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Line CROP 11: Central Apennines
La linea CROP 11: Appennino Centrale

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ABSTRACT - The CROP 11 profile extends for 265 km from Marina di Tarquinia (on the Tyrrhenian coast) to Vasto (near Pescara, on the Adriatic coast). The line presents a west-east direction in order to study the crustal structure of this segment of the Apenninic chain where the northern and southern Apenninic arcs join together. On the surface the trace of the profile cuts across the Apenninic chain, from the Burdigalian foredeep in the west to the recent Pliocene foredeep overlying the Adriatic foreland. CROP 11 was acquired in two periods: the first 109 km in 1996 and a further 156 km in 1999. Processing of CROP 11 started in 1997 and was completed at the end of 2001. Data interpretation is still under way.

KEY-WORDS: Central Apennines, reflection seismic, crust, structural setting

RIASSUNTO - Il profilo CROP 11 si estende per 265 km attraverso l'Italia centrale, tra Marina di Tarquinia, sulla costa tirrenica, e Vasto, sulla costa adriatica. La sua direzione è sostanzialmente Ovest-Est ed è stato progettato per analizzare la struttura crostale in un settore in cui si affiancano i due grandi "archi" formati dalle strutture appenniniche settentrionali e centro-meridionali; in superficie, il profilo attraversa l'intero orogeno, dai resti della fase burdigaliana fino all'avanfossa più recente, e raggiunge l'avampaese. La linea è stata acquisita in due fasi: nel 1996 (109 km) e nel 1999 (156 km); il processing è iniziato nel 1997 e si è completato nel 2001. Attualmente è in corso l'interpretazione.

PAROLE CHIAVE: Appennino Centrale, sismica a riflessione, crosta, assetto strutturale

1. - INTRODUCTION

The CROP 11 profile extends for 265 km across Central Italy, from Marina di Tarquinia (on the Tyrrhenian coast) to Vasto (on the Adriatic coast), crossing, at as high an angle as possible, the main tectonic structures of the central Apennines (fig. 1). The line was acquired in two stages: the first 109 km in 1996 and the second 156 km in 1999. Processing of the CROP 11 lines began in 1997 and was completed at the end of 2001. Starting in 1989, the CROP 11 working groups, which include people from universities, CNR and industrial research structures, participated in the various phases of the CROP 11 project (TOZZI *et alii*, 1992). The CROP 11 working groups are currently interpreting data from the eastern part of the NVR profile, which extends from Vasto to Maiella; these data will be calibrated and substantially improved by integration with information provided by ENI-AGIP, mainly consisting of commercial seismic profiles and borehole data.

Preliminary studies directed at the acquisition of the CROP 11 deep seismic line provided us with the

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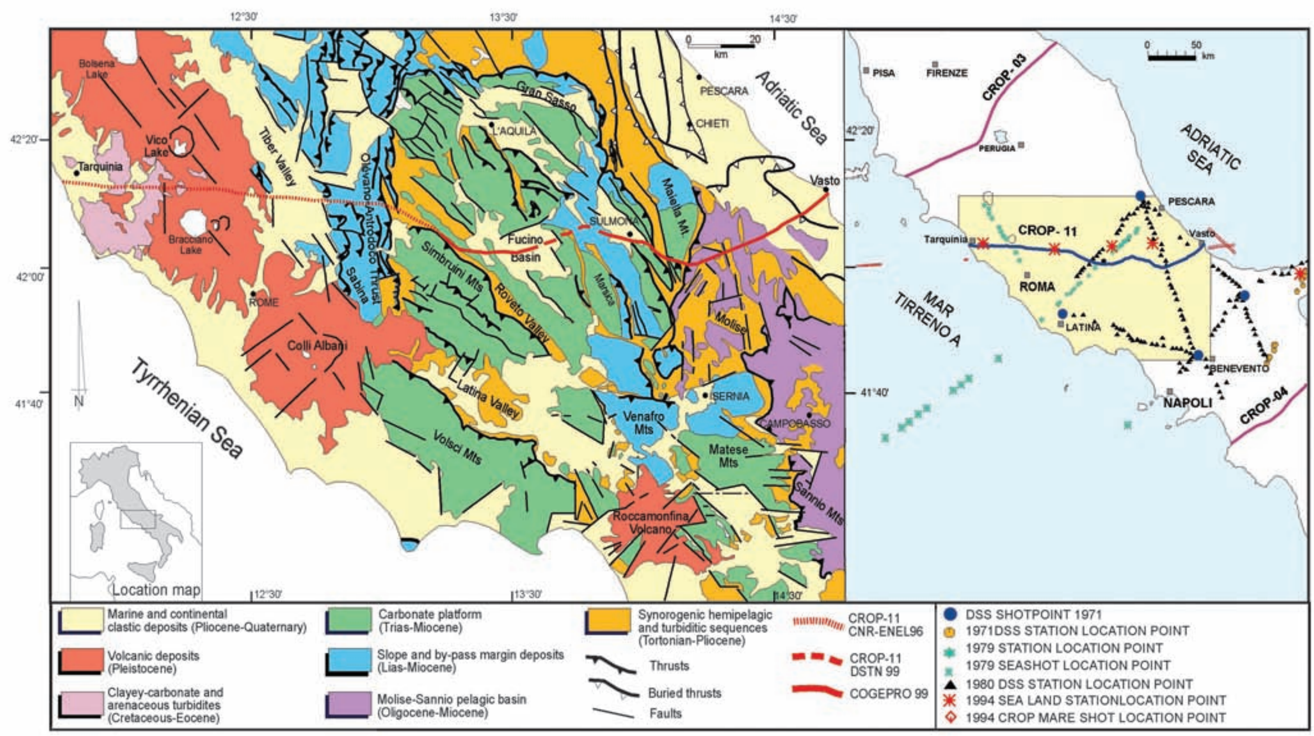

Fig. 1 - Geologic framework of Central Italy and position of the CROP 11 seismic line and DSS geophysical data.
- Schema geologico dell'Italia centrale e posizione della linea sismica CROP 11e dei dati geofisici DSS.

opportunity to review and revise all the geological and geophysical data available for Central Italy.

2. - THE GEOLOGICAL SETTING OF THE CENTRAL APENNINES

The central Apenninic chain is a Neogene fold-and-thrust belt that developed on ensialic crust after the Europe-Africa collision during the Alpine orogeny (ROYDEN *et alii*, 1987; DOGLIONI, 1991; BIGI *et alii*, 1992; CAVINATO & DE CELLES, 1999). Four main geodynamic provinces can be recognized in the central Apennines (from east to west) (fig. 1): a deformed intra-orogenic foreland (Apulia-Adriatic) made up of several blocks that have undergone rotation in different directions and of varying degrees since the Late Cretaceous; 2) a deformed foredeep (Adriatic trough) that is widely overthrust by the Apenninic chain; 3) a thrust belt (Apennines) that developed from the Early Cenozoic to the Pleistocene; and 4) a hinterland (Tyrrhenian basin), including large volcanic centers, that is now undergoing extensional tectonics.

The major thrust systems in the central Apennines strike NW-SE and dip gently towards the southwest. They include, from SW to NE: the Lepini, Simbruini, Velino-Sirente, Marsica, Morrone, Gran Sasso and Maiella thrust sheets (fig. 1). Additional thrusts and related folds are concealed beneath several km of Pliocene-Quaternary syn-orogenic sediments northeast of the topographic front of the range (fig. 1; BIGI *et alii*, 1992; PATACCA *et alii*, 1992; CIPOLLARI & COSENTINO, 1997; GHISETTI & VEZZANI, 1997). The exposed sequences consist of thick Triassic-middle Miocene carbonate platform, slope and ramp facies (from 5 to 3 km thick; fig. 1; BALLY *et alii*, 1986). The kinematic history of thrusting in the central Apennines is recorded by Miocene through Pliocene syn-orogenic sediments in foredeeps, which were progressively involved in the chain towards the Adriatic foreland (PATACCA *et alii*, 1992; CIPOLLARI & COSENTINO, 1997; CIPOLLARI *et alii*, 1997). Starting in the Messinian and continuing through the Early Pliocene, multi-phased deformational events formed NW-SE and NNW-SSE thrust sheets (Lepini, Simbruini, Velino-Magnola, Sirente, Marsica units; fig. 1). The Olevano-Antrodoco and Gran Sasso thrust systems are significant out-of-sequence thrusts that truncate some of the north to northwest-striking systems (fig. 1; CIPOLLARI & COSENTINO, 1997; GHISETTI & VEZZANI, 1997).

NW-SE and E-W high-angle normal fault systems, generally southwest and south-dipping, and extensional basins, of generally post-Messinian age, formed across the southwestern part of the thrust belt and are superimposed upon the compressional Neogene structure (CAVINATO & DE CELLES, 1999) (fig. 1). The extensional basins were progressively filled by alluvial and lacustrine deposits. The major Pliocene-Quaternary extensional basins include Tiberino, Rieti, L'Aquila, Fucino, and Sulmona basins (fig. 1).

The evolution of these geodynamic units suggests: the flexural retreat towards the NE of the edge of the Adriatic block, with a passive sinking of the lithosphere and associated roll-back mechanisms (ROYDEN *et alii*, 1987; DOGLIONI, 1991) and the progressive eastward advance of the Apenninic chain with in-sequence and out-of-sequence faults, transport of piggy-back basins and incorporation of fore deep basins. Strike-slip faulting and rotations have severely complicated the relationships among the geodynamic units, both in the chain and in the foreland (MOSTARDINI & MERLINI, 1986; PATACCA & SCANDONE, 1989; PATACCA *et alii*, 1990).

One of the major constraints of this geodynamic context is the contrast in geophysical features, which indicates the presence of at least two distinct tectonic regions. The geological, geochemical and geophysical data of the Adriatic region (to the east) refer to an old, inactive crust having a relatively simple surface structure (MORELLI, 1975; HOOKER *et alii*, 1985; ARISI ROTA & FICHERA, 1987; FEDI & RAPOLLA, 1992; DELLA VEDOVA *et alii*, 1988; NICOLICH, 1989; CARROZZO *et alii*, 1992; SCARASCIA *et alii*, 1994). The Tyrrhenian region (to the west) is characterized instead by a young, very active and thinned crust (see the afore-mentioned authors and TOZZI *et alii*, 1992).

One major problem is the involvement of the basement in the thrust tectonics. In the past, the Apenninic basement has been interpreted as not being involved in the Apennine orogeny. New evidence nowadays suggests the opposite: 1) the interpretation of the seismic data (CROP 03, see this volume) suggests that the basement was involved ("wedged Adria") in the Apenninic orogeny; 2) recent gravimetric data (DI FILIPPO & TORO, 1993) indicate the existence of buried steps of the basement in western areas of the Central Apennines (e.g. Latina valley); 3) the high degree of shortening of the surface units (CAVINATO *et alii*, 1994) could be better explained by basement involvement.

The cross-sections presented here (fig. 2) have been reconstructed from surface (bedding, dip-domains, stratigraphic and tectonic contacts) and subsurface data. The extrapolation of surface geometry to depth has been made keeping the relationships between tectonic boundaries and bedding constant, using the poor seismic data that are available for Central Italy. These preliminary CROP 11 cross-sections were largely influenced by the different interpretations of researchers working in the same area (CROP 11 working group). The authors cannot involve the basement in the thrust belt in the interpretations of figure 2. The main problems were the geometry of extensional tectonics, the importance of the main NW-SE and N-S transcurrent lineaments, the occurrence of out-of-sequence thrusts and the probable occurrence of block rotations.

3. - GEOPHYSICAL DATA

Using the updated geological and geophysical data, we propose a model of the deep structure underneath Central Italy, assuming that a subduction mechanism took place.

The general negative slope of the gravimetric curve suggests lower mantle densities in the western than in the eastern part of the model. This can be justified by the heat flow values and the spreading of the Tyrrhenian Sea. The minimum corresponding to the central part of the chain has been modeled by a wedge with low density intruding into the upper mantle. This wedge is interpreted as part of a slab of Adriatic lithosphere subducting towards the Tyrrhenian Sea (comparison was also made with reconstructions of the deep setting in Northern and Southern Italy).

A previous 2D interpretation, based on Bouguer and DSS data, shows a possible doubling of the Moho underneath the Apennines, according to a westward subduction (or passive sinking) of the Adria micro-plate (BERNABINI *et alii*, 1996). The authors have assumed a decrease in lateral density in the lower crust and within the lithospheric mantle of the Tyrrhenian area (characterized by high heat flow) (fig. 3). A preliminary 3D reconstruction has also been attempted by using the stripping-off technique. A strong residual gravity anomaly (-30 mGal), located along the central Apenninic chain, has been detected between the positive anomalies of both the Adriatic and the Tyrrhenian coasts. There is a fundamental difference in the behaviour of the gravity anomalies in the northern and southern sectors of the Apennines, separated by a sharp E-W trending of the iso-anomalies that is probably related to a NE-SW (W-E) activity of the major faults.

Interpretation of the gravity data reveals two main characteristics of the lower crust and upper mantle in Central Italy. First, the minimum present in the central part of the curve can be modeled by incorporating sub-Moho density differences.

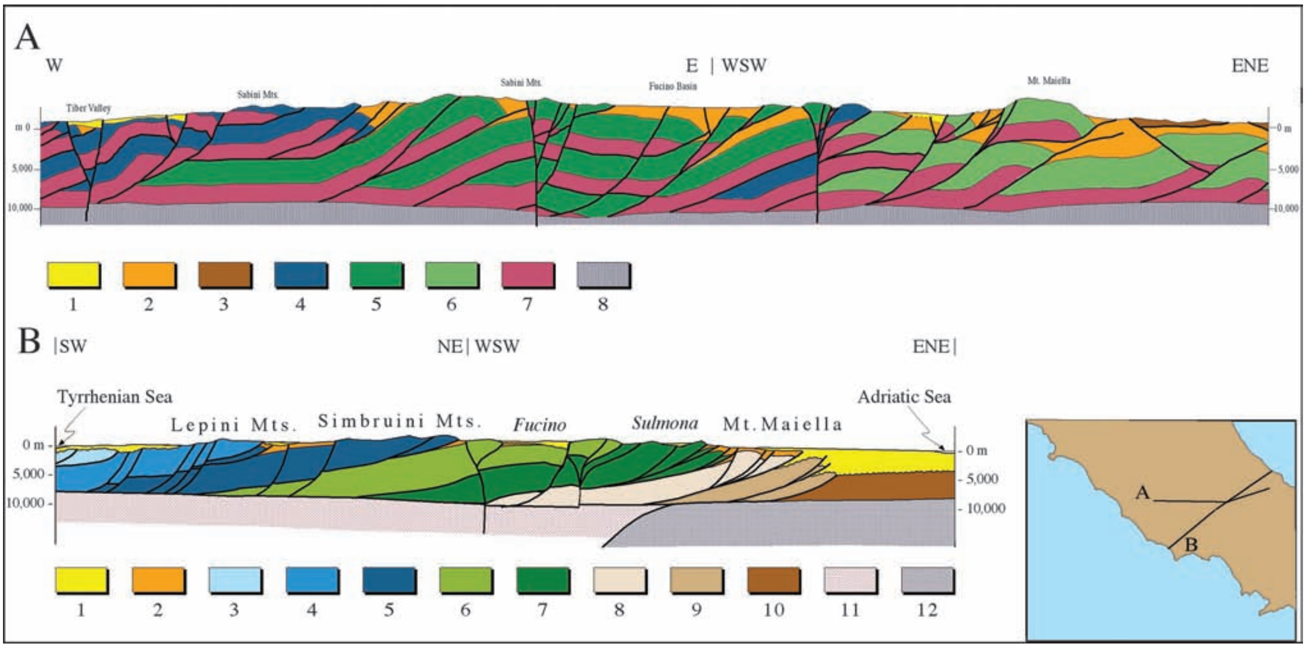

Fig. 2 - Schematic cross-sections of the central Apennine thrust belt. A 1) marine and continental deposits (Plio-Quaternary); 2) syn-orogenic deposits (Upper Tortonian-Lower Pliocene); 3) allochthonous deposits (Oligo-Miocene); 4) Umbro-Sabina and Marsica slope and by-pass marginal deposits (Lias-Miocene); 5) Latium-Abruzzi carbonate platform(Lias-Miocene); 6) Adriatic carbonate platform (Lias-Miocene): 7) Triassic car-bonate platform (Trias); 8) magnetic basement (from SALVINI *et alii*, 1997, modified). B 1) marine and continental post-orogenic sedimentary cover of the Tyrrhenian side of the Apennines and of the intramontane basins (Upper Messinian-Quaternary) and marine syn- and post-orogenic deposits of the Adriatic side of the Apennines (Lower Pliocene-Quaternary); 2) syn-orogenic deposits of the different Apennine fore-deep basins (Upper Tortonian to Lower Pliocene); 3) Mt. Circeo tectonic unit; 4) Lepini Mts. tectonic unit; 5) Ernici Mts. and Simbruini Mts. tectonic unit; 6) Marsica tectonic unit; 7) Morrone Mts. and Queglia tectonic unit; 8) Mt. Maiella tectonic unit; 9) Casoli-Bomba tectonic unit; 10) Adriatic foreland; 11) magnetic basement of the Apennine thrust belt; 12) magnetic basement of the Adriatic foreland (from CIPOLLARI *et alii*, 1999).

- Sezioni geologiche schematiche attraverso la catena appenninica dell'Italia centrale. A 1) Depositi marini e continentali (Plio-Quaternario); 2) Depositi sin-orogenici (Tortoniano sup. - Pliocene inf.); 3) Coltri Alloctone molisane (Oligo-Miocene); 4) Depositi di margine e bacinali Umbro-Sabini e della Marsica (Lias- Miocene); 5) Piattaforma Laziale-Abruzzese (Lias- Miocene); 6) Piattaforma carbonatica Adriatica (Lias-Miocene); 7) Piattaforma carbonatica Triassica (Trias); 8) Basamento magnetico.(da SALVINI et alii*, 1999). B 1) Coperture post-orogene sedimentarie marine e continentali del margine tirrenico, dei bacini intramontani e (Messiniano sup.-Quaternario) e depositi marini sin e post orogeni del margine adriatico (Pliocene inf.-Quaternario); 2) Depositi sin-orogeni dei differenti bacini di avanfossa dell'Appennino (Tortoniano- Pliocene inf.); 3) Unità tettonica del M. Circeo; 4) Unità tettonica dei M. Lepini; 5) Unità tettonica dei Simbruini-Ernici; 6) Unità tettonica Marsica; 7) Unità tettonica del M. Morrone-Queglia; 8) Unità tettonica del M. Maiella; 9) Unità tettonica di Casoli-Bomba; 10) Avampaese Adriatico; 11) Basamento magnetico della catena appenninica; 12) Basamento magnetico dell'avampaese adriatico (da CIPOLLARI* et alii*, 1999).*

This involves a wedge-like body within the upper mantle beneath the core of the Apenninic chain having a density similar to that of the lighter lower crust. Secondly, keeping the Moho at the known depth of 20-25 km while following the regional trend of the gravity curve requires us to decrease the densities of both the lower crust and the upper mantle on the Tyrrhenian side with respect to the values on the Adriatic side.

There is a density decrease of the lower crust from the central sector westwards: in the upper mantle the parts with differing densities are separated by a lighter wedge. This model assumes a density of 3.32 g/cm^3 for the Adriatic side and 3.26 g/cm^3 for the Tyrrhenian side.

The low-density wedge below the Moho can be interpreted as a low-density slab of Adriatic lithosphere subducting towards the Tyrrhenian Sea. The presence of this slab subducting towards the west has already been hypothesized for the Northern and Southern Apennines, where strong evidence of earthquake hypocenters has revealed surfaces that are progressively dipping towards the Tyrrhenian Sea (AMATO *et alii*, 1998; PATACCA & SCANDONE, 1989 and bibliography inside; GIARDINI & VELONÀ, 1992). Deep earthquakes are not present in Central Italy, so the presence of such a slab (PATACCA & SCANDONE, 1989) is not supported by seismic data. Currently gravimetric data are the only deep geophysical data available to support this hypothesis.

From the geodynamic point of view, the presence of this slab is not just possible, but indeed a necessity (DOGLIONI, 1991).

It would correspond to an intermediate crustal domain identified by the deep seismic soundings (in CAVINATO *et alii*, 1994, according to SCARASCIA *et alii*, 1994) (fig. 4). In fact, DSS has identified a doubled crustal domain between the Adriatic and the Tyrrhenian with different physical characteristics.

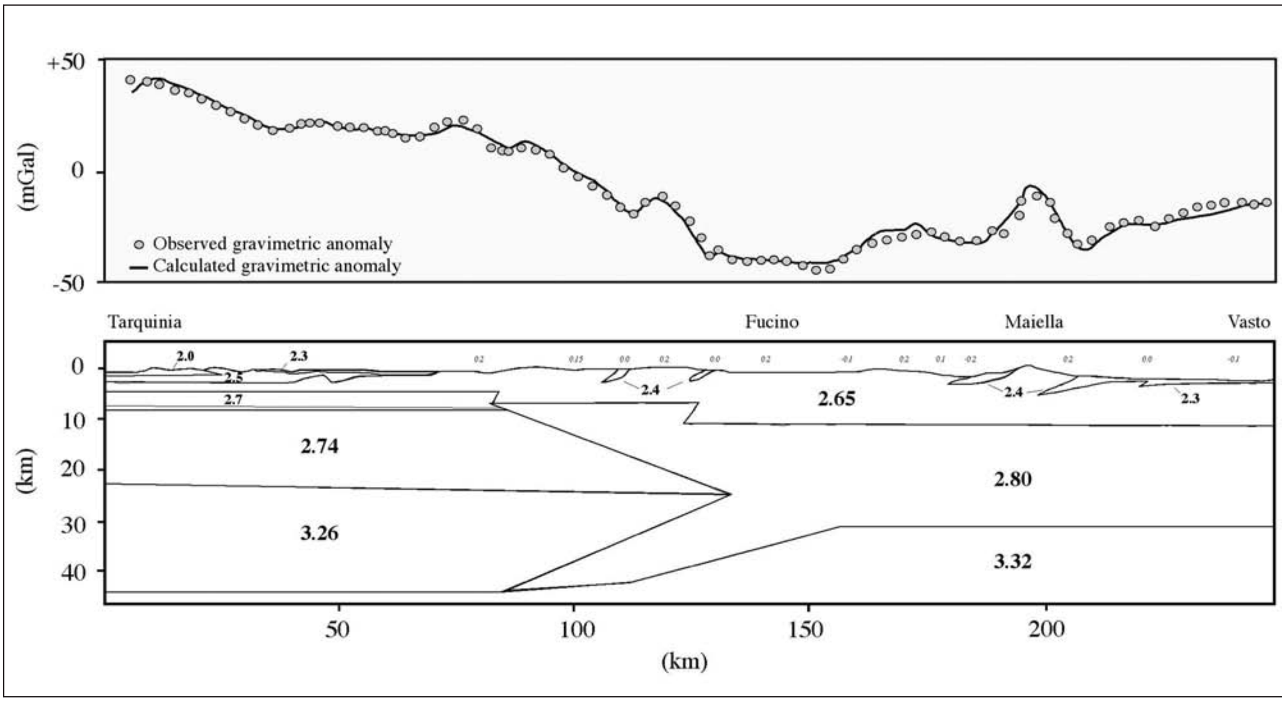

Fig. 3 - Simplified gravimetric model along the CROP 11 line, based on 1980 DSS data (Latina-Pescara) (from BERNABINI *et alii*, 1996, modified).
- *Modello gravimetrico semplificato (da* BERNABINI et alii*, 1996, modificato)*

The presence of a lateral dishomogeneity in the lower crust and upper mantle is a feature peculiar to this part of the lithosphere. In some other chains a reduction in seismic wave velocity along the Moho can be observed along the side towards which the slab dips. However, gravimetric studies performed in Europe (NFP 20, ECORS) generally do not indicate horizontal variations in the upper mantle, whose density ranges from 3.05 to 3.32 g/cm^3 (REY *et alii*, 1990; GUALTIERI *et alii*, 1992). Despite this, the lower densities in the western part of the Italian peninsula with respect to the eastern side can be justified by the values of heat flow and the spreading of the Tyrrhenian Sea.

4. - SEISMIC ACQUISITION

The seismic profile CROP 11 was acquired from the Tyrrhenian Sea (Marina di Tarquinia) to the Adriatic Sea (Vasto) for a length of 265 km (fig. 1). In 1989 the CROP 11 working group began drawning up the preliminary trace of the seismic line, integrating it with CROP surveys and analyses (structural and stratigraphic). In 1991 the proposed trace and the scientific data were discussed in a Meeting (TOZZI *et alii*, 1992).

The profile was acquired in two different periods. The first part started in 1996 and was run for 109 km from Marina di Tarquina to Colli di Monte Bove (fig. 1). Starting with our joint work on the CROP 04 and CROP 03 acquisition and data processing, our cooperation with the G.A.P. (Acquisition and Processing Group), has played an important role in any pre-survey planning. Drawing on its experience in a similar geological setting during the first part of CROP 03 (Tuscan units and great extension of volcanic units), the G.A.P. committee proposed the same acquisition parameters as in CROP 03 (dynamite energy source, symmetric split-spread) from Marina di Tarquinia to the Tiber River (fig. 5). Before reaching the Tiber River, and once the profile had passed across the Sabina thrust belt, the G.A.P. proposed a change in the group interval from 60 to 40 m.

Data acquisition was performed by the "Osservatorio Geofisico Sperimentale", now known as the "Istituto Nazionale di Oceanografia e di Geofisica Sperimentale" (O.G.S.-Trieste), with an accurate quality control applied in the field through the installation of a micro-processing centre under the close supervision of the G.A.P. (fig. 6).

Acquisition was suspended for three years due to a lack of funds and was completed at the end of 1999. The 156 km of the second part of the profile were jointly financed by CNR and ENEL (7 km 1996 with residual financial funds), the Dipartimento Servizi Tecnici Nazionali (D.S.T.N.) (37 km, from

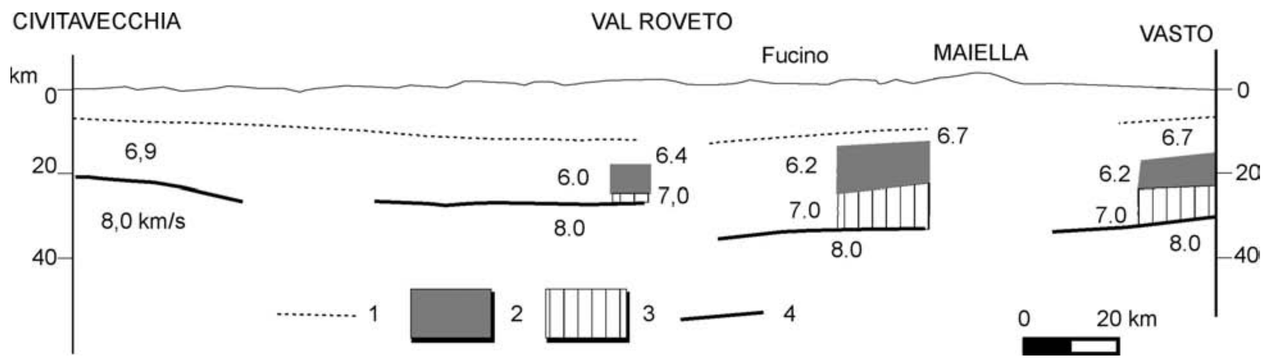

Fig. 4 - Crustal section along the CROP 11 line based on DSS data. 1) Aeromagnetic basement; 2) crustal low-velocity layer; 3) lower crust; 4) Moho (from BERNABINI *et alii*, 1996, modified).

Sezione geologica crostale lungo la traccia del profilo CROP 11 basata su dati DSS. 1) Basamento aeromagne-tico; 2) Intervallo crostale a bassa velocità; 3) Crosta inferiore; 4) Moho (da BERNABINI et alii*, 1996, modificata)*

Corcumello to Prezza) and by CO.GE.PRO. (Consorzio Geofisica Profonda) a consortium between the O.G.S. and GEOTEC for the 112 km from Prezza to Vasto (fig. 1).

The data acquired are generally of good quality, in particular from the Tiber Valley across the Apenninic chain to the Fucino basin, although there is some variability due to the different shallow lithologies and surface structural trends and different local noise conditions.

The processing was carried out at the O.G.S. seismic processing centre by L. Cernobori. The processing sequence is that normally used for on-shore data processing, although it focuses on the specific targets of the project; thus, the processing parameters were chosen so as to highlight deep geological structures without neglecting those near the surface (BERTELLI *et alii*, this volume).

During the 1995 CROP off-shore acquisition, in collaboration with the CNR (Istituto Rischio Sismico, Milano) the seismic signals were acquired in several stations along the trace of CROP 11 (BIELLA *et alii*, 1997). This data permit to confirm that the Tyrrhenian crustal tickness is about 22 km and in the eastern part (from Vasto to Maiella) the adriatic crust is 35 km thick.

5. - PRELIMINARY RESULTS

The interpretation of the lines started in the middle of 2001 with the easternmost part, from Vasto to Maiella. The preliminary results were presented at the GNGTS Congress (BILLI *et alii*, 2001) and are summarized here.

Identification of the main reflectors recognized between 0 and 5 seconds TWT is based on the integration of the seismic data with the surface geology and subsurface information derived from several wells drilled in the region for petroleum exploration. Company lines and data have contributed to improving the reconstruction converted by means of GeoSec software, using velocity values that were obtained from borehole calibrations on the line, as well as from subsurface regional information.

Between Mt. Maiella and the Adriatic shoreline, the CROP 11 line cuts across the outer margin of the Apennine thrust belt and the inner margin of the Apulia foreland.

The portion of Apulia foreland explored by commercial boreholes consists of a thick pile (more than 6000 m) of Mesozoic-Tertiary shallow-water carbonates (as well as Triassic evaporites) conformably overlying Permian-Triassic siliciclastic deposits (see Puglia 1 and Gargano 1 wells) and disconformably overlain by Pliocene-Pleistocene clays, sands and subordinate conglomerates. Messinian evaporites commonly occur on top of the Mesozoic-Tertiary carbonates. Due to the acoustic-impedance contrast, a continuous strong reflector generally marks the top of the Apulia carbonates (including the Messinian evaporites). Between 4 and 5 seconds TWT, a sudden change occurs in the seismic facies. A layered unit characterized by a package of well-defined continuous reflectors underlies the massive unit of the platform carbonates that shows only discontinuous irregular reflectors. This change marks the contact between the Middle-Upper Triassic dolomites and anhydrites and the Permian-Lower Triassic Verrucano-like siliciclastic deposits.

In the Furci-Scerni area, the Pliocene-Pleistocene autochthonous deposits disconformably covering the Apulia carbonates and evaporites are

Fig. 5 - Photo gallery of the CROP 11 acquisition phase. A) Tarquinia area; B) Colli di Monte Bove area; C) Tagliacozzo-Fucino area; D) Fucino area.
- Galleria fotografica della linea CROP 11. A) Zona di Tarquinia; B) Colli di Monte Bove; C) Zona di Tagliacozzo-Fucino; D) Area del Fucino.

tectonically overlain by rootless nappes (Molise units). The allochthonous sheets basically consist of Middle Cretaceous-Upper Miocene basinal carbonates followed by uppermost Tortonian-Lower Messinian siliciclastic flysch deposits. In the study region, the Molise nappes are unconformably overlain by Upper Messinian to Lower Pleistocene thrust-sheet-top deposits.

From the Adriatic coast to the eastern margin of the Frentani Mountains, the top of the foreland Apulia carbonates for about 25 kilometres takes the shape of a regular homocline gently dipping towards the west. The top of the carbonates lies at about 1.8 seconds TWT in the east and 2 seconds in the west. Moving westwards from the eastern foot of the Frentani mountains, the structural setting of the Apulia carbonates provides evidence for a severe compressional deformation. The top of the platform climbs from 2 seconds east of Pennadomo 1 to about 1 seconds (i.e., less than 1000 metres below sea level) in correspondence to the Bomba area. West of the Bomba structure, the top of the platform rapidly deepens to about 2.5 seconds TWT. In this area, the Torricella Peligna 2 well bottomholed at 2472 m (1697 m below sea level) without reaching the Apulia platform. Further west, the top of the Apulia platform rises rapidly to shallower levels and finally reaches the surface in correspondence to the eastern flank of Mt. Maiella.

The deepening of the Apulia carbonates from Mt. Maiella to the Torricella Peligna structural depression has been interpreted as the expression of a thrust-fold cascade, that is, of a stack of partly overlapping ramp anticlines, derived from at least three imbricates the highest of which is represented by the Maiella anticline. The subsequent rise of the Apulia carbonates from the Torricella Peligna depression to the Bomba ridge has been interpreted as a first-order back-thrust feature related to a triangle zone at the base of the platform that in late Pliocene-early Pleistocene times

Fig. 6 - The G.A.P and CROP 11 working group at Celano (AQ) during the acquisition of CROP 11.
- *Il G.A.P. e il working group del CROP 11 a Celano (Aq) durante le fasi di acquisizione della linea* CROP 11.

allowed tectonic transport to take place from a hinterland-dipping thrust-flat surface (sole thrust of the Apenninic system) to a foreland-dipping ramp. Other authors have recently interpreted the western flank of the Bomba ridge as the footwall of a normal-fault system responsible for the deepening of the Apulia carbonates in the Torricella Peligna area.

The deep crustal structures in the area crossed by the CROP 11 are well imaged in correspondence to the Apulian foreland. A reflector is recognised at around 7 s TWT, gently dipping towards the west. It can be easily followed up to the Bomba ridge area where there are complex structures and velocity changes near the surface and at depth. Other deeper and sub-parallel reflective intervals are imaged at 10 s and at 12 s TWT. These can be assigned to a layered lower crust of about 2.5 s thickness (about 9 km). The Moho can be identified at the base of the lowermost interval, at 12.5 s reflection time (around 32 km depth). This discontinuity deepens towards the west and reaches 13 to 14 s TWT beneath Mt. Maiella.

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