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Line CROP 03: Northern Apennines

La linea CROP 03: Appennino Settentrionale

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Abstract - This paper is to offer a brief description of the CROP 03 profile: a comprehensive review of the results of the CROP 03 project is contained in a Special Volume of the Memorie della Società Geologica Italiana (Pialli et alii, 1998), containing more than 50 papers and offering a range of different, geodynamic interpretations.

The CROP 03 profile, acquired during the 1993, extends across the whole Central Italy, from Punta Ala (on the Tyrrhenian coast) to Gabicce (near Pesaro, on the Adriatic coast), crossing, almost orthogonally, the main tectonic features of the Northern Apennines.

Important contributions to the CROP 03 project have been supplied by other geophysical techniques: a wide angle reflection survey (DSS) and three Expanding Spread experiments have been carried out in addition to the NVR survey. The interpretation or re-interpretation of existing magnetic, heath flow and seismological data was performed and new gravity data had been collected as well. Finally, the interpretation of the NVR profile has been calibrated and substantially improved by using other "shallow" seismic profiles and deep boreholes.

As a consequence of its complex tectonic evolution, the Northern Appenines can be divided into two large, different structural domains, whose distinction is underlined by the main geophysical and geological characters, and is easily readable in the CROP 03 profile as well.

1) A western, "Tyrrhenian" domain, whose main features consist of positive Bouguer anomalies, high values of heat flow, thinned crust with a brand new Moho (22-25 km) and an extensional regime lasting since 15 Ma.
2) An eastern, "Adriatic" domain, where gravity anomalies are negative, heat flow is low, a compressional stress field is acting today in the foreland (Adriatic Sea), and started in its inner sector 15 Ma.

In the western portion of the profile ("Tuscan sector", CDP 0-4500) the signature of the lower crust is represented by a laterally fairly continuous pack of mixed, medium to high amplitude, reflectors, located in between 4 and 7 s (two ways travel-time, TWT). A group of, strong, almost flat reflectors, locally assuming the character of bright spots, are present at intermediate depth (4-5 s TWT), close to the top of the lower crust, in correspondence with the geothermal fields of Larderello and M. Amiata. The most relevant structural feature in the upper crust is the presence of five main ENE dipping undulate crustal scale normal faults, which the Miocene-Pleistocene, continental and shallow marine basins of Tuscany are related to.

The intermediate sector (CDP 4500-5600, from Valdichiana to Valtiberina basin) represents a sort of highly reflective window, where the overall signal increases. Below this zone, seismic refraction data depict a Moho doubling, while the shallow levels are characterised by the superposition of the Tuscan Units on the Umbria-Marche Units.

In the easternmost portion ("Umbria-Marche sector", CDP 5600-8100), the signals of lower crust are less pronounced than in the western part of the profile, and depict an overall dip toward south-west. On the contrary, the shallow structures of the Umbria-Marche fold and thrust belts are clearly recognisable, allowing a detailed geometric and kinematic reconstruction: a total shortening of about 60 km (30 %) has been evaluated.

In conclusion, the CROP 03 profile gives an opportunity of exploring some key-questions of the geology of the Northern Apennines, giving new data about:

- The localisation and geometry of the major crustal shear zones, responsible for the extension in Tuscany and the compression in the Marche-Adriatic sector;
- The presence and geodynamical significance of the crustal doubling, located in correspondence of the strong gravimetric gradients between Umbria and Tuscany;
- The geological processes which produces phenomena of great practical relevance, such as the geothermal fields of Tuscany and the earthquakes of the Umbria-Marche region;
- The contemporaneous activity of extension and compression in adjacent domains, which represents a distinctive character of the Northern Apennines throughout their whole evolution history.

Key-Words: Northern Apennines, reflection seismic, deep crust.

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RIASSUNTO - Scopo di questa nota è di descrivere brevemente i caratteri principali del profilo CROP03. Una descrizione più estesa dei risultati del progetto è contenuta nel Volume 52 delle Memorie della Società Geologica Italiana, che comprende circa 50 articoli sui diversi aspetti ed interpretazioni del profilo.

Il profilo CROP03 è stato acquisito nel 1993, e si estende attraverso l'Italia centrale, dalla costa tirrenica (Punta Ala) a quella adriatica (Gabicce, vicino Pesaro), in direzione più o meno ortogonale alle principali strutture dell'Appennino settentrionale.

L'acquisizione del profilo a riflessione NVR, è stata accompagnata da un esperimento di sismica a riflessione ad alto angolo e da tre esperimenti di tipo "Expanding Spread". Sono stati inoltre raccolti nuovi dati gravimetrici, e ulteriori contributi sono venuti dalla rielaborazione dei dati aeromagnetici, sismologici e del flusso di calore. La disponibilità di altri profili sismici a riflessione e di perforazioni profonde, forniti dall'ENI/AGIP e dall'ENEL, è stata fondamentale per la calibrazione e l'interpretazione del profilo.

Particolare cura è stata posta, nelle fasi di progettazione del profilo alla scelta dei parametri di acquisizione e della sequenza di processing, nonché alla individuazione del tracciato ottimale. Questa attenzione è stata ripagata da risultati che possono essere considerati buoni, anche in considerazione della complessità dell'area attraversata.

In generale, i risultati del profilo possono essere letti come una conferma della divisione dell'Appennino settentrionale in due grandi domini strutturali, che si differenziano nettamente, sia dal punto di vista geologico che geofisico:
- il "dominio tirrenico", caratterizzato da anomalie di Bouger positive, alti valori del flusso di calore, crosta assottigliata (22-25 km) e da estensione crostale attiva negli ultimi 15 Ma;
- il "dominio adriatico", caratterizzato da anomalie gravimetriche negative, basso flusso di calore, spessori crostali più elevati (circa 35 km) e compressione attiva, migrante da W verso E, negli ultimi 15 Ma.

Nel settore occidentale del profilo (toscano, CDP 0-4500) il carattere sismico della crosta inferiore è a tratti ben riconoscibile, a profondità comprese tra 4 e 7 s (tempi doppi), mentre attorno al tetto della crosta inferiore è presente una serie di riflettori marcati, sub-orizzontali, posti in corrispondenza dei campi geotermici della Toscana. Nella crosta superiore, il carattere distintivo è la presenza di zone di taglio distensive, immergenti verso est, cui sono associati i bacini marini e continentali della regione dal Miocene al Pleistocene.

Nel settore orientale (umbro-marchigiano, CDP 5600-8100) il segnale della crosta inferiore è assai meno pronunciato e solo localmente è riconoscibile un'immersione generale verso ovest. Al contrario, le strutture della copertura sedimentaria e del basamento sono ben riconoscibili e consentono di giungere ad una stima accurata del raccorciamento subito dalla catena umbro-marchigiana.

Tra il settore tirrenico e quello adriatico si individua una zona intermedia (CDP 4500-5600), in corrispondenza del "gradino" crostale individuato anche dalla sismica a rifrazione e, in superficie, dalla sovrapposizione delle unità toscane su quelle umbre. Questa parte del profilo si mostra come una sorta di "finestra", caratterizzata da alta riflettività, che è stata interpretata come espressione di una serie di embricazioni crostali. Tuttavia, è proprio questa la parte del profilo più controversa, quella in cui concentrare gli sforzi per ulteriori elaborazioni ed interpretazioni, per cercare di capire meglio i rapporti e le interazioni tra i due settori dell'Appennino settentrionale.

Nell'insieme, i dati offerti dal profilo CROP03 ci consentono di interrogarci su alcune delle questioni-chiave che riguardano la geologia dell'Appennino settentrionale, come per esempio:
- localizzare, nella copertura e nella crosta, le maggiori zone di taglio che guidano l'estensione della crosta Toscana ed il raccorciamento di quella adriatica;
- esplorare il significato strutturale del forte gradiente gravimetrico esistente al confine tra Toscana e Umbria;
- capire meglio alcuni temi di rilevante interesse applicativo, come la genesi e l'evoluzione della struttura che genera i campi geotermici della Toscana, o i processi tettonici responsabili della sismicità nell'area di catena umbro-marchigiana;
- capire meglio il meccanismo che genera la contemporanea presenza di campi di sforzi compressivi ed estensionali in domini strutturali adiacenti, un carattere distintivo del sistema Tirreno-Appennini.

PAROLE CHIAVE: Appennino settentrionale, sismica a riflessione, crosta profonda.

1.- INTRODUCTION

The CROP 03 profile, acquired during 1993, extends across the whole of Central Italy, from Punta Ala (on the Tyrrhenian coast) to Gabicce (near Pesaro, on the Adriatic coast), crossing, at as high an angle as possible, the main tectonic features of the Northern Apennines (fig. 1).

Many research units participated, over a five-year period, in the different phases of the CROP 03 project, involving more than one hundred people from both university and industrial research structures. The project was admirably directed by Giampaolo PIALLI, who dedicated to it almost ten years of intense activity, and through whose immense and continuous efforts a variety of earth scientists with different ideas and backgrounds were able to work together. This work is summarised in a special issue of the Memorie della Società Geologica Italiana (PIALLI *et alii*, 1998), which includes about 50 papers, dealing with the major geophysical and geological themes generated by the CROP 03 profile and proposing a range of possible geodynamic interpretations.

The choice of the profile trace was preceded by an analysis of the existing commercial seismic lines, recorded throughout the region. This analysis convinced us that, in order to obtain good reflectors at depth in the Northern Apennines, it was necessary to pass through flysch-like units (mainly sandstones and marls), thick enough to transmit at depth elastic energy so that buried structures could be revealed. Conversely, we had to avoid, as far as possible, the outcrops of carbonates. We were therefore forced to trace a transect exploiting as much as possible outcrops consisting of flysch-like units.

In order to obtain the most complete set of data possible, other geophysical experiments in addition to the NVR survey were carried out as part of the CROP 03 project (fig. 2). In particular:
- a wide angle reflection survey (DSS), with mirrors almost coincident with the reflection profile (DE FRANCO *et alii*, 1998);
- three expanding spread experiments, located in the most critical areas (ZANZI, 1998).

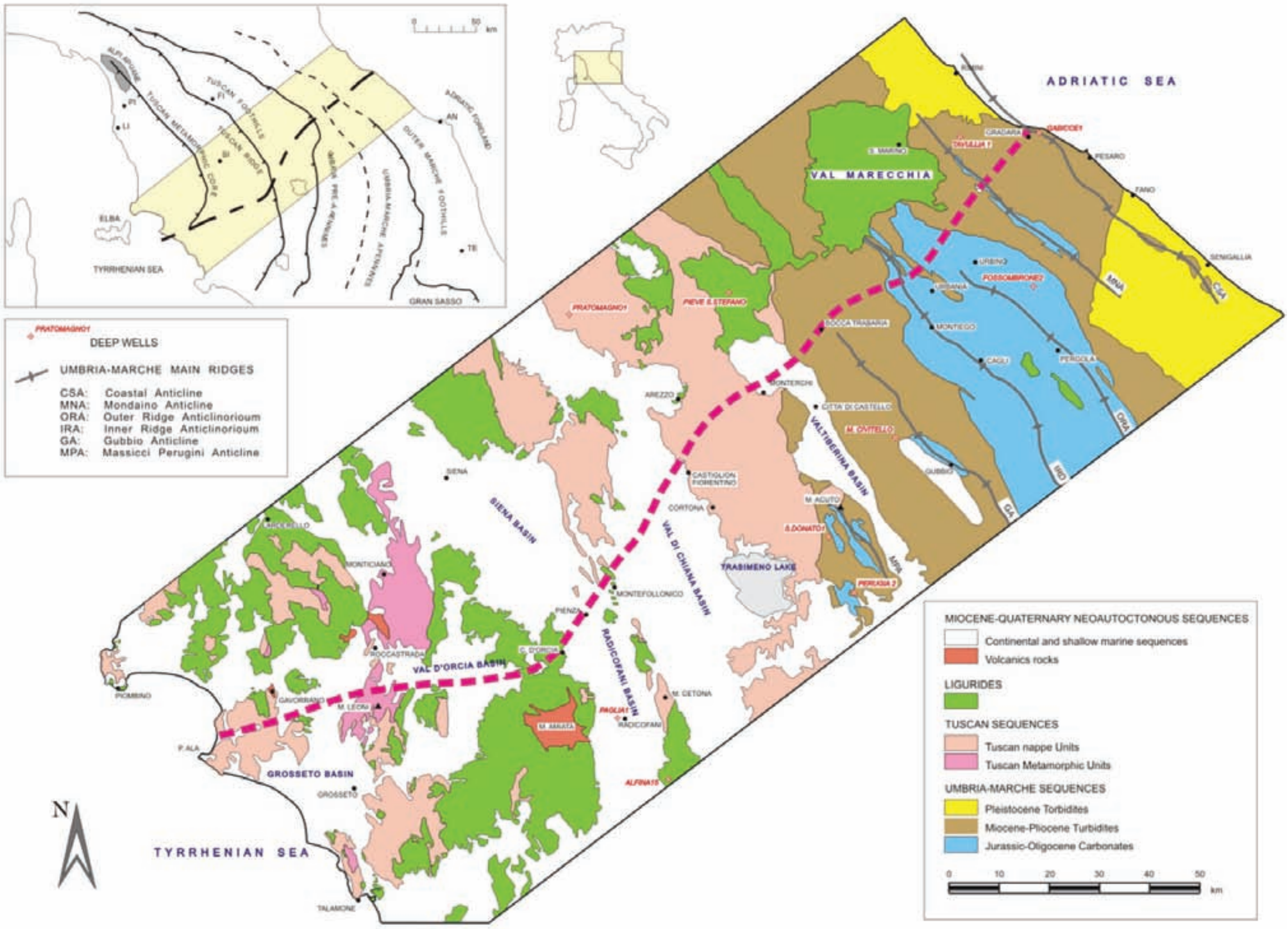

Fig. 1 - Geological setting of the region crossed by line CROP 03.
- Schema geologico della regione attraversata dal profilo CROP 03.

Important contributions to the CROP 03 project were provided by the the use of other geophysical techniques and by the interpretation or re-interpretation of existing magnetic, heat flow and seismological data. New gravity data along the CROP 03 line were also collected.

Moreover, the interpretation of the NVR profile was calibrated and substantially improved by the use of further information, made available by ENI-AGIP and ENEL, mainly consisting of commercial "shallow" seismic profiles and deep boreholes (fig. 2).

2. – THE NORTHERN APPENNINES

After the Alps, the Northern Apennines (hereinafter, NA) constitute the best known mountain ridge of Italy and has been studied since the beginning of this century (SIGNORINI, 1940; MIGLIORINI, 1948; TREVISAN, 1952; MERLA, 1952; SELLI, 1954). During last forty years, new generations of Italian and foreign geologists from Academia and Industry, have greatly extended our knowledge and, with the help of commercial seismic reflection lines and deep seismic refraction profiles, shifted interest from surface geology to geology concerned with deeper levels.

At present most research work attempts to understand the deep causes, geodynamic processes and mechanisms responsible for NA building and the closely linked formation of the Northern Tyrrhenian Sea (hereinafter, NTS).

Moreover, the NA is one of the key areas for the study of the genetic relationships between the Apennine belt and the Alpine orogene.

These problems can only be unravelled by means of interdisciplinary work, carried out by teams in which the work of geologists and geophysicists is closely integrated. It is with this philosophy that the CROP Project was initiated.

Starting from the stratigraphy, the NA region shows the exposures of the following major tectono-stratigraphic units (fig. 1):

I) *Miocene - Quaternary neoautoctonous sequences*. They include the sediments that fill the extensional basins from the eastern border of the Corsica-Sardinia

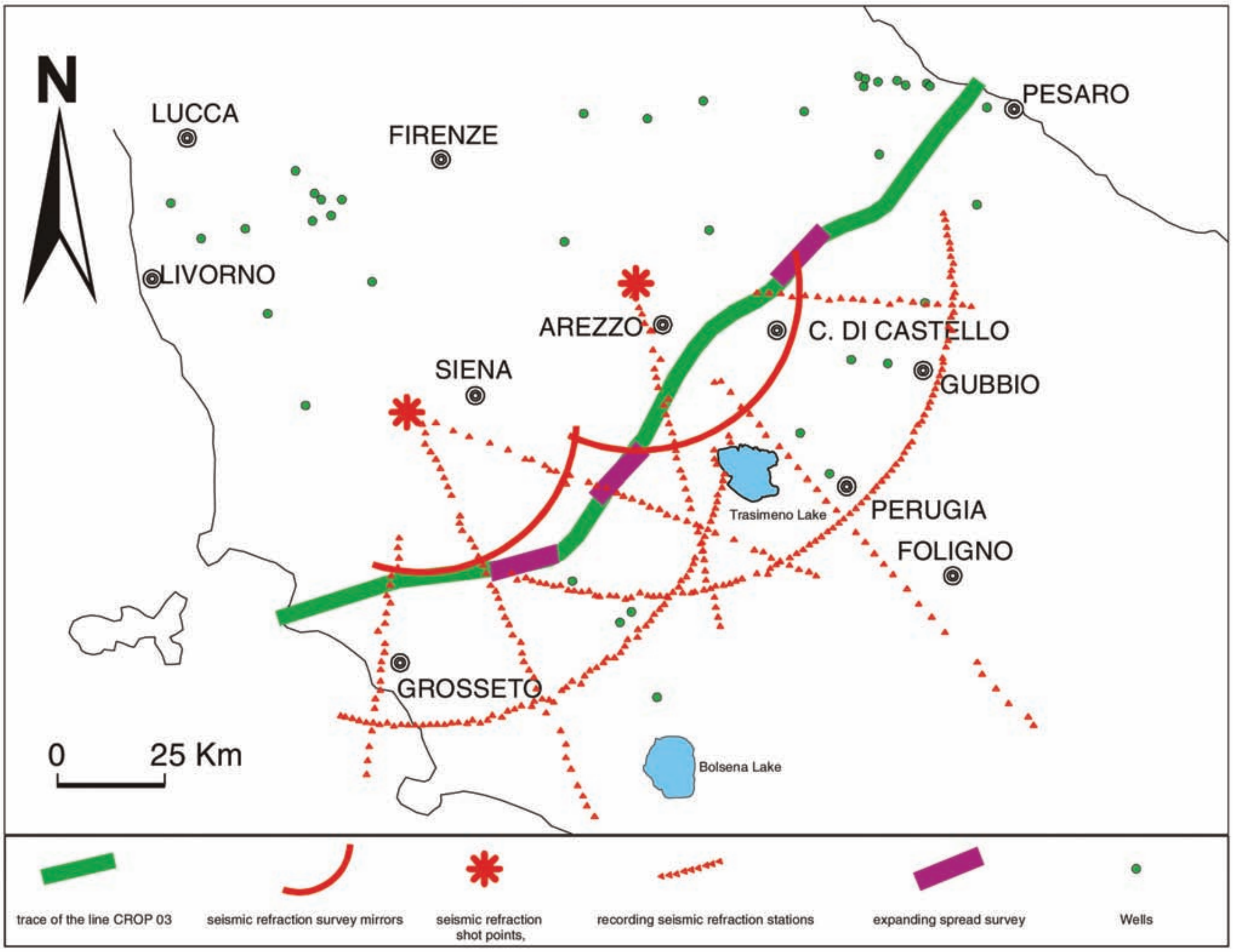

Fig. 2 - Data base of the CROP 03 project.
- Localizzazione degli esperimenti e dei dati utilizzati nel progetto CROP 03.

block to the western border of the Umbria Marche thrust and fold belt. Tertiary and Quaternary volcanic and magmatic products are included in these.

II) *Ligurid units* - They include the Liguride sequences, the Schistes Lustré thrust over them and the epiligurids which sealed the Alpine building since the M. Eocene. These units were displaced eastwards, onto the Adria crust, from the Late Oligocene.

III) *Tuscan Nappe units* - They consist of a Mesozoic through Tertiary sedimentary sequence detached either on top of Triassic evaporites or on top of the Paleozoic phyllites and thrust over a homologous, but metamorphosed sequence.

IV) *Tuscan metamorphic units* - These include the "autocthonous" and "parautocthonous" Paleozoic basement, with polyphase tectonics referable to the Hercynian phases, and the Mesozoic through Tertiary cover, quite similar to that of the Tuscan Nappe, but affected by greenschist facies metamorphism of Early Miocene age (DEINO *et alii*, 1992)

V) *Umbria - Marche sequences*. The Umbria - Marche sedimentary sequence, principally evaporites plus platform and pelagic carbonates, was deposited on the stretching and subsiding Adria continental crust from the Triassic to the early Tertiary. The basement of this domain does not crop out, but has been drilled by the Perugia 2 and S.Donato1 wells (MARTINIS & PIERI, 1964; ANELLI *et alii*, 1994).

The deposition of these sequences is related to the Triassic-Lower Cretaceous evolution of the Mediterranean Tethys, most of them deposited in a passive margin tectonic environment. This extensional phase was followed by an active-margin phase, in which the Alpine chain formed (Late Cretaceous-Middle Eocene), involving also the Ligurian domain of the Apennines.

The NA are the result of the convergence between the already formed Alpine orogene and the continental crust of the Adria promontory: the convergence developed in response to the rapid rotation of the Corsica-Sardinia microcontinent during Upper Oligocene - Early Miocene, continued throughout the Tertiary age and is still going on along the Romagna-Adriatic front (AMATO & SELVAGGI, 1991, MINELLI *et alii*, 1991). From Upper Oligocene (Macigno Fm.) to the present the eastward moving NA generated foredeeps that were progressively incorporated into the tectonic pile. The present-day Adriatic Sea is the expression of the latest foredeep, currently still in the process of formation.

According to BARCHI *et alii* (1998a), the NA consist of two main, complex thrust systems, - named, respectively, Etruscan belt and Umbria belt. The inner Etruscan belt was formed in the Late Oligocene-Early Miocene time interval, concurrently with the rotation of the Corsica block (i.e. the opening of the Provençal Basin): its crest coincides with the Elba Ridge, in the Northern Tyrrhenian Sea, its external front marks the superposition of the Tuscan Nappe units on the Umbria-Marche units.

The outer, Umbrian belt was built up in the Middle Miocene-present day time interval, after which the Corsica rotation was accomplished, concurrently with the formation of the Tyrrhenian Sea. It embodied progressively adjacent foreland sectors, and very recently reached the Adriatic offshore. Its crest zone is located below Perugia and its external front is the active Adriatic front.

In connection with the opening of the NTS, the Etruscan belt underwent severe extension, deeply transposing the previously formed compressional structures and producing the present-day, thinned crust. Extension started in Middle Miocene in the Corsica basin (BARTOLE *et alii*, 1991), and continued during the Upper Miocene-Middle Pliocene in Tuscany, allowing post-orogenic basins to form. Extension, accompanied by uplift, originating the present landscape, reached internal Umbria in the Upper Pliocene and is still ongoing in the axial zone of the Umbria-Marche Apennines.

Extension and uplift migrated from west to east in the same way as compression, so that while western sectors of Apennines underwent extension, thrusts were acting in Marche-Romagna area.

As a consequence of its complex tectonic evolution, the NA can be divided into two broad, different structural domains. The distinction between them is highlighted by the main geophysical and geological characteristics, and is also clear in the CROP 03 profile.

In the western extended "Tyrrhenian" domain, the main features are positive Bouguer anomalies, high values of heat flow, thinned crust with a brand new Moho (22-25 km) and an extensional regime that has lasted for 15 Ma. All these characteristics can be linked to an intrusion of the astenosphere that, during its widening, stretched the Tuscan crust and gave rise to the NTS and to the principal graben systems.

In the eastern, complex "Adriatic" domain, gravity anomalies are negative, heat flow is low, a compressional stress field is acting today in the foreland (Adriatic Sea), and started in its inner sector 15 Ma. Such a complex domain displays in the foreland a west-dipping, relatively thick (35 km), old crust, which in the inner sector underlies crustal slices of lesser thickness (MAGNANI, 2000).

3. – ACQUISITION PARAMETERS AND PROCESSING TECHNIQUES

The choice of the optimal acquisition parameters and of the appropriate processing sequence was a fundamental issue of this subproject and required the co-operation of many individuals and organisations, among which the Acquisition and Processing Group played a major role. Indeed, the complexity of the area and the poor data quality of the Southern Apennines CROP 04 profile, which was the first experience of a crustal seismic NVR profile crossing the Apennines (see SCANDONE *et alii* this volume), suggested that a dedicated effort was needed, especially for the selection of the energy source and of the location in the field of the present profile.

As regards the studies for the selection of the acquisition parameters, detailed descriptions can be found in MAZZOTTI (1991) and BERTELLI & MAZZOTTI (1998). The pre-survey planning included the analysis and evaluation of many factors: theoretical geophysical considerations, including ray tracing and acquisition parameter simulations, accurate analysis of 42 commercial seismic profiles made available by ENI/AGIP and by ENEL, analysis of the effectiveness of different energy sources, study of outcropping formations and of the subsurface structure along the profile, folding of the multiple coverage and so on. It was concluded that a significant correlation exists between the quality of the seismic data and the outcropping lithologies along the entire profile. The most critical areas for signal penetration are the Plio-Quaternary basins of Val di Chiana and Val D'Orcia and the carbonatic ridge of Mt. Cetona. Moreover, a correlation exists between the seismic response in various lithologies and the type of energy source used. In particular the vibroseis source is less effective than explosive sources for obtaining an acceptable penetration at high reflection times. These analyses led us to prefer explosives as an energy source and to decide on the following parameters:

- Symmetrical split-spread with maximum offset of 5700 m and a group interval of 60 m.
- Theoretical fold 3200%.
- As a general rule, single-hole shot point (20-40 m deep), with a minimum charge of 15 Kg.
- Linear receiver pattern (90 m long) with a total of 24 geophones/group. 10 Hz geophones.
- 25 seconds recording time with 2 ms sampling interval.

Following the theoretical work, a detailed scouting of the field track was carried out to minimise the curvatures of the profile and to optimise the source and receiver locations on the basis of outcropping formations and of environmental aspects. Thanks to this stage, it was possible to reduce to less than 20 Km the segments of the profile with shot holes drilled with heliborne equipment. Moreover, prior to the start of the data acquisition, a field test to check the validity of the chosen parameters was carried out close to the town of Monterchi, near the Val Tiberina.

The actual acquisition started on 1992 and was performed by a joint venture of the companies DGS, GEOITALIA and OGS. An accurate quality control was performed in the field through the installation of a micro-processing centre and thanks to the supervision carried out by AGIP and ENEL representatives and by members of the Acquisition and Processing Group.

The data acquired are generally of good quality, although there is some variability due to the different shallow lithologies and surface structural trends and to different local noise conditions.

The processing was carried out at the ENI/AGIP seismic processing centre and is described in some detail in Bertelli *et alii* (1998). The processing sequence is the conventional one of 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. The aim was therefore to reconstruct the geometrical features of the reflectors without carrying out any specific true amplitude control of the seismic signal.

The most common types of noises in the data include incoherent ambient noise, generally caused by human activities at the surface, reverberations in the subsurface and surface seismic waves (ground roll). To avoid the generation of artifacts and the creation of a forced coherence in the data, the coherency enhancement technique were not included in the processing. Also, special attention was paid to all the multichannel operations, such as array simulation and post-stack time migration.

Particular care was taken to compute the static corrections to a (fixed) datum plane by applying refraction methods. Array simulation was also applied to enhance the signal and to attenuate random noise and steeply dipping coherent noise. After shaping the signal to a minimum phase, predictive deconvolution was performed to remove reverberations and to boost mildly the frequency spectrum. No spiking deconvolution was performed. A rather complex and time-consuming stage of the processing was the determination of an optimal stacking velocity field. This stage involved the close co-operation between geologists and geophysicists and resulted in the creation of a velocity model (Tab. 1) consistent with the geological and geophysical knowledge of the area. As a final step, post-stack time migration, of up to 8 seconds, focused on diffracted events and highlighted the geometry of the structures. The smoothed, optimised stacking velocity field was used as a migration velocity field. The final seismic section obtained from the processing may be considered satisfactory.

4. – MAIN FEATURES OF THE NVR SEISMIC PROFILE

In this chapter we present a brief and, as far as possible, objective description of the main characteristics of the CROP 03 NVR profile. A more extensive description can be found in the Volume edited by Pialli *et alii* (1998), which contains other possible interpretations.

The CROP 03 NVR profile, displayed in Plates 55-60, can be divided into three portions, characterised by different reflection patterns: a Tuscan sector (CDP 0-4500), an intermediate sector (CDP 4500-5600), corresponding at the surface to the Valdichiana - Valtiberina zone, and an Umbria-Marche sector (CDP 5600-8100). The Tuscan and the Umbria-Marche sectors constitute the on-shore portions, respectively, of the above-mentioned Tyrrhenian and Adriatic domains, while the intermediate sector is localised in the transitional zone,

Table 1- *A velocity model for the CROP 03 line.*
– Modello di velocità generalizzato usato per il profilo CROP 03.

	UpA - UMA		OMF		AOS	
	A	B	A	B	A	B
Pleistocene				1962	1809-2071	2004
Pliocene		2636	2300	2767	2436-2071	2004
Miocene turbidites	3987	3475	3226-3800	3777	3208-3696	
Marly group	4345	3360-3842	3340	3070	3300-3400	2875
Scaglia group	5551	4990	5460	4726	4900-5500	4013
Multilayer	5000-5810	5228-6046	5600	5473-6037	5200-5700	5072
Calcare Massiccio	5662	6290	6000-6150		5900	5888
Evaporites	6323	6598	6300	6195	5900	6300
Basement	5100				3900	3889

Seismic interval velocities registered in the deep wells of the structural provinces of the Umbria-Marche fold and thrust belt. UpA= Umbria pre-Apennines; UMA= Umbria-Marche Apennines; OMF= Outer Marche Foothills; AOS= Adriatic Off-Shore.
"A" Columns: data registered in the deep wells along the CROP 03 profile. Wells considered: M. Civitello, S.Donato, Tavullia1, Gabicce1, Canopo1, Alessandra1.
"B" Columns: mean data available for the region - after BALLY *et alii (1986).*

where the seismic refraction experiments show the presence of a Moho step (PONZIANI *et alii*, 1995; DE FRANCO *et alii*, 1998).

In the Tuscan sector, the westernmost portion of the profile (CDP 0-2850) shows fairly good reflectors both at shallow levels and at depth. The signature of the lower crust is represented by a laterally fairly continuous pack of mixed, medium to high amplitude, reflectors, located between 4 and 7 s (two way travel-time, TWT). At the very start of the profile, close to the Tyrrhenian coast this pack appears to be doubled at depth, and a similar, second pack of reflectors can be observed, dipping eastwards from 10 to 12 s (TWT). These deep signals have been interpreted alternately as a Moho doubling, indicating an old subduction of the European crust (BARCHI *et alii*, 1998a; DOGLIONI *et alii*, 1998), or as intra-mantle, near-top astenosphere reflections (DECANDIA *et alii*, 1998). Signals from the lower crust deteriorate dramatically between 2850-4500 CDP, where only some ghosts of the original pack can be seen.

The Tuscan sector is also characterised at intermediate depth (4-5 s TWT) by the presence of one, or a group of, strong, almost flat reflectors, close to the interface between lower and upper crust, locally assuming the character of bright spots. These reflections may be related to the "K-horizon", occurring in the geothermal fields of Larderello and M. Amiata (BATINI & NICOLICH, 1984; GIANELLI *et alii* 1988). In particular, west of Pienza, (CDP 2900-3100, corresponding to the projection along the profile of the M.Amiata structure), the NVR profile shows a very strong horizontal reflector, which marks the top of the lower crust at 4.8 s (TWT): this reflector is below the K-horizon, which is located at 3.8 s (TWT) and forms the roof of a transparent zone. These strong reflections have been interpreted either as due to the presence of magmatic fluids (PIALLI *et alii*, 1998; MAGNANI, 2000), or as low angle shear zones, active during extensional tectonics (BERTINI *et alii*, 1991; DECANDIA *et alii*, 1998).

The most significant structural feature in the upper crust of the Tuscan sector is the presence of five main ENE dipping undulate crustal scale normal faults, producing severe extension of the Tuscan crust and deeply disrupting the previously formed, compressional features. At the hangingwall of these extensional shear zones, antithetic, high angle, west-dipping normal faults are present. The Miocene-Pleistocene, continental and marine basins of Tuscany appear to be geometrically and genetically related to these major shear zones.

In Tuscany, owing to intrinsic tectonic and stratigraphic characters, the shallow structures are poorly defined. A rather well-marked reflector indicates the superposition of the Tuscan Nappe on the Umbria-Marche units. The position of the top basement can also be traced in some portions of the profile. In spite of these local, good markers, the interpretations that have been proposed for the shallow structures of this sector are mainly based on commercial seismic profiles and surface geology information.

The intermediate sector (CDP 4500-5600, from Valdichiana toValtiberina basin) represents a sort of highly reflective window, where the overall signal (as well as the presence of diffraction hyperbola) increases, with a distinctive seismic character, different from either the Tuscan and the Umbria-Marche sector. It is interesting to note that it was precisely in this sector that the 1978 DSS campaign drew attention to a Moho doubling (PONZIANI *et alii*, 1995), confirmed by further experiments (DE FRANCO *et alii*, 1998). The reflections between 3-8 s TWT were interpreted as the expression of stacked crustal slivers, related to the same Moho doubling (BARCHI *et alii*, 1998a): however, this zone is very complex and its interpretation is still very controversial: this is probably one of the sectors for which further reprocessing of the geophysical data is above all needed.

At shallower levels, the frontal part of the Tuscan Nappe, with the superposition of the Tuscan Units on the Umbria-Marche Units can be easily recognised, as well as, below it, the antiformal stack of the Perugia Mountains, involving the Triassic Evaporites and the phyllitic Basement, drilled by the S.Donato1 well (ANELLI *et alii*, 1994).

Two gently east-dipping, strong reflectors characterise this sector, which was also involved in an expanding spread experiment (ZANZI, 1998). The shallower reflector is traceable at a depth of about 8 s TWT. Velocity data from different geophysical experiments (DSS, Expanding Spread, NVR) are quite different, and result in contrasting geological interpretations: indeed this reflection has been interpreted in turn as the easternmost portion of the Tuscan Moho (DE FRANCO *et alii*, 1998), as the top of the doubled Adriatic lower crust (BARCHI *et alii*, 1998a), or as a portion of a major extensional detachment (DECANDIA *et alii*, 1998). The deepest, strong reflection of the whole profile is a packet of high amplitude, north-eastern dipping reflectors, localised between 14 and 16 s (TWT), whose origin is a matter of debate.

In the Umbria-Marche, easternmost sector, signals of lower crust are scattered and less pronounced than in the western part of the profile, and depict an overall dip toward south-west. The Adriatic Moho can be placed on the reflectors around 12 s (TWT), a depth comparable with the results of refraction DSS (DE FRANCO *et alii*., 1998). In this sector, the shallow structures of the Umbria-Marche fold and thrust belts are clearly recognisable, because of the presence of a distinctive triplet of reflectors of good lateral continuity which, after calibration with deep boreholes and commercial seismic lines, corresponds from bottom to top to: i) top of "basement" phyllites; ii) base of Calcare Massiccio Fm. (Uppermost Triassic); iii) Marne a Fucoidi Fm. (lower part of the Upper Cretaceous). The top of carbonatic multilayer (Scaglia Variegata and Scaglia Cinerea Fms., Upper Eocene-Oligocene) and the Messinian reflector (recognisable in the easternmost sector of the profile) can also be traced. From a structural point of view, the profile effectively shows the involvement of at least the shallower part of the phyllitic basement in four, major thrust sheets, corresponding to the main anticlinoria that can be mapped at the surface: this structural character is confirmed by the analysis of other local seismic profiles and by some deep wells.

The reconstructed Umbria-Marche folds and thrusts (fig. 3), together with the surface geology information allow a detailed geometric and kinematic reconstruction: a total shortening of about 60 km (30%) was evaluated for the whole Umbria-Marche sector (BARCHI *et alii*, 1998b). It is more difficult to establish whether (and eventually how and where) this shortening can be transferred to the whole Adriatic crust; alternatively, the Umbria-Marche thrust and fold belt could be viewed as completely detached from the subducting Adriatic slab.

5. – FINAL REMARKS

The CROP 03 profile, together with the other studies and experiments performed during the CROP 03 project, offers a significant contribution to understanding the NA, and in particular to defining the crustal structure of both the extensional Tyrrhenian domain, where the Moho is supposed to be very young and at a depth of 22-25 km, and of the compressional Adriatic domain, where the compression is still active and an older, well-stratified crust reaches the depth of about 35 km.

These data give an opportunity to explore some key-questions of the geology of the NA and make it possible to:
- localise the major shear zones responsible for the extension in Tuscany and the compression in the Marche-Adriatic sector;
- ascertain the presence of the inferred crustal dou-

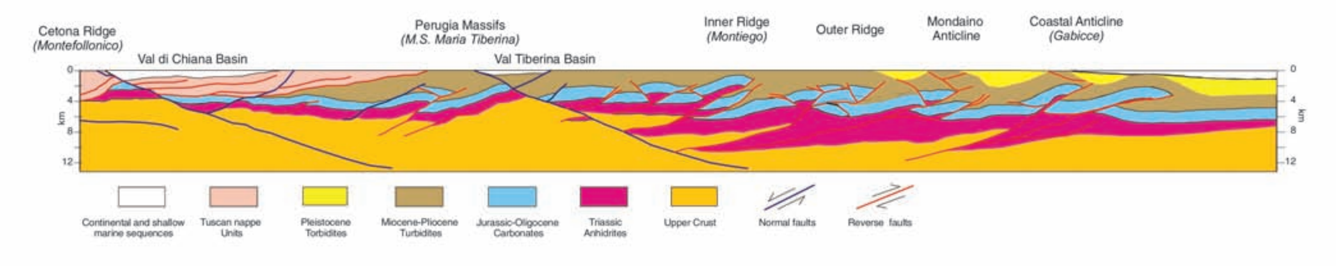

Fig. 3 - Geological interpretation of the seismic reflection line CROP 03, from the M. Cetona to the Adriatic Sea (modified after Barchi *et alii*, 1998a).
- Interpretazione geologica del profilo sismico a riflessione CROP 03, nel tratto compreso tra il M. Cetona ed il Mare Adriatico (da Barchi et alii*, 1998a, modificato).*

bling close to the strong gravimetric gradients between Umbria and Tuscany;
- improve our knowledge of the deep structure of the Tuscan geothermal fields;
- better understand the geological processes driving the seismogenesis of the Umbria-Marche region;
- investigate the contemporaneous activity of extension and compression in adjacent domains, a distinctive character of the NA-NTS system;
- provide insights into the driving forces that led to the present configuration of the whole Northern Apennines orogene.

Finally, the localisation of the CROP 03 profile makes this project an excellent opportunity to investigate the genetic relationships between the Apennine belt and the Alps orogene.

We are, however, far from providing a final, univocal answer to these questions. This is expressed clearly in the following words of Giampaolo Pialli, when he summarised the results of the project. We would like to quote them as a conclusion to this brief report.

" The work done so far is far from being definitive and exhaustive of all of the themes of research that have been pursued. There is a need to go on working on the data collected, to improve them analitically by means of targeted reprocessing of specific sectors of the profile, by collecting and integrating new data, by comparing our data with those coming from other similar projects in other areas of the world and so on. It is hard to say when we will achieve a final and complete spectrum of results. As usually happens in research work, we know the starting point, but we can hardly predict where and when it will end. There is, however, also a need for a pause in our work, for reflecting on some ideas, for establishing the state of the art and for putting forward some points for discussion. At the moment we are just at that point in our research."

REFERENCES

Amato A. & Selvaggi G. (1991) - *Terremoti crostali e subcrostali nell'Appennino Settentrionale.* Studi Geologici Camerti, Vol. Spec. 1991/**1**: 75-82.

Anelli L., Gorza M. & Pieri M. (1994) - *Subsurface well data in the Northern Apennines (Italy).* Mem. Soc. Geol. It., **48**: 461-71.

Bally A.W., Burbi L., Cooper C .& Ghelardoni R. (1986) - *Balanced sections and sismic reflection profiles across the Central Apennines.* Mem. Soc. Geol. It., **35**: 257-310.

Barchi M., Minelli G. & Pialli G. (1998a) - *The CROP 03 Profile: a synthesis of results on deep structures of the Northern Apennines* . Mem. Soc. Geol. It., **52**: 383-400.

Barchi, M.R., De Feyter, A., Magnani, M.B., Minelli G., Pialli G. & Sostera M. (1998b) - *The deformed foreland of the Northern Apennines and its structural style.* Mem. Soc. Geol. It., **52**: 557-578.

Bartole R., Torelli L., Mattei G., Peis D. & Brancolini G. (1991) - *Assetto stratigrafico strutturale del Tirreno Settentrionale: stato dell'arte.* Studi Geol. Camerti, Vol. Spec. 1991/**1**: 115-140.

Batini F. & Nicolich R. (1984) - *The application of seismic reflection method to geothermal exploration* . U.N. Seminar on utilization of geothermal energy for electric power production and space heating . Firenze.

Bertelli L. & Mazzotti A. (1998) - *Planning and acquisition of the NVR CROP 03 seismic profile.* Mem. Soc. Geol. It., **52:** 9 – 22.

Bertelli L., Storer P. & Mazzotti A. (1998) - *Processing strategies for the NVR CROP 03 seimic profile.* Mem. Soc. Geol. It., **52**: 23-32.

Bertini G, Cameli G.M., Costantini A., Decandia F.A., Di Filippo M., Dini I., Elter M., Lazzarotto A., Liotta D., Pandeli E., Sandrelli F. & Toro B. (1991) - *Struttura geologica fra i monti di Campiglia e Rapolano Terme (Toscana Meridionale): stato attuale delle conoscenze e problematiche.* Studi Geologici Camerti, Vol. Spec. 1991/**1**: 155 - 178.

De Franco R., Ponziani F., Biella G., Boniolo G., Corsi A., Maistrello M. & Morrone A. (1998) - *DSS - WAR experiment in support of the CROP 03 project.* Mem. Soc. Geol. It., **52**: 67-90.

Decandia F.A., Lazzarotto A., Liotta D., Cernobori L. & Nicolich R. (1998) - *The CROP 03 traverse: insights on post-collisional evolution of Northern Apennines.* Mem. Soc. Geol. It., **52**: 427-440.

Deino A., Keller J.V.A., Minelli G. & Pialli G. (1992) - *Datazioni $^{40}Ar/^{39}Ar$ del metamorfismo dell'unità di Ortano - Rio Marina (Isola d'Elba): risultati preliminari.* Studi Geologici Camerti, Vol. Spec. 1992/**2**: 187-192.

Doglioni C., Mongelli F. & Pialli G. (1998) - *Appenninic back arc lithospheric boudinage on the former alpine belt*. Mem. Soc. Geol. It., **52**: 457-468.

Gianelli G., Puxeddu M., Batini F., Bertini G., Dini I., Pandeli E., & Nicolich R. (1988) - *Geological model of a young volcano-plutonic sistem: the geotermal region of M. Amiata .(Tuscany , Italy).* Geothermics, **17**, (5-6): 719-734.

Magnani M.B. (2000) - *The structural complexity of the Northern Apennines (Italy) as evidenced by the CROP 03 data*. Tesi di dottorato, Università di Perugia.

Martinis, B. & Pieri, M. (1964) - *Alcune notizie sulla formazione evaporitica del Trias superiore nell'Italia centrale e meridionale.* Mem. Soc. Geol. It., **4**: 648-672.

Mazzotti A. (1991) - *Indagine dei parametri di acquisizione sismica della linea CROP 03*. Studi Geol. Camerti, Vol. Spec. 1991/**1**: 5-12.

Merla G. (1952) - *Geologia dell'Appennino settentrionale*. Boll. Soc. Geol. It., **70**, (1): 95-382.

Migliorini C.I. (1948) - *I cunei composti nell'orogenesi* . Boll. Soc. Geol. It., **67**: 29 -142.

Minelli G., Pialli G .& Scarascia S. (1991*) - Revisione dei profili crostali nell'area dell' Appennino Settentrionale interessata dal profilo CROP 03*. Studi Geologici Camerti, Vol. Spec.1991/**1**: 55-65

Pialli G., Barchi M. & Minelli G. (Eds) (1998) - *Results of the CROP 03 deep seismic reflection profile*. Mem. Soc. Geol. It., **52**: pp. 647

Ponziani F., De Franco R., Minelli G., Biella G., Federico C. & Pialli G. (1995) - *Crustal shortening and duplication of the Moho in the Northern Apennines: a view from seismic refraction data*. Tectonophysics, **252**: 391-418

Scandone P., Mazzotti A., Fradelizio G.L., Patacca E., Stucchi E., Tozzi M. & Zanzi L. (2003) - *Line CROP 04*: *Southern Apennines*. This volume.

Selli R. (1954) - *Il bacino del Metauro* . Giorn. Geol., **24**: 1-294.

Signorini R. (1940) - *Sulla tettonica dell'Appennino romagnolo* . Atti R. Accademia, Classe Sc. Fis. Mat. e Nat. **7**,1: 370-383.

Trevisan L. (1952) - *Sul complesso sedimentario del Miocene Superiore e Pliocene della Val di Cecina e sui movimenti tettonici tardivi in rapporto ai giacimenti di lignite e salgemma* . Boll. Soc. Geol. It., **70**, (1): 65-78.

Zanzi L. (1998) - *Expanding Spread experiments: data processing and results.* Mem. Soc. Geol. It., **52**: 55-66.