic one, generated the Great Caucasus basin with a complete crustal opening of its axial zone. At the same time, the Black Sea area was stretched with the formation of an epicontinental sea and sea channels. The second much more important rift phase initiated in the upper part of the Lower Cretaceous, continued throughout the Upper Cretaceous, and terminated at the end of the Palaeogene.

During this last geodynamic process, the opening of the deep Black Sea took place as a consequence of the formation of two back-arc basins behind the western and eastern Pontides. The western Black Sea basin evolved to the stage of complete crustal opening with a basaltic basement progressively younger from the N (about 110 Ma) to S (about 55 Ma). At the same time, the eastern Black Sea basin evolved to the stage of a very thin continental crust affected by numerous listric faults and block-tilting.

The basin fill revealed by deep seismic consists of very thick Paleogene, mostly Eocene sediments with more than 3 s reflection time in the two deep basins, and more than 5 s in the foredeep of the Balkanides. The huge subsidence of the two deep Black Sea basins is mainly due to isostatic readjustment of the thick sedimentary deposition. In the eastern basin an important contribution to the subsidence was also the thrusting, especially of the eastern Pontides, where the collision of the Arabic plate has deeply deformed the area with strong restriction of the original wider Palaeogene basin.

On the origin and evolution of the Black Sea many are the hypotheses advanced. One group of hypotheses considers the Black Sea as an area of recent oceanization, consequent to important vertical movements and replacements of continental crust with oceanic-type crust.

A second set of hypotheses was formulated following the plate tectonic theory. Some authors considered the Black Sea to be the remnant of a Palaeotethys intervening between Gondwana and Laurasia. Successively, others supported the hypothesis that the Black Sea may represent the remnant of a back-arc marginal basin. The main differences in interpretation are in defining the age of the opening of the basin system.

The main submersion of the Black Sea basin started in the Palaeogene. The main Palaeogenic phases of the orogen essentially affected the Balkan - Pontides - Lesser Caucasus belt. These phases are superimposed upon previous palaeo- and meso-Alpine tectonic phases.

The Black Sea is an area of heterogeneous tectonic structural development. In its central part the infilling rock suite is directly underlain by thin consolidated crust, within which the "basalt" geophysical layer (western Black Sea basin) and the "basalt" and "granitic" geophysical layers (eastern Black Sea basin) are involved. On the periphery, the deep Black Sea basin complex overlaps the platform cover and complexes of Phanerozoic folded structures. The deep Black Sea

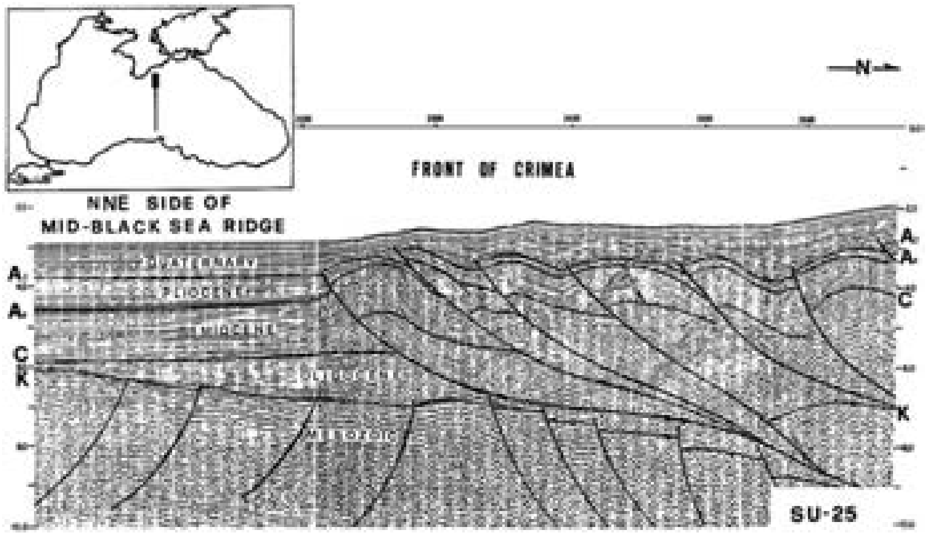

Fig. 15 - Example of interpreted seismic reflection line in front of the Crimean thrusts (Finetti et al.,1988).

basins are limited by continental buried paleoslopes and modern continental slope affected by flexure-rupture zones with evidence of erosion surfaces. The faults contributed to the present aspect of the magnetic anomalies.

Any correct interpretation of the Black Sea evolution must take into account the geological and structural characteristics of its margins, particularly the southern. Since Cretaceous times the entire Balkanide-Pontide system has represented the northern margin of the Neotethys, along which the northward dipping subduction took place. This margin had a complex history in part linked with the closure of the Paleotethys.

The present setting of the Black Sea represents the residual of an original sequence of basins formed during the Mesozoic by crustal extension, whereas the present Black Sea margins are the result of the compressive meso- and neo-Alpine events.

In conclusion, the Black Sea is formed by two back-arc basins which started to generate behind the western Pontides and eastern Pontides arcs about 110 My ago. They reached their maximum extent at the end of the Palaeogene (55 Ma), and successively were partially reduced: the western basin modestly by the Balkanides and Crimea, the eastern basin at a much greater rate by the eastern Pontides and Great Caucasus.

The seismicity of the Black Sea and surrounding areas can be summarised as follows:

- most of the investigated area is aseismic;
- the maximum seismicity is not related to the Black Sea but to well known regional fractures (North Anatolian Fault, Vrancea, etc.);
- the North Anatolian Fault is less active in its central sector and shows a periodic eastward migration of activity;
- the seismicity of the Black Sea s. s. is rather low and superficial (crustal, concentrated in the zone of Yalta, where epicentres mostly fall on the continental slope and near the coast of Turkey).

The north-eastern margin of the Black Sea is characterized by a broad shelf where thrust mechanism earthquakes occur. The focal mechanisms indicate reverse faulting with one of the nodal planes nearly parallel to the margin and compressional stresses acting perpendicularly to it. The extended and pronounced positive magnetic anomaly corresponds perfectly to the Shatsky Ridge (Fig. 14).

The southern margin, characterized by narrow, steeply deeping shelves, is nearly completely aseismic and seems to act as a passive margin. Indeed all the compressional stresses oriented from south to north are released by the intense seismic activity of the North Anatolian Fault or by local reactivation of thrust along the southwestern margin. The resulting picture of the stress field is consistent with the hypothesis that the Black Sea basin is a compressional depression whose oceanic crust is being overthrust by the Caucasian continental crust. This produces progressive loading on the oceanic crust which is sinking into the mantle. Thus the most tectonically active margins (deforming under compressional stresses) began under N-S compression to close the Black Sea basin (Fig.15). The low and poorly understood seismicity affecting the south-eastern part of the Black Sea may be produced by crustal breaking under a differential loading. This area is also strongly deformed by the presently active Alpine deformation, as it is located between the Carpathian deformation and the Anatolian Wrench Fault to the south.

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