From 2D Physiography to 4D Geodynamics: contributions of Deep Geophysics to the knowledge of the Earth's crust in the Mediterranean, and its evolution with special reference to the energy accumulations at the plates subduction zones

C. Morelli

D.I.C.A. - Dipartimento di Ingegneria Civile e Ambientale, University of Trieste, Italy

(Received July 19, 2005; accepted September 19, 2005)

ABSTRACT In the 1950's an important project for the study of the deep interior of the Earth through Applied Geophysics also started in Italy. Modern instruments and methods were developed, experimented and applied on land and at sea by University Institutes and a new, specially dedicated one (1958, Osservatorio Geofisico Sperimentale: OGS; now Istituto Nazionale di Oceanografia e di Geofisica Sperimentale). The initiatives attracted interest, cooperation and enthusiasm also in the European Community, with *e.g*. the creation of scientific societies like the European Seismological Commission (ESC, 1950). Under the ESC's umbrella, the Deep Seismic Sounding (DSS) started a program that produced the first knowledge that went down to the base of the crust (Moho) and revealed the overlapping of the Moho in the subduction zones. The extension to the sea was obvious as soon as the naval means and instruments became available (1960's), also favoured by the institution (1961) of the Intergovernmental Oceanographic Commission of UNESCO (IOC), of which Italy has been a founder and active member. One of the first realizations was the International Bathymetric Map of the Mediterranean (IBCM; 1:1,000,000, 10 sheets; 1963-1981) and its Geological and Geophysical series (Gravity anomalies, 1989; Seismicity, 1991; Plio-Quaternary, 1993; Unconsolidated Sediments, 1993; Magnetic anomalies, 1998). In the meantime, the need for new geophysical technologies to study the deep crust and to coordinate interpretations (to reduce the non-determination of the single methods), also brought Italy to promoting a new multidisciplinary *ad-hoc* program (CROsta Profonda, CROP; 1983-...), whose results are of paramount importance for the advances in geological and geophysical knowledge (advent of 3D and 4D tectonic interpretation). This turned out to be particularly useful for the Mediterranean area, where the land and sea geological conditions are tectonically connected and /or time dependent in their evolution. A few examples of results obtained after 50 years of international cooperation are illustrated for the Central Mediterranean area, where the interactions between three plates (African, European and Adriatic ones) accumulated high tectonic stresses particularly along the subduction zones, as revealed by seismicity. Indeed, in the Mediterranean the belts of potential instability along the actual subduction zones are clearly correlated with seismicity. The GPS preliminary results confirm the regional movements (due to plates actions) and the local ones (connected with local tectonics).

1. Introduction: genesis and evolution of deep crustal research

The geodynamics at the Earth's surface and the resulting environment are strongly influenced by variations in the physical and chemical conditions of the deeper crust and upper mantle. A knowledge of these conditions is therefore the necessary premise for understanding the effects of geodyamics.

Indeed, the upper crust (the rigid part) lies on the (viscous) lower crust: it is therefore, influenced by vertical and horizontal movements as the lower crust is deformed.

In the past century, geological sciences progressed rapidly as the surficial geology was described. However, an understanding of what happens at depth was only possible where deep materials could be studied at the surface (*e.g.* orogens). More recently, as geophysical methods (mainly gravimetric, magnetic, and seismological ones) became available, the depths could be probed.

Mineral exploration greatly improved *Applied Geophysics*, mainly in the exploration of sedimentary basins for petroleum. New experimental technologies and refinements in the interpretation, in connection with progressively deeper drill-holes for testing and industrial exploitation, allowed us to gain a good knowledge on the nature, composition, and development of the upper crust (down to depths of ~10 km, 15 km in the Kola super-deep drilling, and 12 km in the KTB drilling in Germany). Reflection seismic data have thus far allowed us to obtain excellent stratigraphic sections to a depth of ~10 km, with a detailed delineation of the seismic discontinuities and the seismic velocities in the intervals; potential methods such as gravity (see chapter 2.1) and magnetics have permitted the lateral extrapolation of the seismic results; and heat-flow measurements give knowledge about the thermal conditions, and their cause and effect useful for the understanding of the internal physical and chemical conditions and their variations. But recent Geodynamics (≤30 My) obscured all the areas south of the Alps with overthrusts by orogenic transports, centrifugal from the Tyrrhenian region; it is the input of the geophysical prospecting by ENI that permitted a revolutionary advancement of Geology and Tectonics to a depth of 8-10 km [Po Plain: Accademia Nazionale dei Lincei (1959) Pieri and Groppi (1981); Southern Italy: Mostardini e Merlini (1986); Aeromagnetic interpretation: Cassano *et al*. (1986); Northern Appennines: Cassano *et al*. (1996)].

But the application of any method of active geophysics also implies a degree of indetermination, especially when employed "at the limits". In particular, this is true when geophysics is employed to resolve deep crustal themes, without constraints and at a very heavy expense. The solution lies in the "integrated geophysical interpretation" where other geophysical information is available and used in the interpretation process (see chapter 6).

2. Potential methods

The main research programs have been:

2.1. Gravity (1948-1971)

After a careful study of the new instruments and a first survey of north-eastern Italy (1948), a cooperative survey led to the presentation of the first Bouguer anomalies map for Italy in 1963 (Fig. 1). Further, more elaborated editions at 1:500,000 to 1:750,000 scales were published up to 1975 (Morelli, 1975).

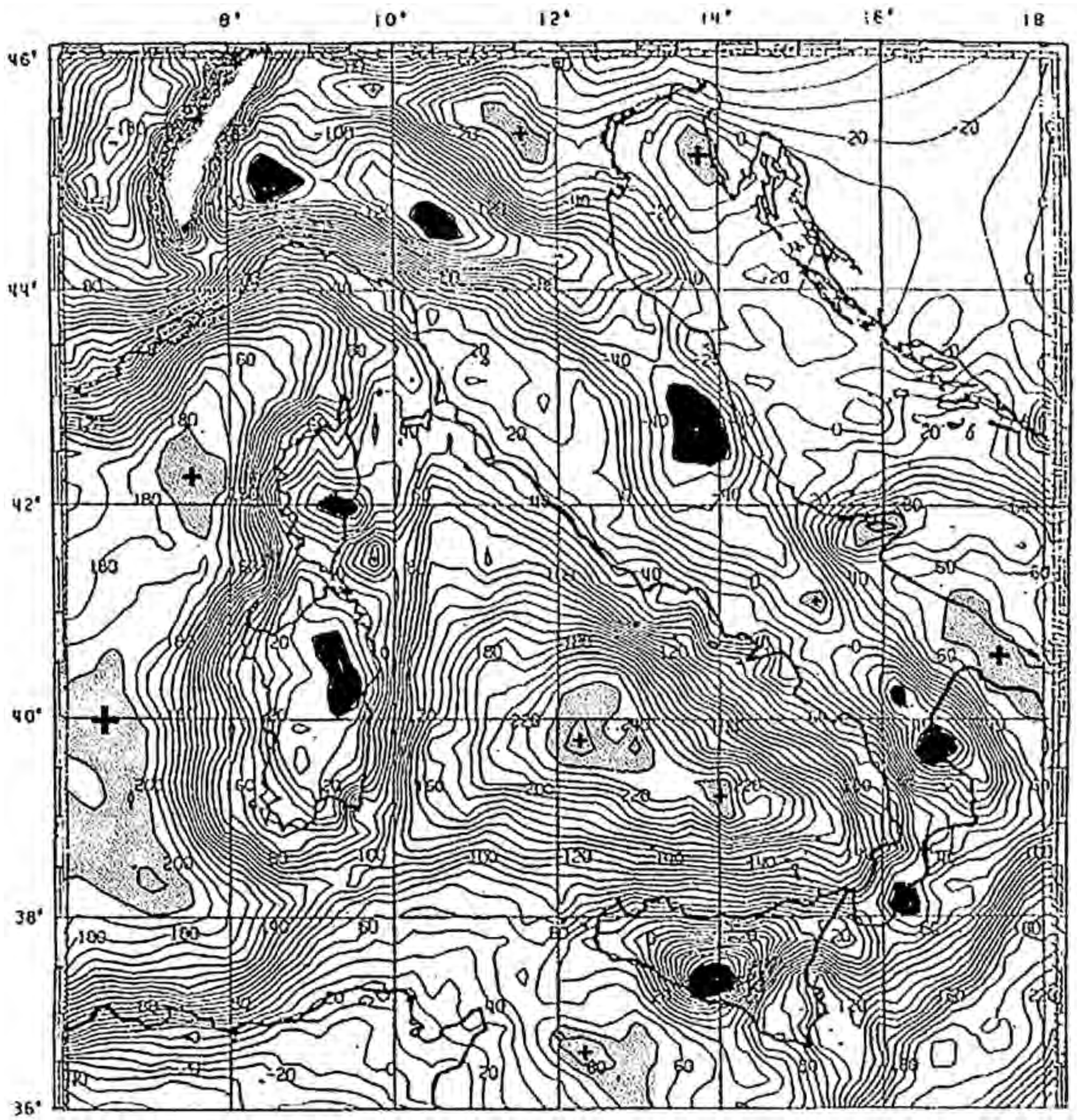

Fig. 1 – The Bouguer gravity anomalies in Italy (spacing 10 mGal); the lowest negative values in black.

The problem of calibration of the gravimeters was initially solved by comparing them to the European (pendulum) stations in the existing Potsdam System. The insufficient accuracy of the stations and the discovery (Morelli, 1946) of a (unacceptable) systematic error in the Potsdam value gave the input for a new project (1954-1971) in international cooperation between the countries with the pertinent modern instruments (123 gravimeters, 50 pendulums, and 11 absolute apparatus).

After years of measurements all over the world, of computations and adjustments, the new International Gravity Standardization Net [IGSN 71: Morelli *et al.* (1974)] was officially accepted

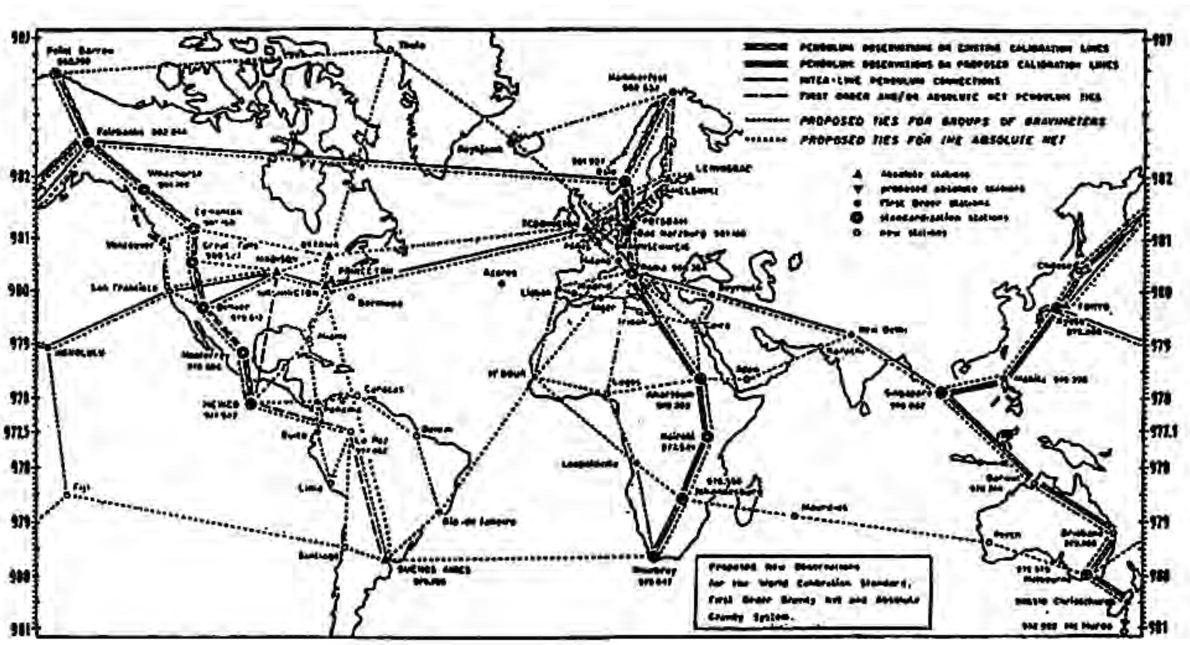

Fig. 2 – The International Gravity Standardization Net 1971 (IGSN 71).

by the International Union of Geodesy and Geophysics (IUGG) and is now also used all over the Earth for science and practice (Fig. 2). The precision of the IGSN 71 values increased all over the world from 10^{-5} to 10^{-8}, satisfying the needs not only in meterology as also in physics, geophysics, geology, volcanology and other sciences, but also as the basis for studies in physical geodesy, particularly the Earth's form (geoid), satellites motions, etc.

2.2. The Heat Flow anomalies

The Heat Flow measurements on land and sea were performed mainly with CNR's funds, and are published in the "Geothermal Atlas of Europe" (Mongelli *et al.*, 1991). They showed the presence of magmatic activity in all the extensional inner-arc Tyrrhenian (*sensu latu*) area; the ophiolites as an indicator of continental collisions; the extension of volcanic submerged provinces and geothermal areas on land and sea. This last point is very important and economically promising for Italy, particularly in the Tuscan geothermal area, where the very pronounced rise of the isotherms and the near surface lithological conditions (good permeability in fractured rocks, under impermeable cover) can be widely followed in a seismic "hot spot" (Horizon K) around the present exploitation area (see also chapter 5.).

3. The Deep Applied Seismic methods

3.1. Deep Seismic Refraction (DSS; 1956-1986)

The last statement of the Introduction is particularly true in the interpretation of potential fields (gravity and magnetic anomalies), that require constraints usually offered by surface geology or drilling (for surficial targets) or seismic data (for deeper ones). So Deep Seismic

Soundings DSS is usually the seismic solution, since it provides the velocity of the seismic waves at depth (from which density can be derived), and the position of the seismic discontinuities that separate the different geological situations. Started in the Alps in 1956, DSS profiles are now used all over the world. In the Mediterranean, the Osservatorio Geofisico Sperimentale (OGS) of Trieste collected 21.160 km of DSS profiles from 1960 to 1982 (Fig. 3), with outstanding results regarding the crustal composition and thickness, discontinuities, subduction, delamination, etc.

The DSS data have been digitized (when necessary) and revised at INGV-Milano (e-mail: maistrello@mi.ingv.it). For the more extended and rational use of the DSS data, especially for the seismic tomographic studies, the 419 DSS seismic sections were revisited and inserted into a parametric data base (e-mail: luciana.deluca@idpa.cnr.it).

Up to now, the only important parameter that DSS profiles have confirmed with certainty is the *crustal thickness* (Fig. 4). For the normal continental crust this is 30 km (Adriatic promontory

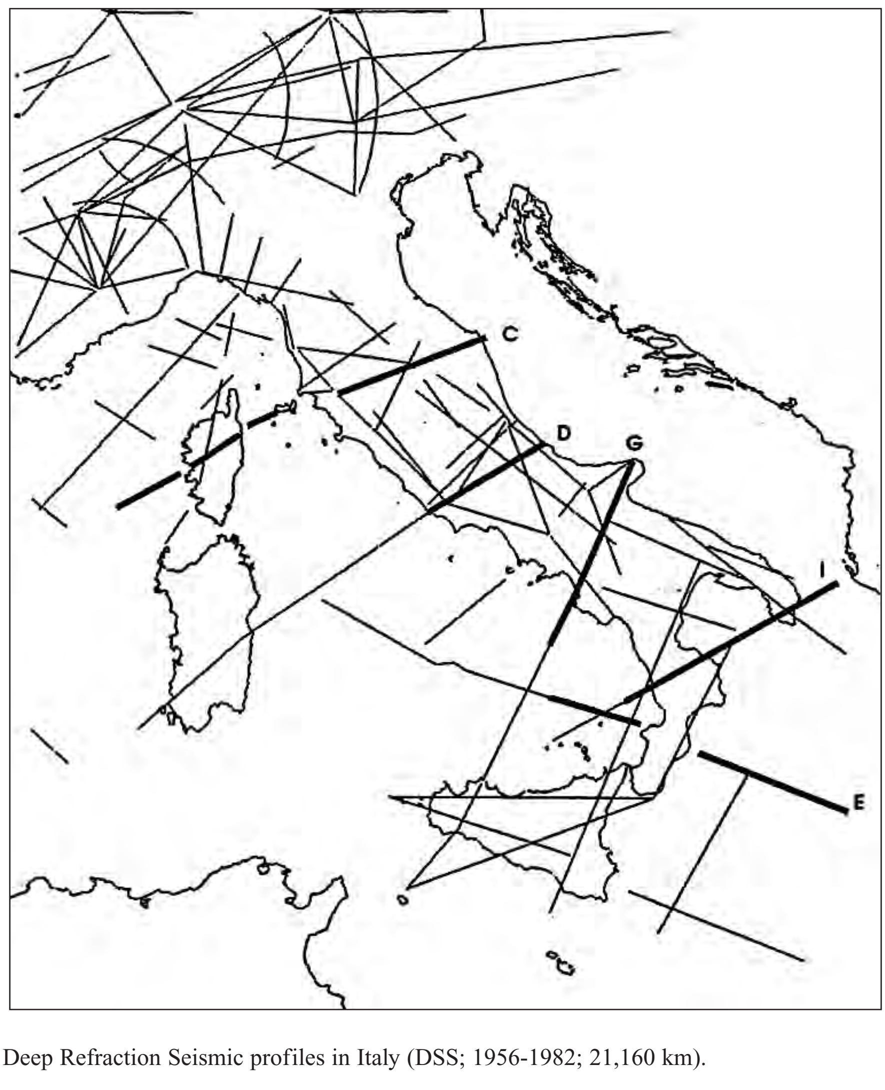

Fig. 3 – The Deep Refraction Seismic profiles in Italy (DSS; 1956-1982; 21,160 km).

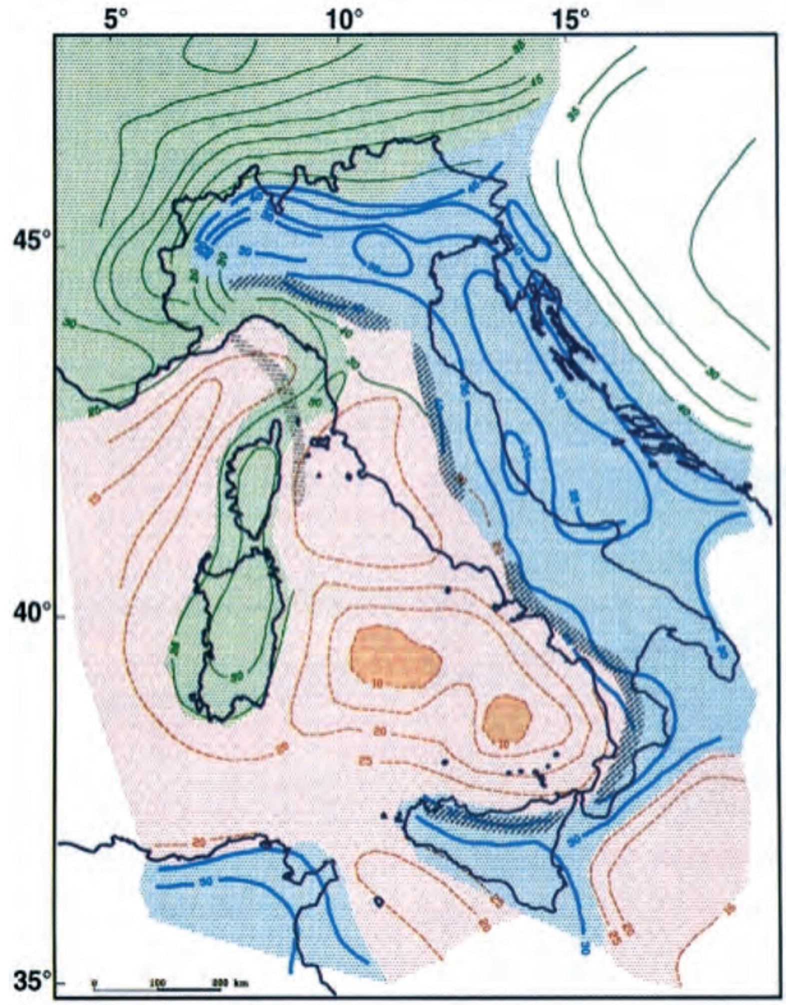

Fig. 4 – The Moho isobaths (equidistance: 5 km) and the different crusts (Nicolich and Dal Piaz, 1991).

and Sardo-Corso block). It is thicker in the orogenic areas (Alps: 70 km, Apennines: 40 km), thinner in the extensional areas (Tuscany and Tyrrhenian peninsula: 20-25 km) and in the rifting areas (Ligurian Sea, Strait of Sicily); and can become very thin (8-10 km) in the oceanic areas (SE Tyrrhenian Sea, Ionian Basin). Moreover, repeated relict subductions of the European crust beneath the Adriatic could be recognized under the thin Northern Apennines and the Ligurian Sea Adriatic crust, whereas the subductions of the Adriatic continental crust are under its thinner part in the Central and Southern Apennines.

Other characteristics revealed by the DSS integrated profiles from the seismic P-velocities in the pertinent crustal layers, that are particularly important are some crustal discontinuities, one of which is the Conrad Transition, which is the transition between the ductile Lower Crust (T>400°C, v=6.7-7.4 km/s) and the rigid Upper Crust (T<400°C, v=6.0-6.4 km/s; Fig. 5).

The input to experimental seismeis through the big explosion program DSS was one of the first initiatives of the European Seismological Commission (ESC). The Sub-Commission for Southern and Western Europe programmed cooperation projects every year, with progressive increase in the number of partecipants, instruments and technology. Till the 1980's almost all the

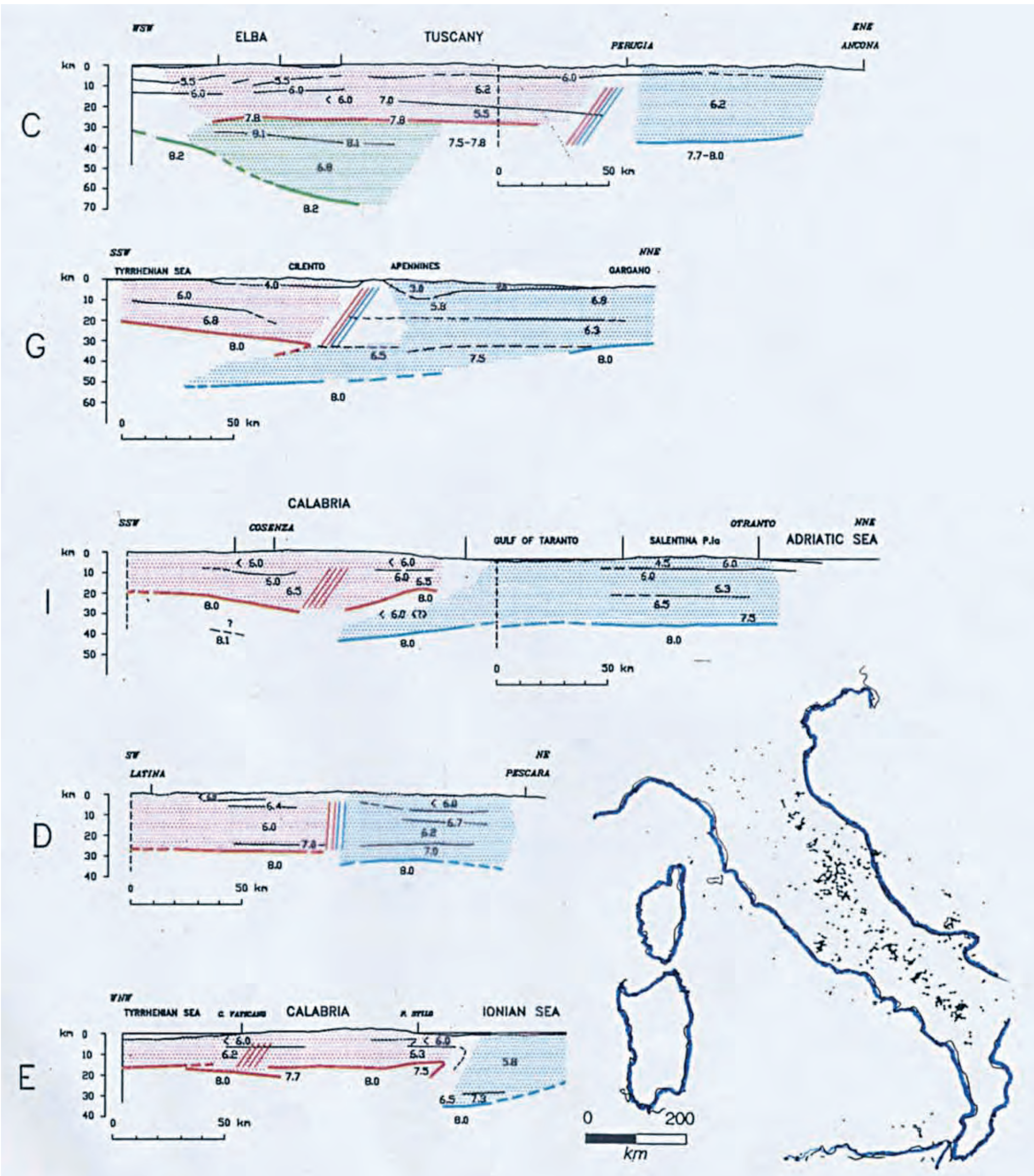

Fig. 5 – Sections C-I of Fig. 3 transversal to the Apennines with the main discontinuities (P-velocities in km/s). The seismicity indicated in the bottom right corner represents the 600 largest events1986-1993) revealed by travel time tomography (Chiarabba and Amato, 1996).

quantitative knowledge on the deep crust in Italy was known from DSS (Morelli, 1993; Scarascia *et al.*, 1994).

In addition to the paramount importance of the velocities accuracy increasing for the focal coordinates determination in Seismology, the knowledge of the discontinuities (Fig. 5) will allow the rational control and interpretation of the focal distribution (see Cassinis and Solarino in this volume): that is of the Seismotectonics (see chapter 5).

3.2. The NVR Deep Reflection Program (CROsta Profonda = CROP; 1983-...)

Deep Reflection Seismics of the COCORP type started in Italy in the frame of the CNR's Gruppo Nazionale di Geofisica della Terra Solida (GNGTS), in agreement with the CNR Committee for Geological Sciences (1983). A joint Commission of geologists and geophysicists devoted the whole of all 1984 to selecting a series of deep seismic reflection profiles interacting with the principal geological themes of the Italian land and sea areas.

In the first executive phase (1985-1988) priority was given to collaboration projects with countries having a border in common with Italy. The first, was the French project ECORS for a common profile on the Western Alps, from Torino to Geneva (1986). Between four different proposals made by a French-Italian ad hoc group, in 1985 the choice fell on a Wide Angle (WA) seismic reflection experiment which was done in the proposed area. In addition to having made the most appropriate choice of the profile, the results demonstrated that without them the interpretation of the profile would have been impossible. Since then, all the CROP profiles have been joined to ad hoc-projected WA seismics, with irreplaceable results.

The program continued in 1987-1988 with a Swiss-Italian study of the Central Alps. From 1989 to 1999, in collaboration with AGIP and ENEL, 1454 km of land profiles and 8300 km of sea profiles were performed in Italy; in 1999-2000, the Transalp Munich-Conegliano profile was made in collaboration with Germany, Austria, and Italy (Fig. 6). The processing and interpretation are under way; an Atlas was published in 2002 and can be requested from Secretariat of IGG in Pisa (e-mail: innocenti@igg.cnr.it).

The extreme difficulties and the drawbacks that led to the late publication of the CROP-04 results are integrated by ad hoc DSS measurements, which, as already mentioned, are imperative constraints for the interpretation.

Another type of blindness obscures the penetrability of the geophysical methods: *e.g.* it is indeed well-known that until a few decades ago the at-depth geological knowledge in Italy was completely obscured by the colossal (in thickness and extension) overthrusts of Tyrrhenian (*sensu latu*) origin, which radially and progressively (starting from ~36 My) covered all the Apenninic and retro-arc areas (see chapter 5.1). In particular, reflection seismics, the most powerful prospecting method, was not applicable in these areas for a long time.

It was only in 1996 that the results of an ad hoc study by an AGIP team was published (La Bella *et al.*, 1996), where it was recognized that the bad quality of the seismic response was mainly caused by the superficial geological conditions: extremely variable topographic and lithological ones, with strong velocity variations in the sub-aerated layer. When these difficulties were overcome with 3D seismics, reliable results were also obtained in mountainous areas. In Basilicata (Southern Italy), the Val d'Agri oil field was thus discovered, which actually later became one of the most important in Europe.

Fig. 6 – The Near Vertical Seismic Reflection CNR Project "CROsta Profonda" in Italy (land: 1450 km, 1996-2004; sea = 8700 km, 1991-1996).

Results from extended Near Vertical Seismic Reflections (NVRs) offer good constraints for other geophysical and geological data. Integrated interpretations outline the main tectonic features (Fig. 7).

Particularly important for geodynamic relations are the results from profiles CROP-03 (Pialli *et al.*, 1998) and CROP-04, indicatives of:

- the subduction towards the west of the Adriatic plate and towards SE of the European plate (see C and G in Fig. 5);
- the huge load of the overthrusts of Tyrrhenian origin in the duplex of Fig. 8.

In addition, the special Flexotir marine seismic (MS) surveys covering some 39,500 km, performed by OGS from 1969 to 1982, provided some very important constraints especially to the IBCM-PQ compilation (Fig. 9; see chapter 4.1.4; the data are available at OGS).

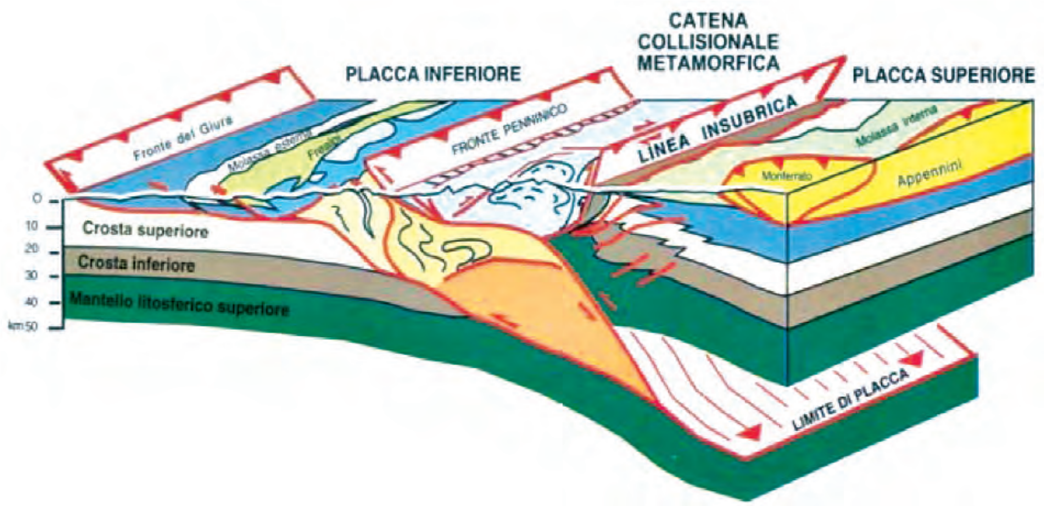

Fig. 7 – Geological – geophysical 3D-Section across the Western Alps CROP – ECORS Profile (revision Dal Piaz, 1997).

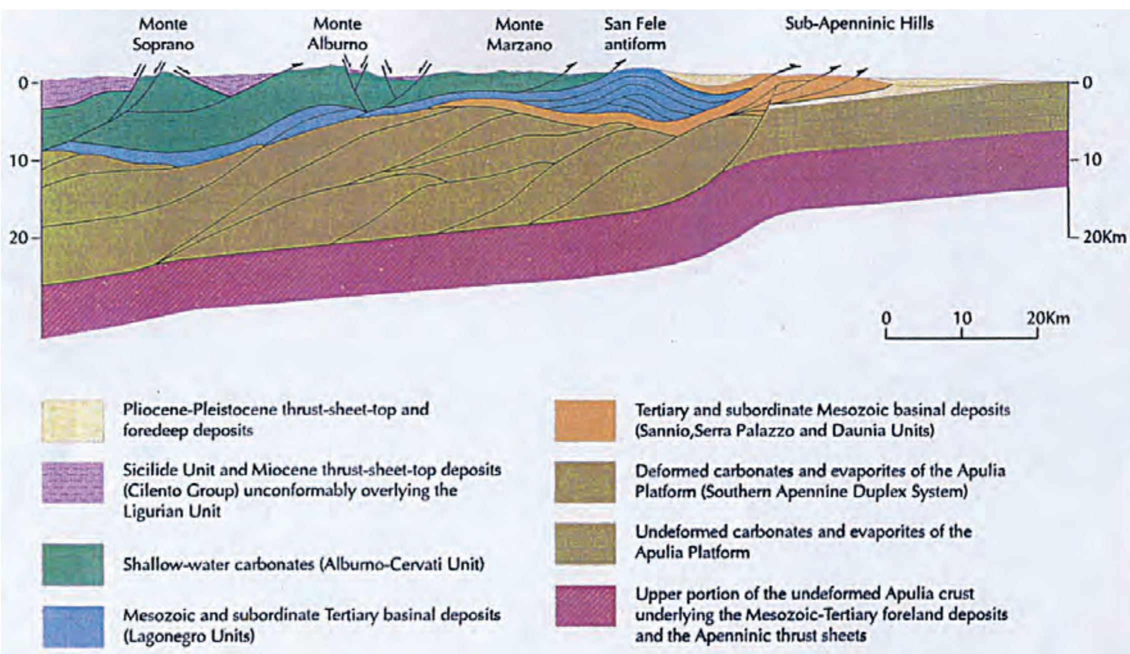

Fig. 8 – Schematic geological section across the southern Apennines along the trace of the seismic line CROP-04. Important is the continuation to a depth of 25 km of the upper portion of the undeformed Apulia crust underlying the Mesozoic-Tertiary foreland deposits and the Apenninic thrust sheets (Mazzotti *et al.*, 2000).

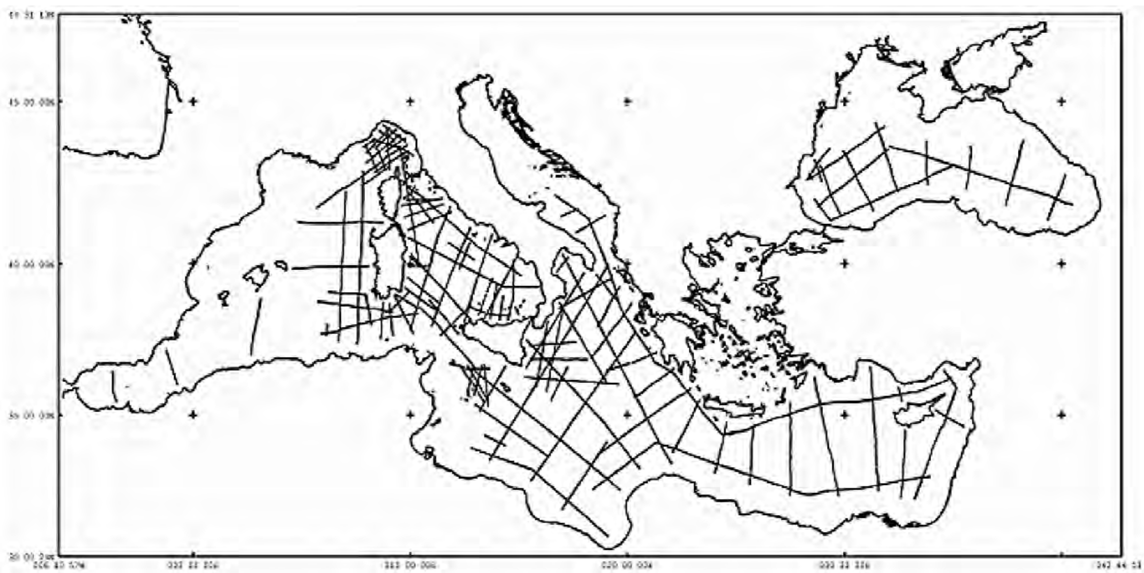

Fig. 9 – The OGS Flexotir profiles (MS; 1969-82; 39,500 km).

4. The International Bathymetric Chart of the Mediterranean (IBCM) and its Geophysical-Geological Series (1961-2004)

Till 1960, even the (deep) bathymetry of the Mediterranean was generally unknown. In 1961, Saclant ASW – La Spezia invited OGS to partecipate to their cruises (bathymetry and geomagnetism), mainly in the Tyrrhenian Sea with a surface ship gravity-meter on a stabilized platform. At the end of the common surveys (1961-1965; 12,000 km), OGS continued alone (1955-1972) on the new CNR's ship Bannock, properly equipped (from 1963) also for echo-sounding, geo-magnetism and Loran C. The regional survey of the Western and Central Mediterranean was performed [217,000 km: Morelli *et al.* (1975a, 1975b, 1975c)]. East to 23° E, the survey was completed by the Department of Geodesy and Geophysics, University of Cambridge (220.000 km) in 1971-1974 (Fig. 10).

With data contributions also from research institutions and private companies, and after 20 years of collaborative work of ad hoc international group, the IBCM (scale 1:1,000,000, 10 sheets; size 4.20 x 2.40 m) was published in 1981 by the Head of the Department of Navigation and Oceanography of the Russian Federation's Navy, St. Petersburg. The new physiographic results formed the basis for compilations of the most pertinent geophysical and geological data (Morelli, 1993).

4.1. The IBCM Geological – Geophysical Series

Indeed, to better understand the important physiographic results (2D), the tectonics and the geodynamics of the area, IOC, with OGS and other Institutes published contributions to a Series of Geophysical-Geological thematic maps as reported in Table 1.

Table 1 - The IBCM maps.

Theme (and publication year)		Illustr. explan. broch.	Bibliography
bathymetry (physiography)	**IBCM** (1981)	**1**	**IOC**-1988; reprint 1997
gravity anomalies	**IBCM-G** (1989)	**2**	**BGTA**: 39, 74/98, 1998
magnetic anomalies	**IBCM-M** (1998) **-M rev.**	**6** **6 bis**	39, 1/36, 1998 41, 79/83, 2000
seismicity	**IBCM-S** (1991)	**3**	40, 79/146, 1999
Plio-Quat. thickness	**IBCM-P/Q** (1993)	**4**	39, 243/284, 1998
unconsol. sedim.	**IBCM-Sed** (1993)	**5**	**Emelyanov** *et al.* (2005)

They offer important constraints and through integrated interpretations outline the main tectonic features (3D) and geodynamic evolutions (4D).

Each map is accompanied by an explanatory brochure (IBCM-S also by a catalogue; on request from OGS). They can be obtained (when available, also in digital form) through the Ocean Mapping, IOC, 75732 Paris. A photographic reduction at a 1:5,000,000 scale is also available.

All the data are deposited in pertinent databases, and properly updated (digitized) when necessary. Details on the voluntary contributions, fall-outs, and benefits of each map are given in the following sub-sections.

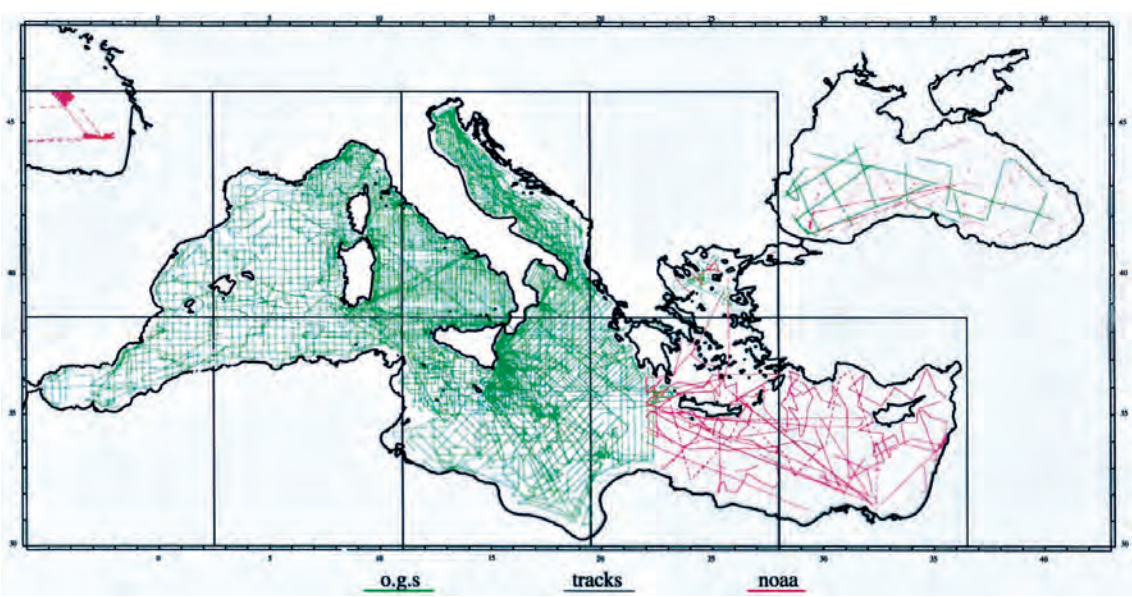

Fig. 10 – The profiles of the International Bathymetric Chart of the Mediterranean (IBCM: Bathymetry + Gravity + Geomagnetism; IOC, 1981).
Saclant + OGS (1961-1965: 112,000 km); OGS (1963-1972: 217,000 km); Univ. Cambridge (red: 1971-1974: 220,000 km); Total: 550,000 km.

4.1.1. IBCM-G (Bouguer Gravity Anomalies)

OGS extended the land-gravity measurements to cover the sea in 1958, using a surface ship gravity-meter during an experimental survey on the Italian Navy's hydrographic ship "Staffetta". As said, these surveys continued from 1961 to 1965 on the ships "Aragonese" and "Maria Paolina" in cooperation with the NATO SACLANT Center, and were then extended in 1966-1972 over all the Mediterranean (up to 23°E) on the CNR ship "Bannock", together with total field magnetic measurements). Eastwards the survey was completed by British ships operated by Cambridge University (Fig. 10).

The gravity data, in digital form, are deposited at the Bureau Gravimétrique International, 18, Avenue Edouard Belin, 31401 Toulouse Cedex 4, France (Fax +33.5.61.25.30.98; http://bgi.ines.fr:8110/) and can be obtained on request.

The results of these surveys were integrated with those obtained on land (Fig. 11), and thus strengthened the tectonic and geodynamic interpretations. E.g., main results in the Central Mediterranean area are (Fig. 4):
- the thickness of the crust: continental on land (30-35 km) only in correspondence to the residuals of the European crust (Sardo-Corso block) or the Adriatic microplate;
- thicker in compressional continental zones (Apennines, 40 km; Alps doublings, 70-80 km);
- thinner in the distensional zones (15-25 km: back arc Tuscanian – Latial crust) or even in the oceanic one (8.0 km, Central and SE Tyrrhenian);
- the existence of sedimentary basins all over the Apenninic foreland from the Po basin to Sicily (see also Fig. 1).

The gravity reference values in the harbours could benefit from the International Gravity Standardization Net (IGSN 71; Fig. 2), newly adopted (International Association of Geodesy, Special Pubbl. n. 4).

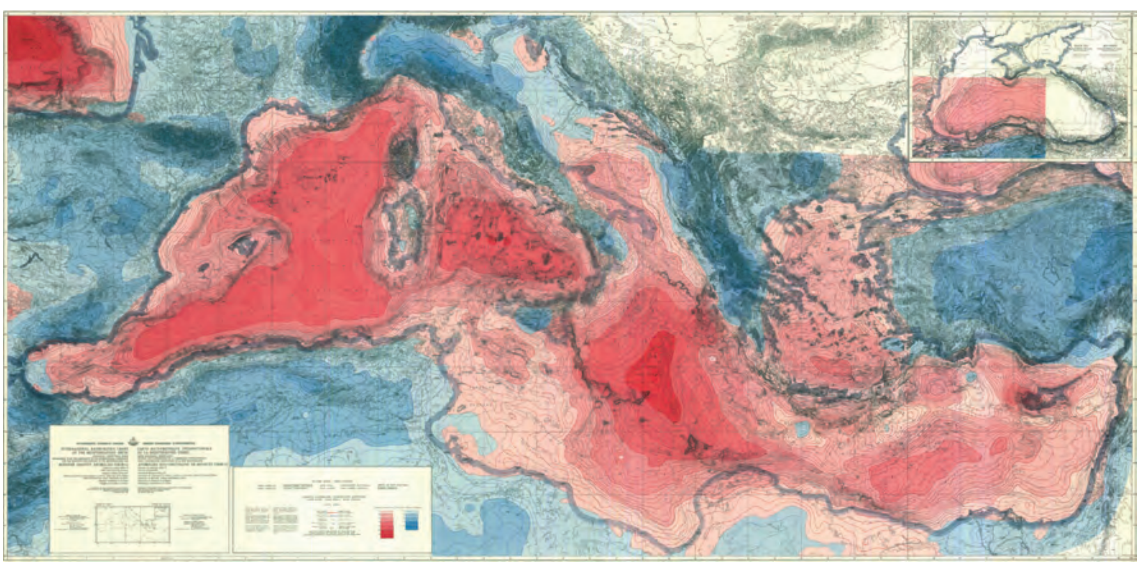

Fig. 11 – The Bouguer gravity anomalies map IBCM-G (equidistance 10 mGal; 1989).

4.1.2. IBCM-M (Magnetic Anomalies)

A few examples are mentioned from the results of the marine magnetic surveys of the Mediterranean Sea. In the Eastern Mediterranean, a remnant of the Paleo-Tethys, regional, mainly negative magnetic anomalies give an inverse magnetization to the old oceanic crust, which is deeply buried under thick sediments (10-12 km). In the Western and Central Mediterranean the magnetic anomalies are mainly bipolar, caused by magmatic bodies in, or over, a recent thin crust mostly fractured by extension (Oligocene in the Western Mediterranean, to very -Recent in the Central Mediterranean). Very strong magnetic anomalies due to the ophiolites define the southern continuation of the Africa-Europe contact in the Ligurian-northern Tyrrhenian Sea, in the arcs of the Eastern Mediterranean, and in the main fault systems (*e.g.* Malta Escarpment). Local magnetic anomalies connected with extensional tectonics exist in the thinned continental margin west of Sardinia, in the Sicily Strait, and in the Aegean Sea. Spreading magnetic anomalies are connected to Miocene to Pliocene rifting in the Tyrrhenian and Ionian Seas (see also Fig. 13).

The results of the magnetic studies were also particularly pertinent the indication of volcanic intrusives in the sedimentary upper crusts; the extension of the sedimentary basins (particularly along all the external front of the-Appennines, from Piemonte to Sicily, and on the Nile and Rhone deltas); the upheaval of the lower crust and upper mantle; and crustal openings, etc.

The undetermind nature of interpretations based upon potential fields (*i.e.* gravity and magnetic anomalies) requires constraints that are usually provided by surface geology or drilling (for near-surface targets) or seismic data (for deeper ones; see chapter 5).

Usually these constraints are provided by seismic methods, as they offer the velocity of the seismic waves at depth (from which density can be derived), and the location of the discontinuities that separate the different geological horizons or bodies (Fig. 5).

The extensive work of observing, processing and presenting the gravity and magnetic anomaly data, integrated with other geophysical and geological data, led to a summary of the very complex tectonic evolution of the Mediterranean area within the general framework of the oblique collision between Africa and Europe (see chapter 6).

4.1.3. IBCM-PQ (Plio-Quaternary Sediments)

Compilation of a map of the thickness of the Plio-Quaternary sediments was started in 1981 by E. Winnock, a geologist at Elf-Aquitaine. After his death in 1985, his work was continued with a large contribution from GEMCO (Groupe d'Étude de la Marge Continentale et de l'Ocean), a research unit associated with CNRS (URA 718) at Villefranche sur Mer and Paris VI. Messrs. E. Tzotzolakis, F. Burollet, and P. N. Kuprin were also major contributors. Russian geologists provided coverage for the Black Sea and contributed much for the Levantine Sea. Seismic surveys used in this mapping were mainly carried out by oil companies (CFP-Total, Elf-Aquitaine, AGIP), some institutes (IFP, OGS - Trieste) and universities (Villefranche sur Mer, Paris VI, Bologna). Generally, the Mio-Pliocene boundary is well-defined, on the continental slope by aerial erosional surfaces, and in the deep parts of basins by the high reflectivity of the Messinian salt deposits. As previously emphasized by D.J. Stanley, the compiled map clearly shows that the distribution of Plio-Quaternary sediments results from two major factors, high rates of alluvial deposition near the mouths of large rivers and/or compressive and overthrusting movements. Thus the Danube-Dnieper, Nile, Rhone, and Ebro submarine deltas are the largest accumulations of terrigenous, principally turbiditic, sediments. Elsewhere, post-Miocene compressive tectonics explains Plio-Quaternary sediment thicknesses, as in southern Sicily and more specifically in front of the northern Apennine range (Fig. 1). By contrast, in the young back-arc basins like the Tyrrhenian and Aegean Seas, irregular topographic relief induces a very complex and sparce Plio-Quaternary sedimentation. The Black Sea is probably also an old back-arc basin, whose Plio-Quaternary sediment thickness reaches 4 km and whose NE margins are presently affected by strong compressive movements. The information on the origin and nature of the colossal overthrusts covering the Italian Peninsula are of paramount importance to Science and (the oil) Industry (Fig. 8).

4.1.4 MS (1969-82; 39,000 km)

For calibrating the IBCM-G, -M and P/Q results and interpreting the DSS profiles at sea, OGS carried out the formerly-mentioned Flexotir special survey of regional marine seismic profiles with the CNR's ship "Marsili", equipped with a seismic recorder DFS (Texas Instruments), a neutral buoyant streamer (24 traces, 2400 m long) and two IFP Flexotir guns. The MS-profiles (Fig. 9) provided not only detailed sections for the upper strata, but also the initial information for the deeper part of the crust in all the Mediterranean area.

4.1.5. IBCM-S (Seismicity)

To produce a map of seismicity, one has to place symbols representing earthquakes occurrences on a geographically based map. Current practice is to assign attributes to the epicenter, according to earthquake parameters, such as focal depth, magnitude, etc., and to draw a symbol centered on the earthquake epicenter's map location. The symbol itself varies in size, shape, ornamentation, color etc., according to these parameters. The chosen base map was naturally the IBCM bathymetric chart. Ideally the epicenter data set should have been worked out specifically for that purpose, with one record per physical seismic event, and parameters

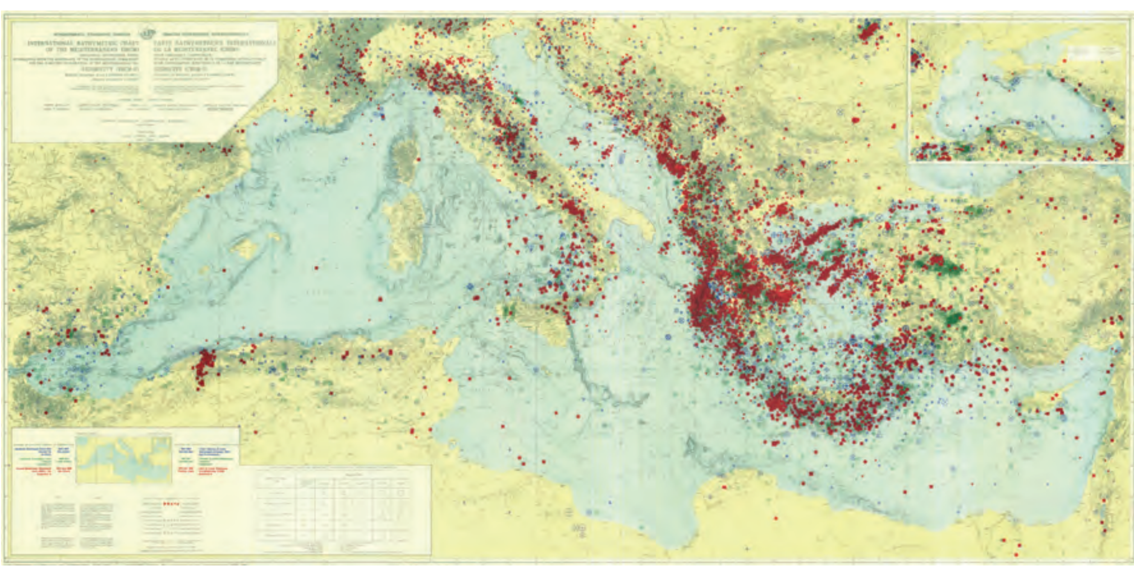

Fig. 12 – The seismicity map for the Mediterranean area (IBCM-S; 1991).

estimated/computed through a homogeneous procedure. Unfortunately, this was clearly impossible, as no general earthquake database had yet been established for the Mediterranean and its surroundings. A decision was therefore taken to rely on data sets which effectively ruled out non-instrumental seismicity data (most often called Historical Seismicity) easily accessible to users.

Beginning in 1976, the European-Mediterranean Seismological Centre (EMSC) in Strasbourg computed and disseminated earthquake locations (epicenters and focal depths) in a homogeneous manner. Although EMSC has not determined earthquake magnitudes, but has simply reported estimations made by other institutions, the EMSC data set's homogeneity was considered of primary importance, because earthquake location is the most important parameter. For the instrumental period before 1976, the data set chosen was the earthquake catalogue published by the International Seismological Centre (ISC). This catalogue often reports several determinations of an earthquake's parameters issued by different institutions, together with the ISC's own determination when computed (from 1964 on). A careful analysis of the ISC's data set was conducted in order to unravel its intimate characteristics. A rationale was finally developed to select which of the parameters to adopt, so as to end up with a final data set showing one determination for each physical seismic event.

Data on 33,000 earthquakes for the period 1904-1998 was compiled by EMSC (Fig. 12) after necessary and exhaustive studies on the philosophy for handling data of different qualities. The results have found innovative application in plate tectonics, neotectonics, and related problems.

4.1.6. IBCM-SED (Unconsolidated Sediments)

Compilation of the IBCM-SED map was entrusted to Dr. Prof. E.M. Emelyanov and K.M. Shimkus of the USSR by the IBCM Editorial Board, with the participation of Dr. I.S. Chumakov (1980-1982) and later Dr. Prof. P.N. Kuprin (Emelyanov *et al.,* 2005). Work on the map began in 1980 with requests to scientists in other countries for sedimentary data contributions. Collection of this data progressed very slowly, due, in large part, to the isolation of the principal investigators. A considerable amount of time was devoted to adopting a legend for the map, especially in the choice of a classification for the bottom sediments according to their grain-size composition. The legend suggested by Emelyanov, Shimkus and Kuprin in 1986 was accepted.

The map gives, in a general way, a maximum amount of information about the composition, genesis, and grain-size of the recent layer (upper 5 cm) of sediments. It was very important to arrive at a common classification for both the shallow water and deep sea sediments. In the past, and at present, both types have been mapped according to different principles of classification. The first priority was to eliminate these differences in interpreting the sediments of the Mediterranean and the Black Seas. The authors' new legend helps to solve these problems and ease the difficult and, in some cases, impossible task of comparing the rapidly increasing volumes of new data, especially for the nearshore areas.

After detailed comparative studies on the basically different western and eastern sedimentological classification schemes, a Unified International Scale was adopted, so that the explanatory chapter on IBCM-SED represents a practical treatise on modern sedimentology. Indeed, the contents are wide reaching: after illustration of the basis and the characteristics of the maps and the main features of sedimentation, of the distribution and the composition of the sediments, details are given on the lithological-geothermal zones of sedimentation and facies of sediments, the effects of river drainage, and technogenous pollution. A discourse on the uses of the map and an extended list of references makes the explanation very practical.

In addition to the studies related to the sea bottom, the results are of paramount importance for most of the problems related to the physical and chemical history and evolution of the bottom and water circulation, fluids and energy transfer; but also technical ones such as sound propagation.

4.2. IBCM-II (digitized)

The first phase of the IBCM project has been drawn to a successful conclusion, but the demand for more accurate data is increasing progressively for a variety of scientific, economic, and social purposes. Mindful of the technological changes that have taken place since its inception, it is planned that the second phase of IBCM will incorporate radical new designs in terms of its presentation and resolution. This product, IBCM-II, will be an experimental prototype and will be based entirely on a digital database (Fig. 13). The nature of the database will be raster (a Digital Terrain Model or DTM), consisting of gridded seamless data for land and sea on a 0.1’ grid (185 m or less depending upon the latitude).

At its meeting in Monaco (April 12-14, 1999), CGOM examined the above proposal for the IBCM-II prototype and its guidelines, and saw in it an innovative step, which may hold promise for the future. The 11th Mediterranean Black Sea Hydrographic Commission (which met in Split

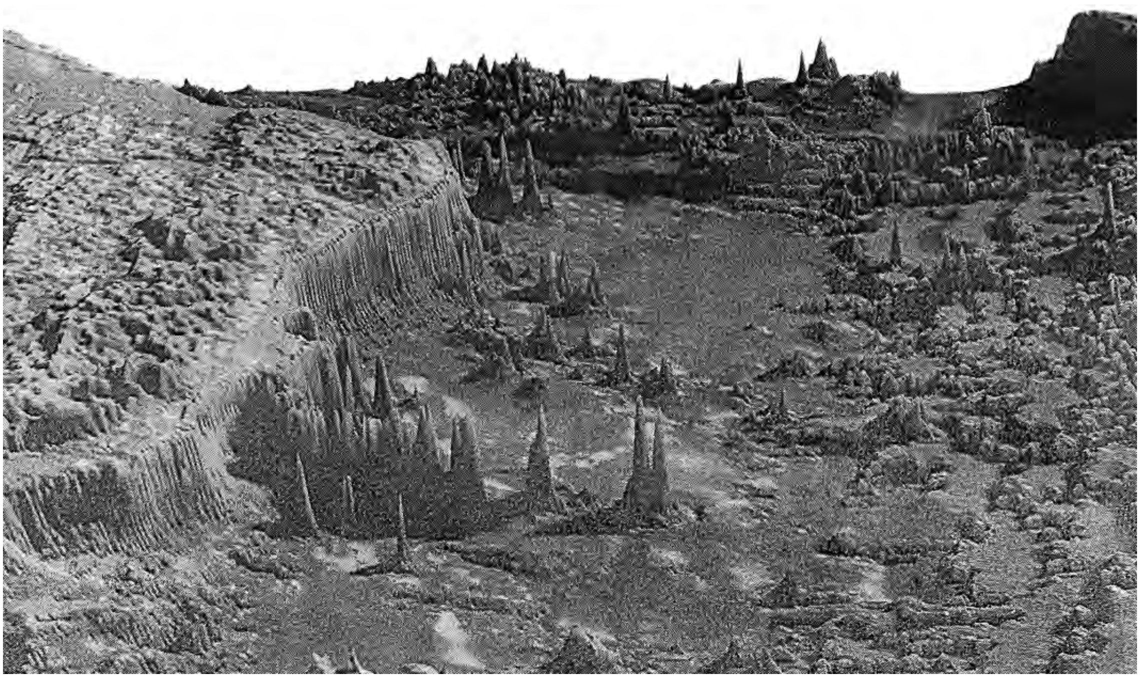

Fig. 13 – Virtual 3D example for IBCM II.

June 7-11, 1999) accepted these guidelines, and issued its Decision 10, inviting the Voluntary Hydrographic Offices (VHOs) concerned to provide releasable data for the compilation.

Needless to say, within IOC and other interested organizations, the IBCM-II will, like the IBCM-I, be at the disposal of the various IBC programs now being developed in different parts of the world, which are:

IBCWP - Western Pacific	IBCCA - Caribbean and Gulf of Mexico
IBCAO - Arctic Ocean	IBCEA - Central Eastern Atlantic
IBCSEP - SE Pacific	IBCWIO - Western Indian Ocean
In preparation:	IBCSO - Southern Ocean (Antarctic).

5. Some benefits for the understanding of the tectonic evolution in the Central Mediterranean

5.1 From the "Alps" and "Apennines" orogens to the Alps-Apennines System

Historical Geology began in the Alps (notwithstanding the strong logistical difficulties). The collision of the African Plate with Europe that formed the Alps (with subductions and indentations) also brought to the surface parts of the deep Earth's crust and mantle that were later on modified by erosion. Especially in the post-glacial periods (the last one: 70,000 – 11,000 years BP) the melting of the glaciers produced heavy erosion and upheaval.

On the other hand, the Apennines were formed more recently (mainly between 15 and 5 My BP). However, although less elevated and more accessible than the Alps, their study and interpretation was made much more difficult due to interactions between the two plates, subsequent to, and as a result of, the Alpine Orogeny. These interactions produced overlapping orogens "transversal" to the actual Italian Peninsula, active at different times and with different intensities, on the actually subducted area between the Sardinia-Corsica Block and the Balkans.

The opening of the present Mediterranean (after the closure in the Cretaceous due to the African-European collision) started (Fig. 13) with the back-arc of the Provençal Basin associated with the subduction of the African margin beneath that of Europe. The advancement of the European margin towards the SE produced the strong orogenic thrusts and the rifting of the seafloor that is summarized in Table 2 (Bigi *et al.*, 1990).

Table 2 - Advancement of the European margin

Age (My)	Late Orogenic Transport	Opening (Basins)	Directions
40		Western Mediterranean	Western Corsica
	North African Foreland		Eastern Sardinia
19			
19	Western Maghrebides	South Balearic	S
7	Dinarides		SW
	Southern Alps		S
5.3	Alps		W to NW+N
5.3	Eastern Maghrebides		SSE
	Calabria	Southern Tyrrhenian	SE
	Apennines	Southeast Tyrrhenian	NE
0	Eastern Alps		S

The above-mentioned orogenic belts are clearly connected with the openings of the back-arc Tyrrhenian and Ligurian Basins revealed by the positive gravity anomalies (Fig. 1) and the thinned oceanic crust (Fig. 4). The stretching and folding of the crust in the mentioned basins are clearly reflected in the intense volcanic activity in the Neogene revealed by the detailed aeromagnetic survey by AGIP in 1986 (Fig. 15).

During the Neogene, the Apennines continued to move radially towards NE, east, and SE (Fig. 16), with an accretionary wedge and an elevated internal ridge in an extensional regime. This built up the sediments on the Mesozoic passive continental margin of the Adriatic Microplate, that are revealed in the series of negative gravity anomalies all over the external Apenninic Arc from the Po Plain to Sicily (Fig. 1).

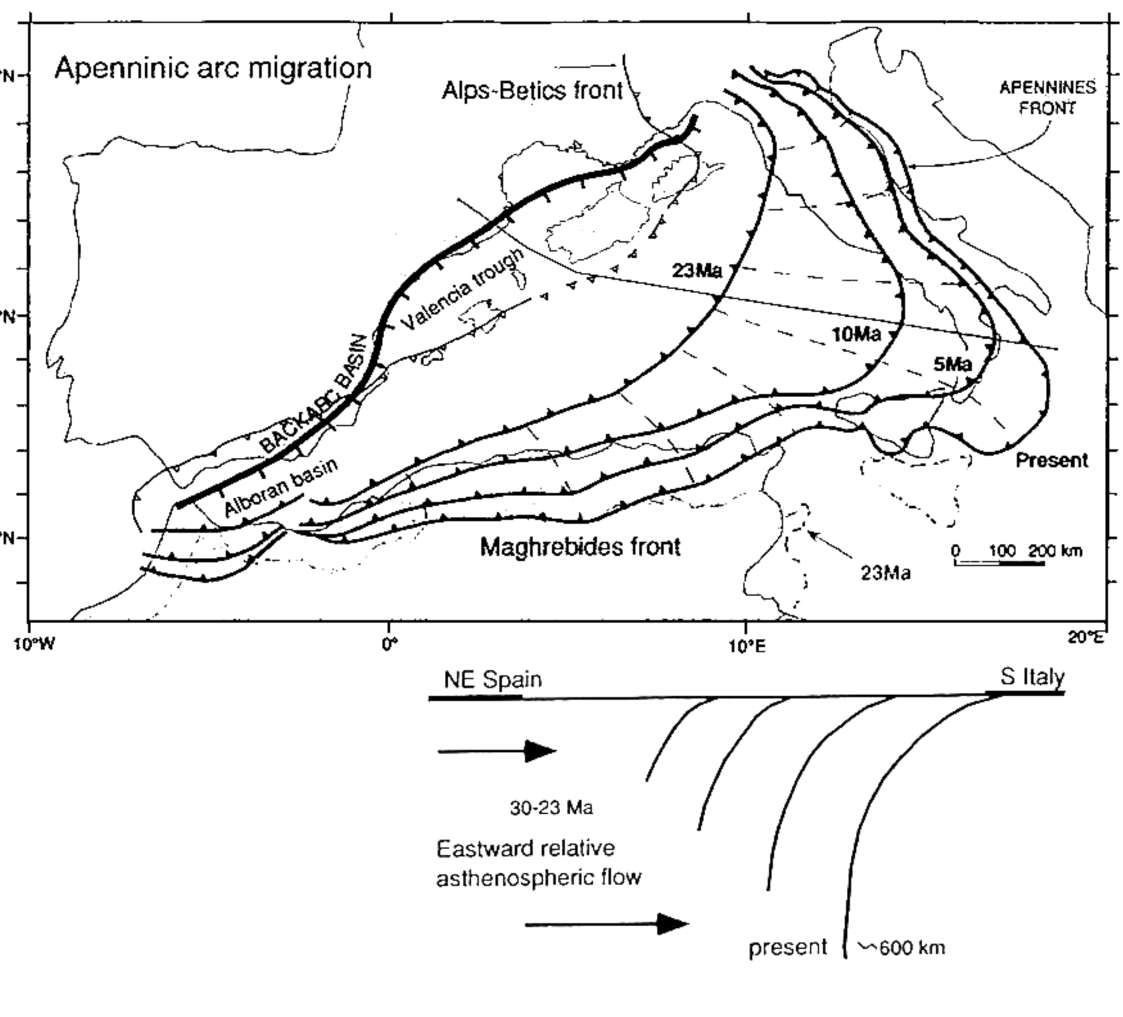

Fig. 15 – The westward subducted African lithosphere originated the Western Mediterranean opening in the late Oligocene. Its arc migrated eastwards till the actual position (Doglioni, 1991).

The upward action of a diapir facilitated the shifting of the different orogenic transports over the western continental margin of the Adriatic Microplate ("Tyrrhenian – Apennines System"), with consequent progressive and always more marked collapse of the same area. The sinking of the present Tyrrhenian Sea was caused by the subsequent (Recent: ~1 My) collapse of this diapir.

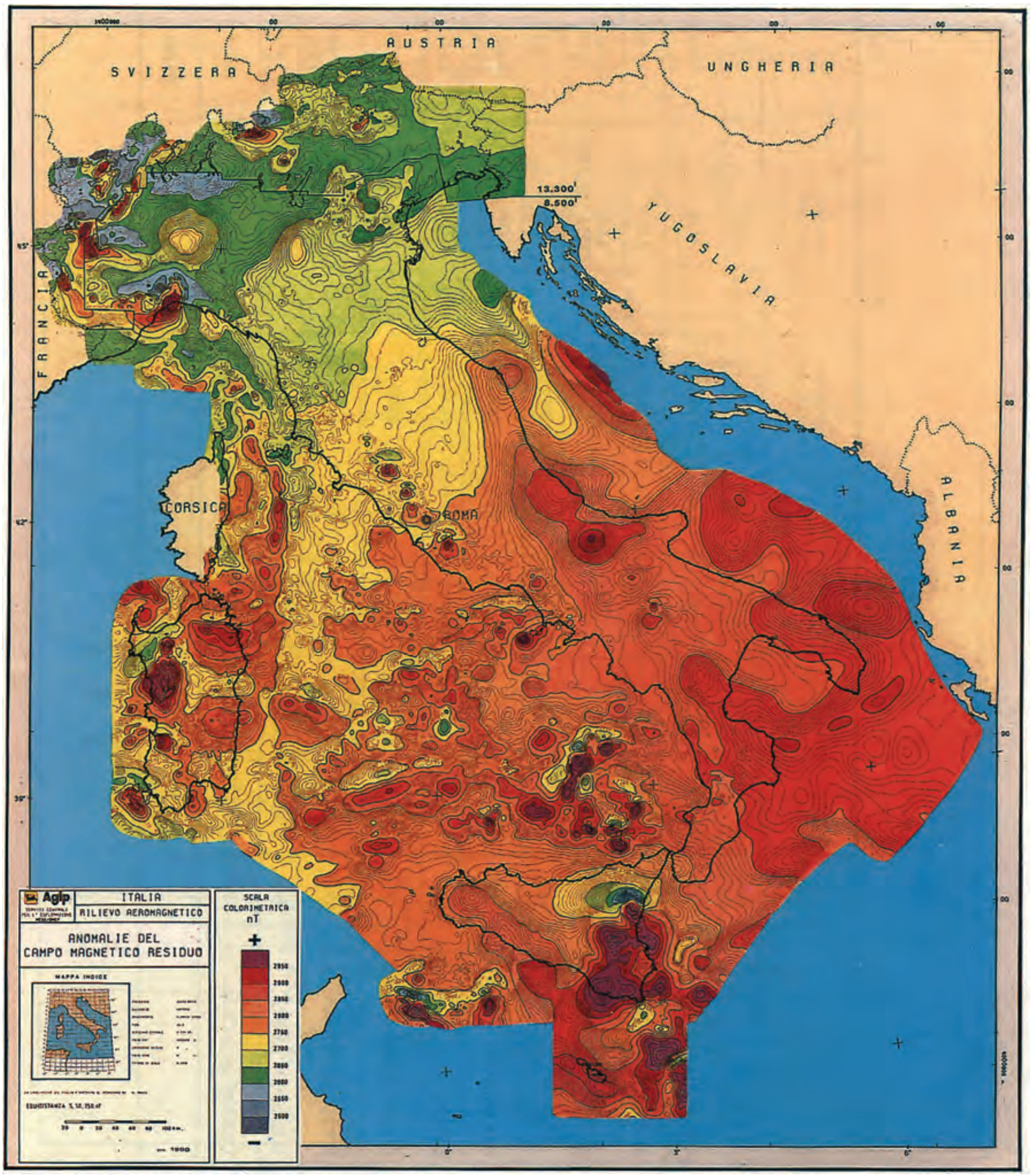

Fig. 15 – Contour map of the residual magnetic field in Italy (AGIP, 1984).

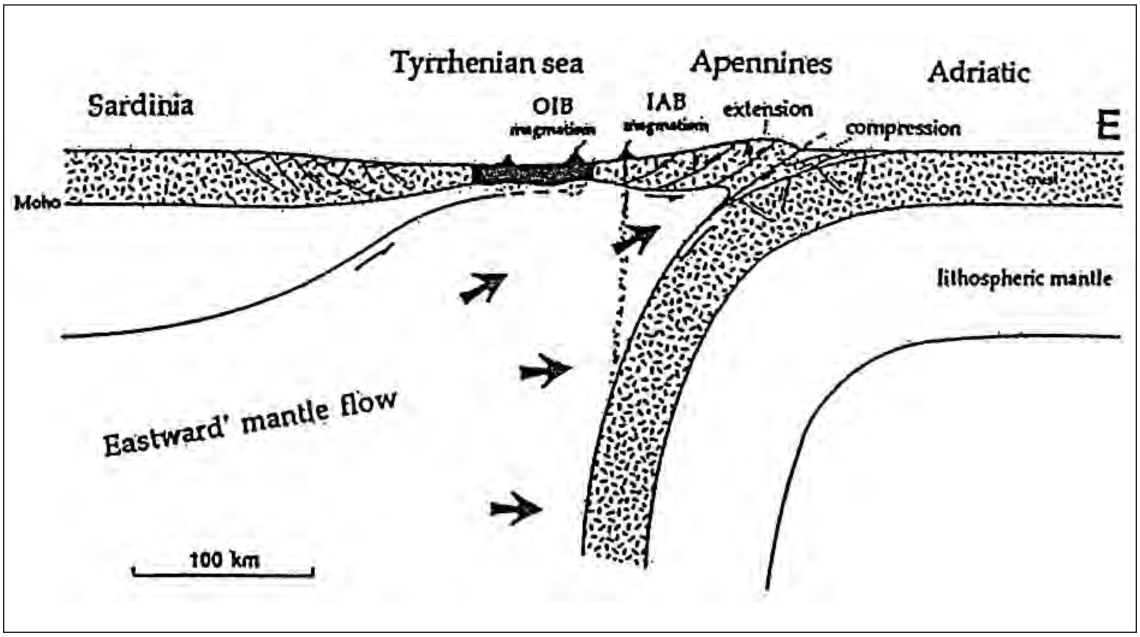

Fig. 16 – Schematic section of the system Tyrrhenian-Apennines (Doglioni and Flores, 1997). OIB = oceanic islands basalt; IAB = insular arc basalt.

Fragments of the Alps emerge in the Apennines (Tuscany, Elba, Pontine Islands, Calabria) and have been dispersed and fractured on the bottom of the Tyrrhenian Basin; they are supposed to be buried beneath the Western Apennines, and demonstrate that the Alps are therefore part of the Apenninec Arc.

The Apennines of today are characterized by a frontal wedge acting below sea level, whereas the more elevated ridge is rising and expanding with consequent superficial seismicity (at ~10-15 km depth). Farther west, towards the Tyrrhenian, the subsidence is mainly a consequence of the thermal cooling; the seismicity is reduced, but the focal depth increases (Fig. 16).

These different tectonic fields have been and still are expanding the Apenninic Arc eastwards, with velocities in the order of some mm/y.

5.2. Confirmations (preliminary results) from the GPS repeated measurements

The latest confirmation of the above movements comes from the repeated GPS measurements, by the University of Padova Group, of the permanent stations in Italy of the European Geodetic Reference Net (EUREF 1993-1998, global velocity 21-33 mm/y, azimuth 50°-57°), with the addition of other ad hoc reference stations in Italy (January 1999 – July 2000). The preliminary regional results (Caporali *et al.*, 2002), limited to those that exceeded the threeshold of indetermination (3 mm/y), can be summarized as follows (Fig. 17):

- ***extensional*** regime in the internal arc of the Northern and Southern Apennines, in the Sicily

Channel and in the Ligurian and Tyrrhenian Seas (with generation of oceanic crust and volcanism in the SE Tyrrhenian);

- ***compressional*** regime in the NE external Apenninic Arc, the Adriatic Foreland and Friuli, the northern Sicily coasts.

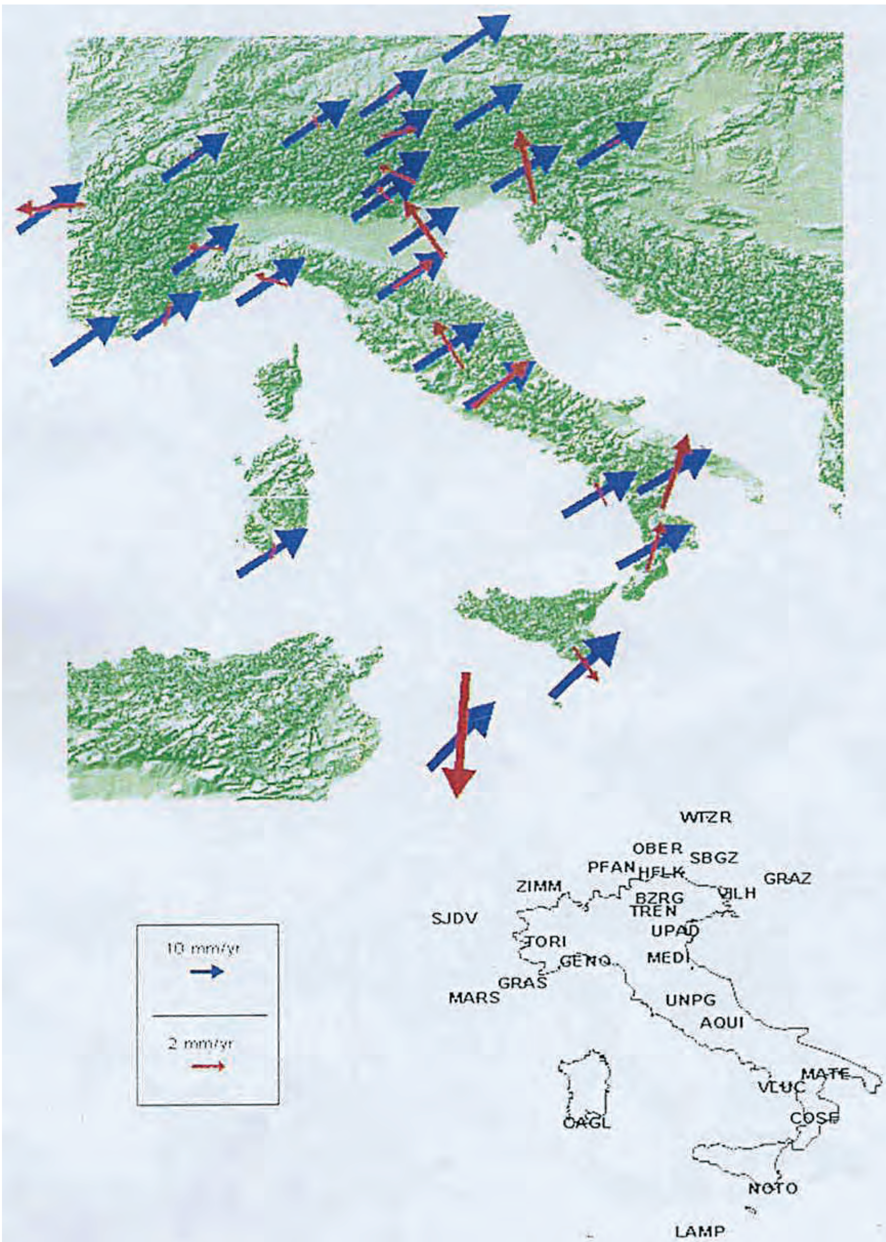

Fig. 17 – Velocities of the permanent GPS stations according to a rigid plate model (NUVEL1A NNR) (blue), and their corrections (red), as determined from GPS data. Note the different scales for rigid plate velocities and for additional velocities. The final velocity is the sum of the model value and the correction [which should be indicative of local tectonics; Caporali *et al.* (2002)].

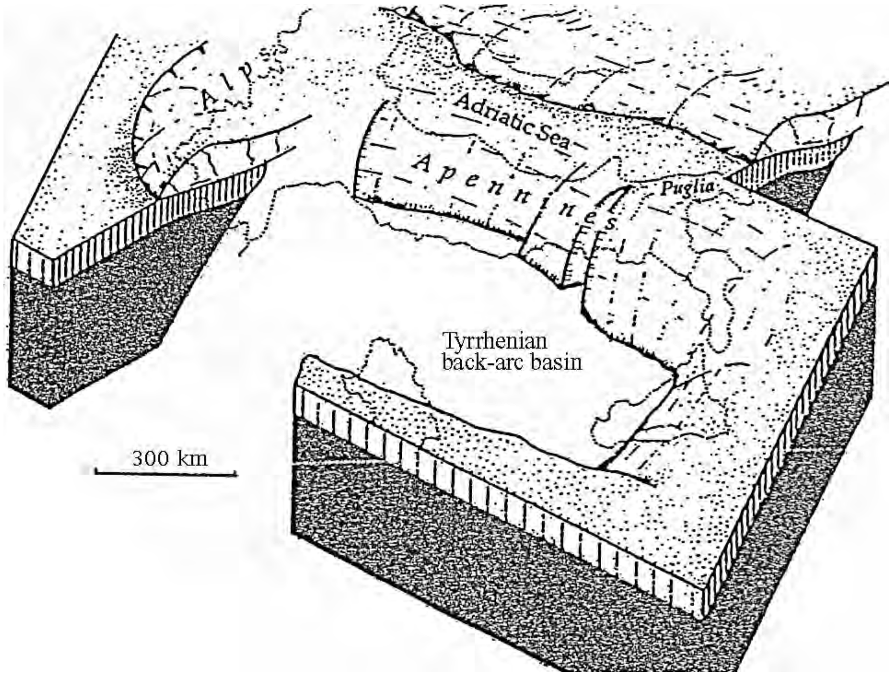

Fig. 18 – Schematic 3D diagram showing that the Adriatic plate is subducting westwards underneath the Apennines, while it is thrusting the European plate generating the Alps. The Adriatic plate is also subducting towards ENE, generating the Dinaric orogen (Doglioni and Flores, 1997).

The above results are in general agreement with those obtained from the Moho thickness (Fig. 4) and the Heat Flow (§ 2.2): in the areas of distension there is shallow Moho and high Heat Flow values (≥120 mW/m^2), in the areas of compression the Moho is deeper and Heat Flow values are ≤80 mW/m^2 (Zito *et al.*, 2004).

The GPS results are also in agreement with the indentation of the Adriatic Microplate with the European one in the Eastern Alps, with the flexure of the Adriatic lithosphere below the Western Apennines, and the subduction of the Ionian lithosphere below the Calabrian Arc (Fig. 18).

For problems of Geodynamics the importance of this geodetic (“direct”) method is evident, allowing continuous monitoring with denser stations as needed.

6. Conclusions from integrated land and sea geophysical and geological results

The results of the above mentioned geophysical researches on land and on sea, with the addition of the pertinent recent geologic advancements, permit to summarize following descriptions and conclusions [for more extended informations, see e.g. *Doglioni and Flores* (1997)].

The Alps and Apennines are two mountain complexes with very different character, that form a unique system:

- the Alps have a deep foreland with windows of metamorphic rocks, and remarkable structural and morphological highs;
- the Apennines have a less deep foredeep, a frontal active accretionary wedge and an internal elevated ridge in an extensional regime; few surficial outcrops exist of basement rocks partially inherited from preceding "Alpine" phases; modest structural and morphological highs, and the Tyrrhenian Sea as back-arc basin with outcrops of Hercynian basement; thin crust (where oceanic, less than 8 km thick).

Both the Alps, the Apennines and the Tellian-Numidian and Atlasian thrust zones are young colliding systems, in which the basic principle of the structural evolution is ramp-like tectonics.

In each system, three main units could be ascertained:

- the inactive foreland and the foredeep filled with young sediments;
- the central or axial zone with strongly folded and overthrust formations, being metamorphized in many cases;
- the hinterland which in respect to the central zone behaves as a more or less rigid block (compressed in an earlier orogenic phase). The internal upper unit shows a crustal thickening by back folding and thrusting (*e.g.* Southern Alps) or presents an extensional region with a thinned crust (*e.g*. Northern Apennines).

The improved knowledge about the Alps-Apennine System derives from combining the geophysical results on land and sea (particularly DSS and CROP). They agree with the geological results that for the Tyrrhenian area, indicate a clear eastward migration of crustal fracturing from Tortonian in the west to Plio-Pleistocene in the east, and a similar continental fracturing and related magmatism in Tuscany.

Collisional tectonics is predominant in the Alps, where the Adriatic plate acted as a hinterland against the European plate foreland. The main results: westward and northward oriented overthrusting on the European crust, bending and subducted at the lower European crust, European Moho up to till 70 km depth with the Adriatic mantle indented above, crustal doubling (Adriatic over the European one).

In the Apennines, on the contrary, the Adriatic plate acted as a foreland, against the overthrusts generated by the Tuscan and Tyrrhenian mantellic bodies, heated, elevated and migrated NE-wards and SE-wards, respectively. Also the Adriatic plate is bending and subducted under this load, centripetally towards the Tyrrhenian Sea, so that the Adriatic Moho from 35 km depth is presumed to descend through a flexure down to 40-50 km below the Tuscan and Tyrrhenian coasts. The external peri-Apenninic area is still in compression and includes thick sedimentary basins, from the Po-plain to the Island of Sicily. The internal area is in extension, overlapped by thin, stretched crusts of Ligurian and Tyrrhenian origin, whose remnants occupy most of both areas, with two areas of oceanic crust in the SE-Tyrrhenian and in the Ionian sea.

Rifting and opening is also in action in the Ligurian Sea and Sicilian Strait.

From these comparing studies the following conclusions can also be made:

- all crustal sections through the young colliding systems studied here show a clearly expressed asymmetric lithospheric structure;
- crustal thickening is mainly caused by stacking of sedimentary and crystalline formations;
- in the internal zone crustal doubling with or without mantle slices at the base of the upper unit are characteristic;

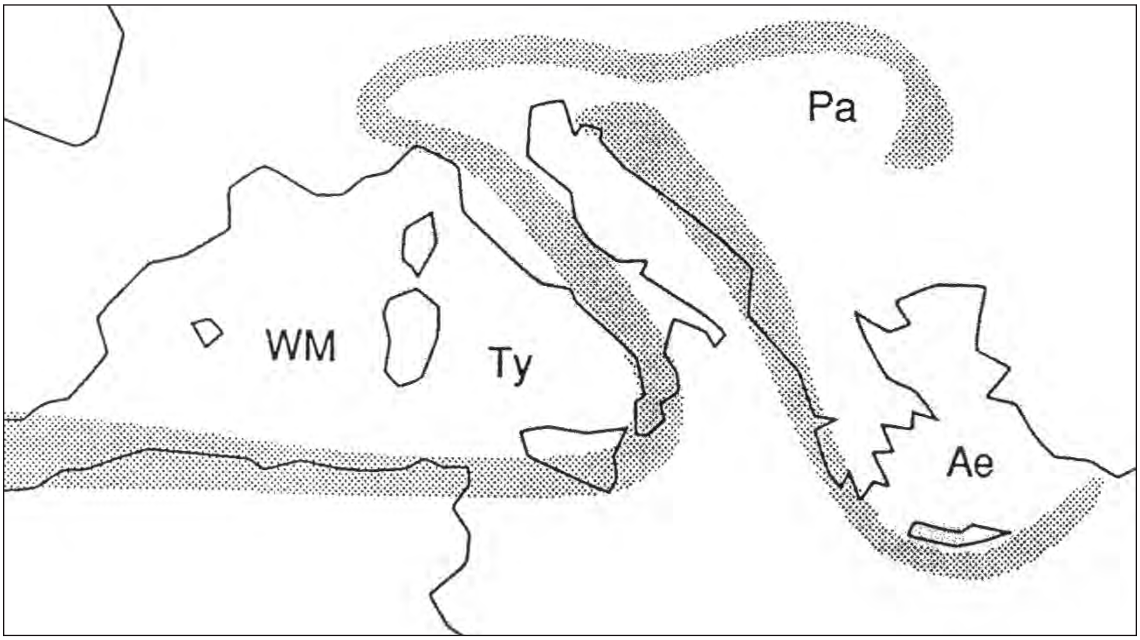

Fig. 17 - Actual positions of the European and African subducting plate margins (instability belts) in the Mediterranean region.

- thus the deepest crustal formation are found beneath the hinterland block.

Outstanding is the correlation between the Mediterranean seismicity sketches of Fig. 11 and the areas of subductions of the different Lithospheres (Fig. 19):

- the European beneath the African in the Western Mediterranean, and beneath the Adriatic in the Alpine, Apenninic and Dalmatic-Balcanic regions;
- the African beneath the European in the Eastern Mediterranenan.

Since the areas of subduction concentrate the maxima of tensions, they also originate fracturing of rocks and dislocations along faults (earthquakes) and – when at sea – Tsunamis.

The effects on land are confirmed also by the map of seismic hazard in Italy (Fig. 20).

Obviously, the rapid improvements in the seismic networks in the last years have increased the accuracy of the fall outs (particularly depth; tomography; velocity of the crustal layers, hence more accurate coordinates of the foci; etc.). Therefore, the new seismicity maps can have more details, but the general aspects (as Fig. 12) remain unchanged.

In conclusion, the actual sea bottom reflects a synthesis of the Mediterranean Geodynamics:

- in the Western Mediterranean (<30 My) of its eastwards opening through island arcs with lithosphere subduction, colossal overthrusts (which formed the Apennines), dipirs rising and collapsing; and the formation of new oceanic crust (Tyrrhenian);
- in the Eastern Mediterranean (remnant of the primordial Tethys), where the surface of the oceanic crust is very deep, covered by a thick (up to 10-15 km) sedimentary cover, with subductions in action (Africa beneath Europe) in the Aegean and Anatolian Islands Arc.

All these geodynamics characters could be recognized by the deep geophysical parameters in the last half-a-century of international cooperation (precision bathymetry, seismic reflection and

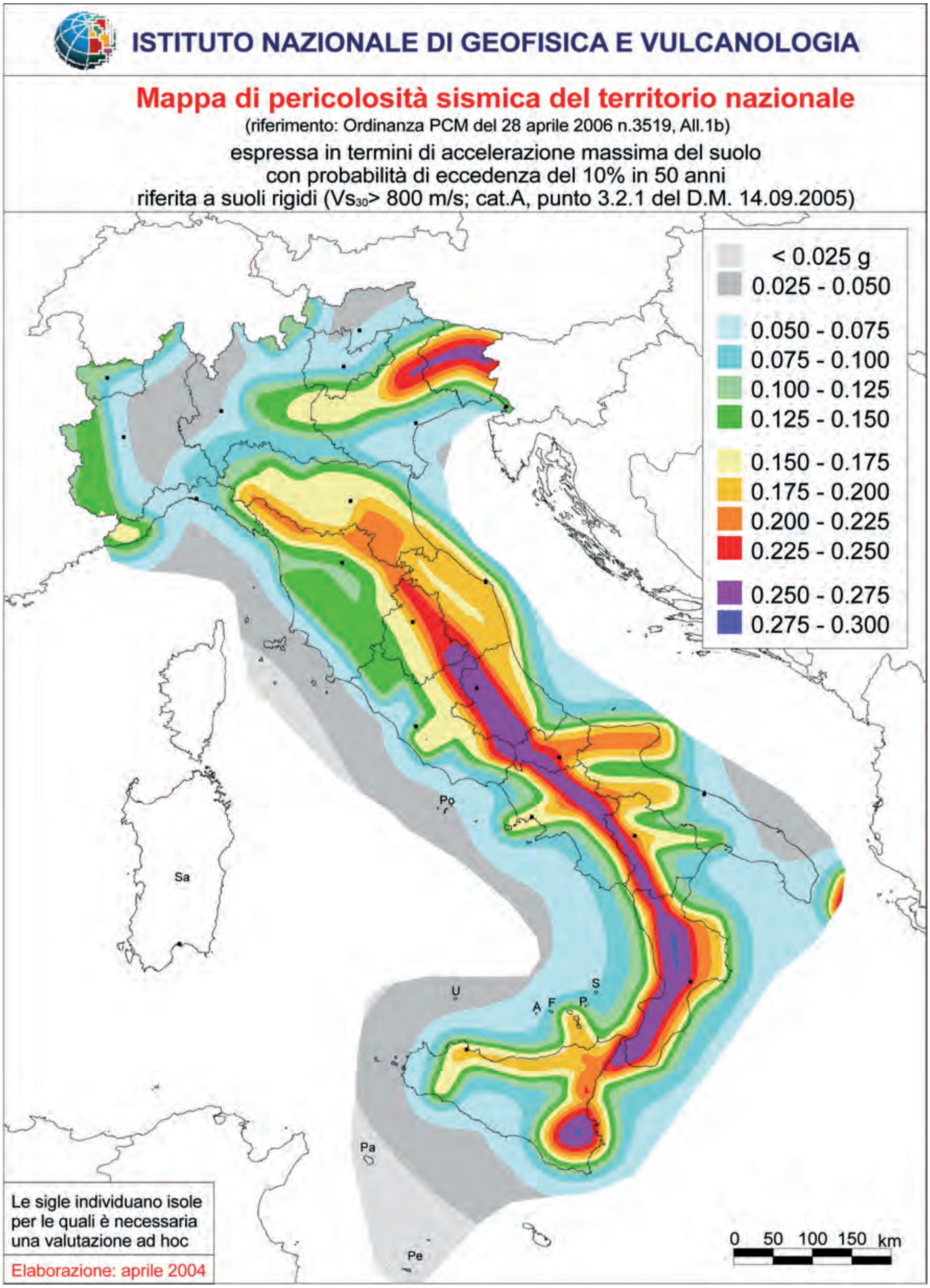

Fig. 20 - The map of seismic hazard in Italy (ordinance PMC 20.3.2003, n. 3274).

refraction profiling, gravity and magnetic anomalies, seismicity, heat-flow measurements, etc.).

This allow nowadays to apply the "integrated geophysical and geological interpretation".

Another important sea result are the details of the actions through which operated the principal motor: that is, the astenospheric horizontal (currents, plates transportations; Fig. 20) and vertical (diapirs) movements.

7. Fall-outs

One of the principal tasks of the above-summarized programs have been to place at the disposal of the interested researchers the results for the formulation of regional geodynamic projects: these data are a contribution to the knowledge into depth of the crustal structure, and important not only for science, but also for the economy and the prevention of social risks.

It is also to be mentioned that the results presented here are a contribution of common efforts realized with relatively modest funds, but mostly in national and/or international collaboration. Most of them are fundamental ones, which often changed our knowledge and, in conclusion, confirm the validity of the international efforts and collaboration.

A non-negligible fall-out has been, finally, the preparation of hundreds of highly specialized researchers, organized *i.e.* in a National Institute (of Oceanography and Experimental Geophysics, OGS) and adhering freely to a National Coordinating Group for Solid Earth Geophysics, where the ideas and the results can be presented and discussed (more than 600 participants at the last annual congresses, with more than 250 original papers, mainly by young scientists and later on published also in international journals).

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Corresponding author: Carlo Morelli
Dipartimento di Ingegneria Civile e Ambientale, Università degli Studi di Trieste
Via Valerio 10, 34127 Trieste
phone: 040 5587158; fax: 040 5583497; e-mail: morellic@univ.trieste.it