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3 figg.

An historical perspective to the CROP Project

Una rassegna storica del Progetto CROP

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ABSTRACT - Thanks to the promotional and operational activity of the newly-created (1958) OGS and with the active participation of the University and CNR (from 1968), in Italy in the post-World War 2 period a coordinate research initiative was launched for the study of the intermediate and deep crust with the methods of active seismics. From 1956, in reply to requests for international collaboration, the research was focussed first of all on the Alps, and subsequently on all the Peninsula and surrounding seas, integrated with other pertinent geophysical methods (gravity, geomagnetism, heat flow). Till 1986 this has meant observations on land totalling 21,160 km of Seismic Refraction Profiles (DSS) and, at sea, 40,000 km of Reflection Seismics (MS), which permitted a first regional knowledge of the crust.

The improvements in the years '70, thanks to a Consortium of American Universities (COCORP; BARAZANGI & BROWN, 1986), of the on-land reflection seismic methods to adapt them to the greater depths with the necessary detail, induced the CNR Gruppo Nazionale di Geofisica della Terra Solida (GNGTS) to propose the CROsta Profonda (CROP) Project, indicated in figure 3 which, from 1986 to 1991, with the participation also of ENI and ENEL, was performed as described in the following reports.

The following is a summary of developments in the period 1956-1986.

KEY WORDS: CROP Project, deep crust

RIASSUNTO - Per l'attività promozionale ed operativa del neo-costituito (1958) OGS e con la partecipazione attiva degli Istituti universitari e CNR (dal 1968), si è sviluppata in Italia nell'immediato dopoguerra un'attività di ricerca coordinata per lo studio della crosta intermedia e profonda, con i metodi della sismica attiva. Dal 1956, per rispondere anzitutto alla richiesta di collaborazione internazionale, le ricerche hanno interessato dapprima le Alpi, estendendosi poi a tutta la Penisola ed ai mari circostanti, ed integrate con gli altri metodi geofisici pertinenti (gravità, geomagnetismo, flusso di calore). Fino al 1986 sono stati così osservati in terra 21.160 km di profili di Sismica a Rifrazione Profonda (DSS) ed in mare 40.000 km di Sismica a Riflessione (MS), che hanno consentito una prima conoscenza regionale della crosta.

Lo sviluppo a cura di un Consorzio di Università americane negli anni '70 dei metodi della sismica a riflessione in terra per renderli idonei anche alle grandi profondità con i dettagli necessari (COCORP; BARAZANGI & BROWN, 1986), ha indotto il Gruppo Nazionale di Geofisica della Terra Solida (GNGTS) del CNR a proporre (1985) il Progetto CROsta Profonda (CROP), indicato in figura 3 e realizzato dal 1986 al 1991, con la partecipazione anche dell'ENI e dell'ENEL, secondo quanto esposto nelle relazioni che seguono.

Qui viene sintetizzato l'iter del menzionato sviluppo nel periodo 1956-1986.

PAROLE CHIAVE: Progetto CROP, crosta profonda

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1. - FOREWORD: 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. Knowledge of the latter is thus a pre-requisite for knowing the former and for understanding the complex tectonic evolution at the surface.

The geological sciences have progressed remarkably in the past century, from a description of the surface evidence, to the study of deep rocks brought to the surface by orogenic processes and finally to an understanding of deep processes. This, in particular, gained a significant improvement when proper geophysical methods became available (mainly gravity, magnetic and seismological).

Mineral exploration has given a strong impulse to applied geophysics, mainly in the sedimentary basins (hydrocarbon research). New experimental technologies and refinements in the interpretation, in connection with progressively deeper drill holes for testing and industrial exploitation, has allowed us to reach a good level of knowledge on the nature, composition and development of the upper crust (down to a depth of ~10 km, 15 km in the Kola super-deep drilling, and 12 km in the KTB drilling in Germany). The seismic reflection data have thus allowed us to obtain excellent stratigraphic sections to a depth of ~ 10 km, with a detailed individualization of the seismic discontinuities and related seismic velocities; the potential methods (gravity and magnetic) have permitted the lateral extrapolation of seismic results; heat flow, a knowledge of thermal conditions, their cause and effect for an understanding of the internal physical and chemical conditions and their variations.

Knowledge of the above-mentioned geophysical parameters 10 km below the Earth's surface is essential, particularly for such a geologically young country like Italy, where the conditions at depth are extremely variable at short distances and in relatively short geological time intervals; for example, from the variations in thickness and nature of the crust (from 8 km, oceanic, in the Tyrrhenian Sea, to 70 km, continental, in the Alps), to the effects at the Earth's surface (uplifts, earthquakes and volcanism).

Thus, in Italy, a knowledge of the intermediate and deeper crust is a priority, not only for science, but also for environmental protection and for economic reasons. Decades of efforts by Universities and Institutes, guided by CNR and later converged into the CROP Project (CROsta Profonda), has led to the acquisition of a vast amount of geophysical data and has effectively improved our knowledge on this subject. This Atlas presents all the seismic profiles acquired in the framework of this project.

The original idea started in the frame of the European Seismological Commission (ESC), proposed as a Federation in 1950 at a Workshop in Verona organized by the Istituto Nazionale di Geofisica, ING (CALOI) and the Osservatorio Geofisico Sperimentale, OGS (MORELLI), and recognized as ESC by the UGGI General Assembly (Bruxelles, 1951). In the subsequent UGGI General Assembly (Roma, 1954), a Group was created within the ESC (later "Large Seismic Profiles" for the realization of large explosions : Deep Seismic Sounding = DSS) for the study of the Earth's crust, which turned into a common European project (essential point, due to the large number of personnel involved and the lack of necessary means: instruments, people and funds). The Group - later divided into geographical sub-groups - has since then acquised experiences and organized meetings for the discussion and publication of its results every year.

Almost all that is quantitatively known about the deep crust in Europe and surrounding seas is thanks to this Group, the Italian part of which is a section of the CNR Gruppo Nazionale di Geofisica della Terra Solida (GNGTS). The Italian participation has always been active from the organizational and operative point of view as well as in an interpretative role. The commendation goes mainly to OGS, which has guided all the experience in international cooperation of the DSS SW-Europe Sub-Group, in Italy. The international cooperation in the European Geotraverse (EGT) 1985/1986 of the European Science Foundation has been particularly important. The organizational aspects of this cooperation, for all the southern sector from the Alps to Southern Tunisia (125 field cruises, 2 CNR ships; BLUNDELL *et alii*, 1992) have been assigned to OGS. OGS has also completed a national program (1956-1982; fig. 1), which allowed us to acquire a regional knowledge to depth of almost all the land and the surrounding seas. The initial support, funds and means, was almost exclusively provided by CNR, and has only recently been replaced by the Ministry for Research and University.

2. – RESULTS PRECEDING THE CROP

The Deep Seismic Sounding (DSS) methodology has been largely applied to gaining insights on the structures of the crust. Information on its thickness (MORELLI, 1993) and on the wave propa-

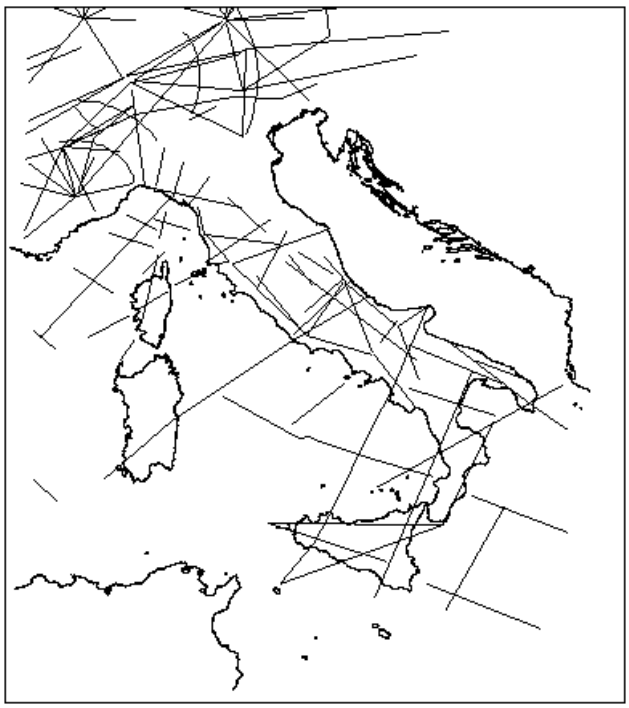

Fig. 1 - The Deep Seismic Refraction Profiles (DSS) acquired by OGS (21,160 km) in the period 1956-82

- I profili di Sismica a Rifrazione Profonda (DSS) realizzati dall'OGS nel periodo 1956-82 (21.160 km)

gation velocities represents relevant contributions to the research. Recently the results of the DSS profiles have been digitized and reinterpreted by the Istituto di Ricerca del Rischio Sismico CNR, Milano (IRRS; e.g. SCARASCIA *et alii*, 1984), and are available to the scientific community.

In the period 1969-1982, 39,500 km of regional marine seismic profiles (MS) were recorded by the CNR vessel "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 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 (FINETTI & MORELLI, 1973; fig. 2).

The magnetic tapes with the analogic data are now being digitized by OGS, and are available on request for scientific purposes.

Their interpretation revealed the widespread existence of a thick evaporitic layer (Messinian in age) in the Mediterranean, the presence of sedimentary layers below it and of sedimentary basins all around the Tyrrhenian coasts. It also evidenced the continuation of the continental crust between Sicily and Tunisia (subsided and fractured), its presence in the entire northern and central Adriatic and its thin and subsided nature in the Ligurian Sea and in the Sardinia Channel. A thin oceanic crust covered by thick sediments was revealed in the SE Tyrrhenian and in the Ionian Seas.

The map of the Bouguer anomalies on land has been compiled following the initiative of the former Italian Geodetic Commission, by a group of Institutions and Universities between 1952-1963 at a 1:1.000.000 scale, with approximately 2631 first-order stations on land, and 488 on the sea bottom (with remotely controlled gravity-meters). It was completed in 1973, with 270,000 stations kindly offered by AGIP for the CNR

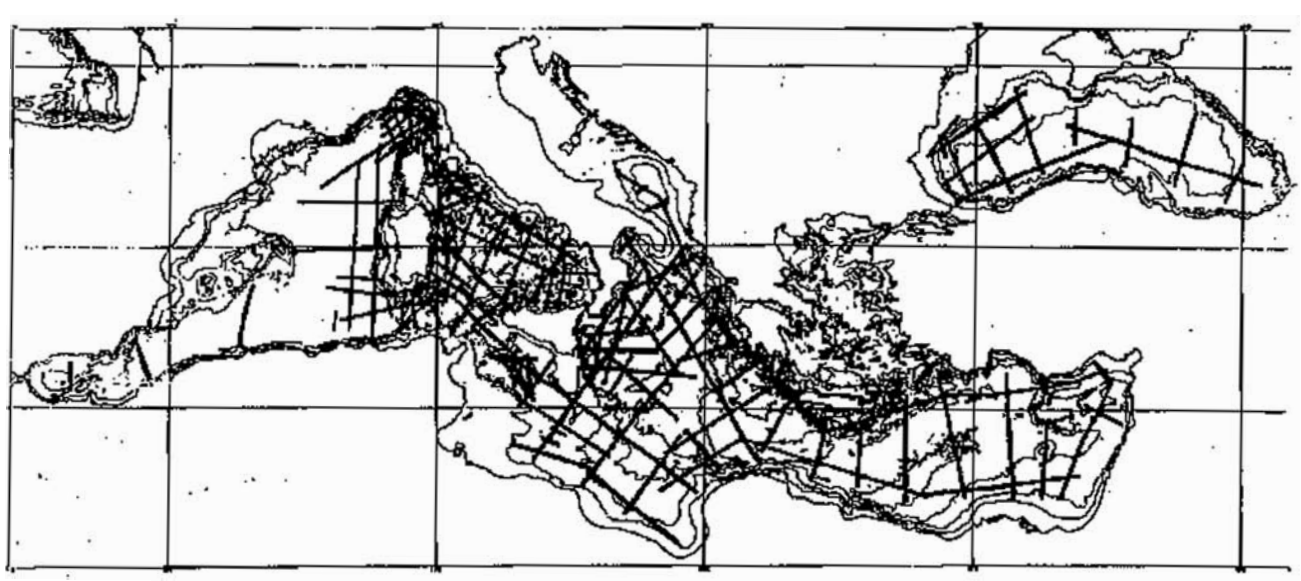

Fig.2 - The Deep Seismic Reflection Profiles (NVR) in the Mediterranean Sea by OGS (MS; 1969-1982).

- I profili di Sismica a Riflessione Profonda (NVR) nel Mediterraneo, realizzati dall'OGS (MS; 1969-1992).

Structural Model of Italy at a scale of 1:1.000.000. All the values are deposited in digital form at the Servizio Geologico d'Italia, Rome, from which they can be obtained, upon request, for scientific purposes.

The main results are: wide and strong regional anomalies, strictly anti-correlated with the Moho depth; regional negative anomalies indicating (for the first time) the existence of sedimentary basins all along the external peri-Apenninic chain, from Piedmont to Sicily.

The gravity measurements were extended to the sea by OGS in 1958 with a surface ship gravity-meter, with an experimental survey on the Navy's hydrographic ship "Staffetta"; they continued in 1961-65, in cooperation with the SACLANT Center, on the ships "Aragonese" and "Maria Paolina"; in 1966-1972 (with total field magnetic measurements) they were continued on the CNR ship "Bannock", extended to all the Mediterranean (up to 23° East).

The gravity data, in digital form, are deposited at the Bureau Gravimétrique International, 18 Ave. Edouard Belin, 31401 Toulouse, Cedex France (Fax +33.5.61253098; http://bgi.ines.fr:8110/) and can be obtained upon request.

These measurements permitted to extend the profile obtained onshore out to sea, and so to strengthen the tectonic and geodynamic interpretations. These surveys also provided the basis for studies on physical geodesy, particularly satellite motions and the Earth's form (geoid).

A by-product of great practical importance was the production of detailed bathymetric and morphologic maps, firstly for all the Italian seas, and then for the whole of the Mediterranean Sea. This initiative was assumed by the Intergovernmental Oceanographic Commission of UNESCO (IOC).

The survey in the western and central Mediterranean by SACLANT and OGS in 1961-1965, by OGS between 1965-1972, and the surveys eastwards to 26° E by the University of Cambridge in 1971-1974, produced the bulk of the bathymetric, gravity and magnetic data. Under the auspices of the IOC-FAO-CIESM, and with the data contribution from research institutes and private companies, after a 20-year long collaboration of an ad-hoc international group, the International Bathymetric Chart of the Mediterranean (IBCM; scale 1:1.000.000, 10 sheets) was published in 1981 by the Head of the Department of Navigation and Oceanography, St. Petersburg, Russian Federation. The importance of the physiographic results suggested their integration with the most pertinent geophysical and geological data. The following thematic maps were also published on the same scale:
- Bouguer Gravity Anomalies (IBCM-G; 1989);
- Seismicity (IBCM-S; 1991);
- Plio-Quaternary Thickness (IBCM-P/Q; 1993);
- Unconsolidated Sediments (IBCM-Sed; 1998); and
- Magnetic Anomalies (IBCM-M; 2000).

Each map has an explanatory brochure (IBCM-S, with catalogue) and can be obtained (when available, also in digital form) from Ocean Mapping, IOC, 75732 Paris, Fax +33.1.4568.5810. A photographic reduction at 1:5.000.000 is also available.

Heat flow measurements on land and at sea were performed mainly with CNR funds, and are published in the "Atlas of Europe". They allowed us to identify: the presence of magmatic activity in all the extensional Tyrrhenian inner-arc (sensu latu) area; the ophiolitic signature of continental collisions; the areal extent of the submerged volcanic provinces and of the geothermal areas on land and at sea. This last point is very important and economically promising for Italy, particularly in the Tuscan geothermal area, where the very strong rise of the isotherms (Della Vedova *et alii*, 2001) and the near surface lithological conditions (good permeability in fractured rocks, under the impermeable cover) can be followed in a seismic "bright spot" (horizon K) mainly around the present exploitation area.

The scientific contribution from geophysical prospecting played an outstanding role in unraveling the geological structures at depth, which were obscured by the colossal overthrusts of Tyrrhenian (sensu latu) origin, that covered all the Apenninic and retro-arc areas.

The first revelations were in the Po Valley, when AGIP published (Accademia Nazionale dei Lincei, 1959) new and revolutionary data for the Po Plain, with extended details provided by Pieri & Groppi (1981).

The geological and geophysical knowledge acquired for the northern Apennines was summarized in an integrated publication (Cassano *et alii*, 1986), confirming, at all levels, the tectonic pushes prevailing from the West, and the predominance of connected faults and overthrusts.

In Central and Southern Italy, the superficial predominance of the Adriatic plate stretches increasingly westward and the carbonatic series prevails, also with great thickness. In this sector, the centrifugal stresses generated by mantle activity are clearly illustrated in the sedimentary cover in 15 transversal AGIP sections, based on detailed Near

Vertical Reflection (NVR) seismics and many wells (MOSTARDINI & MERLINI, 1986).

At the same time, the results of an ad-hoc study by an AGIP team (LA BELLA *et alii*, 1996) were published. This document reported that the bad quality of the seismic response was mainly caused by the superficial geological conditions: extremely variable topography and lithology ones, with strong velocity variations in the sub-aerated layer. Having overcome these difficulties, reliable results were obtained with 3D seismics, also in mountainous areas. In Basilicata (Southern Italy) the Val d'Agri oil field, which later became one of the most important in Europe, was discovered this way.

All these studies and results, and many others, created an important basis to develop the strategies for the CROP project, to site the new seismic reflection profiles and to plan the research activities.

3. – THE CROSTA PROFONDA (CROP) PROJECT

In the sixties and seventies, NVR seismic experienced an impressive improvement of its capabilities, mainly as a consequence of extensive research and of improvements in the hardware and the software technologies. The depth limit of ~10 km for the investigation of the deep reflectors was overcome in the seventies by a Consortium of USA Universities (COCORP), which brought fundamental technological improvements to the study of the deeper crust and upper mantle, including: very long spreads (of even 20 km), multiple geophones, repeated energizations, digital recording, computer processing with increasingly advanced software. The results were good reflections, normally to the crust bottom. The applications of these methods - which spread from the USA to all the states (or consortia of states) with advanced technologies - has given excellent results, often revolutionary ones, almost everywhere (BARANZAGI & BROWN, 1986). The super-deep drillings (Kola, KTB) have also revealed the great importance of the fluids at depth, also to explain some apparent discrepancies with NVR results (KOZLOVSKY, 1987; EMMERMANN & WOHLENBERG, 1989; MEISSNER & BORTFELD, 1990).

The oldest and most important European Projects are:

- in France, ECORS (IFP & INAG, 1982; BOIS *et alii*, 1986);
- in Germany, DEKORP (MEISSNER *et alii*, 1991);
- in Switzerland, NRP-20 (FINCKH *et alii*, 1987);
- in U.K., BIRPS (Mattheus & THE BIRPS GROUP, 1990);
- in Scandinavia, BABEL (MEISSNER *et alii*, 1992).

In Italy, this initiative started in 1982 within the GNGTS, in agreement with the CNR Committee for Geological Sciences. A joint Commission of geologists and geophysicists devoted the whole of 1984 to selecting a series of deep seismic profiles to interact with the principal geological themes of the Italian land and sea areas.

During the first executive phase (1985-1988) priority was given to projects in collaboration with countries with a common border. The first was the French project, ECORS, for a common profile of the Western Alps, from Torino to Geneva (1986). In 1985, four different proposals were put forward by a French-Italian ad-hoc group, and the choice of a seismic refraction Wide Angle (WA) experiment was made for the proposed area. In addition to the most appropriate choice of profile, the results revealed that without them the interpretation of the profile would have been impossible.

The program continued in 1987/88 with a Swiss-Italian study of the Central Alps (BLUNDELL *et alii*, 1992). From 1989 to 1999, in collaboration with AGIP and ENEL, the land and sea profiles were acquired (in fig. 3 are shown the seismic lines originally scheduled for the Crop Project); in 1999/2000 the Transalpine profile Munich-Conegliano, in a collaboration between Germany, Austria and Italy (TRANSALP), was performed.

Their processing and interpretation are under way; the results so far have been outstanding, especially for CROP 03, thanks to the Profile-Director the late Prof. Pialli (PIALLI *et alii*, 1998).

4. – THE SCIENTIFIC, ECONOMIC AND SOCIAL BENEFITS

In conclusion, the data contained in this Atlas are an invaluable resource for our studies of the Earth, and are at the disposal of all interested researchers.

The advancements in the acquisition of knowledge, the benefits already obtained and those that will be gained, are valuable not only to science but also for their social and economic consequences.

The study of the deeper structures of the crust is an indispensable premise for understanding the geological processes that led to the formation of the mountain chains and sedimentary basins, and that control volcanic and seismic activity. As well as improving our basic knowledge, such research also provides valuable infor-

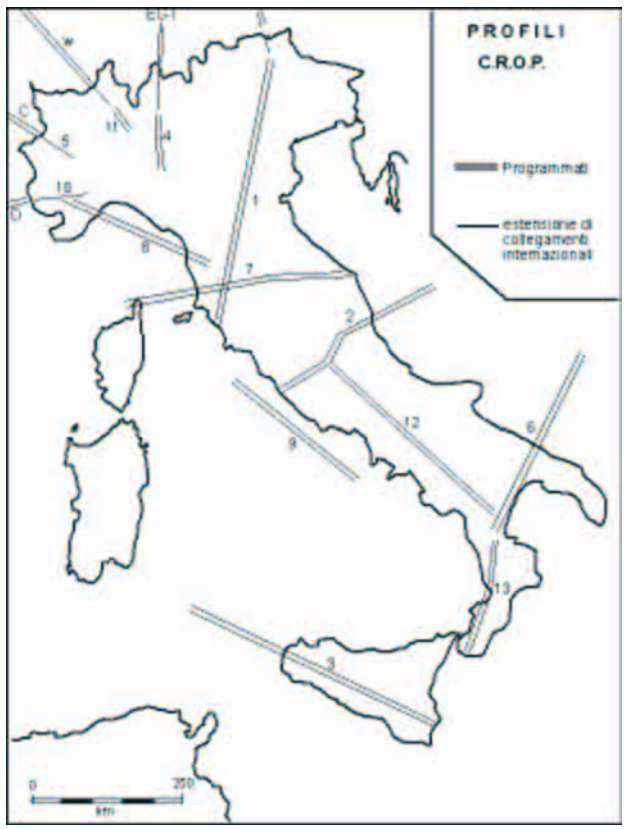

Fig. 3 - Location map of the seismic lines originally scheduled for the CROP Project.

- Mappa di posizione delle linee sismiche originariamente pianificate nell'ambito del Progetto CROP.

mation for the evaluation of potential sources of energy (hydrocarbon accumulations and geothermal reservoirs), for the choice of the most suitable sites for industrial plants, and for the identification of potential earthquake sources.

Indeed, over the last few years the evaluation of the seismic risk has shifted focus from wide seismogenic zones to tectonic structures that are better and better defined as seismic sources. But our knowledge of the seismogenic mechanisms is still too limited to individuate active and seismogenic faults and only touches on restrected areas of national territory. There is a significant advantage in bering able to evaluate the seismic risk from linear sources (faults) on the site of wide seismogenetic zones, allowing us to define the risk differences within the zone precisely (that would otherwise remain almost undifferentiated).

In the deterministic modelling of the seismic risk, an exact knowledge of the seismic source is fundamental for any computation. The identification of single faults (Morelli, 1999) and the association of earthquakes to specific faults, are therefore very important results for any hypothesis on the characteristics of future earthquakes and for proceeding to both the probabilistic and the deterministic modelling of the expected quake.

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