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THE CRUSTAL STRUCTURE OF THE NORTHERN APENNINES (CENTRAL ITALY): AN INSIGHT BY THE CROP03 SEISMIC LINE

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ABSTRACT. In this paper, the CROP03-deep seismic reflection profile in the Northern Apennines is described and re-considered in light of new geophysical data and interpretations made available in the last five years (particularly from heat flow measurements, aeromagnetics, tomography, active stress determination and passive seismology). The crustal structure of the Northern Apennines is shown to be composed of two distinct domains. To the west is the Tyrrhenian domain and to the east is the Adriatic domain. These domains have distinctive geological and geophysical characteristics that exhibit distinct reflectivity patterns at all crustal levels. In the Tyrrhenian domain, the Upper Oligocene-Lower Miocene compressive structures are no longer recognizable, because they are dissected by subsequent extensional tectonic features. The seismic profile highlights the strong asymmetry of extensional deformation, and the upper crust is affected by a set of six major, east-dipping, low-angle normal faults. In the Adriatic domain, compressive tectonics have acted since the Middle-Miocene, and the pattern of shallow contractional structures is well preserved. The geological interpretation of the seismic data supports a thick-skinned style of deformation, where the basement is involved in the major thrust sheets. The good quality of seismic data also allows for determining the total shortening produced by the contractional structures. In the central part of the profile, at the border between the Tyrrhenian and Adriatic domains, seismic data shows the presence of an intermediate sector. The sector consists of a highly reflective window, where the refraction data indicate a local doubling of the crust for about 30 km. A scenario is presented that attempts to describe the geodynamics that drove the tectonic evolution of the Northern Apennines since the Upper Oligocene.

INTRODUCTION

The CROP03 seismic profile was acquired as part of the CROP (CROsta Profonda) Project. The goal of the project was to investigate the crustal structure of the rocks from the Italian peninsula and surrounding seas, and to highlight the relationship between shallow deformation and structures at depth.

The profile extends across central Italy, from Punta Ala (Tyrrhenian coast) to Gabicce (Adriatic coast), and intersects all the main tectonic units of the Northern Apennines (fig. 1B and fig. 2). In addition to the Near Vertical Reflection (NVR) survey, other geophysical experiments were carried out as part of the CROP03 project (fig. 1B). In particular a wide angle refraction survey (Deep Seismic Sounding, DSS) recorded data from locations almost coincident with the reflection profile (De Franco and others, 1998). Three expanding spread experiments were also performed in critical locations (Zanzi, 1998). Further important contributions to the CROP03 project were supplied by the interpretation of magnetic (Cassano and others, 1998; Speranza and Chiappini, 2002), gravity (Marson and others, 1998; Scarascia and others, 1998), surface heat flow (Mongelli and others, 1998) and seismological data (Amato and others, 1998). The interpretation of the NVR profile was calibrated and substantially improved by further information derived from commercial seismic pro-

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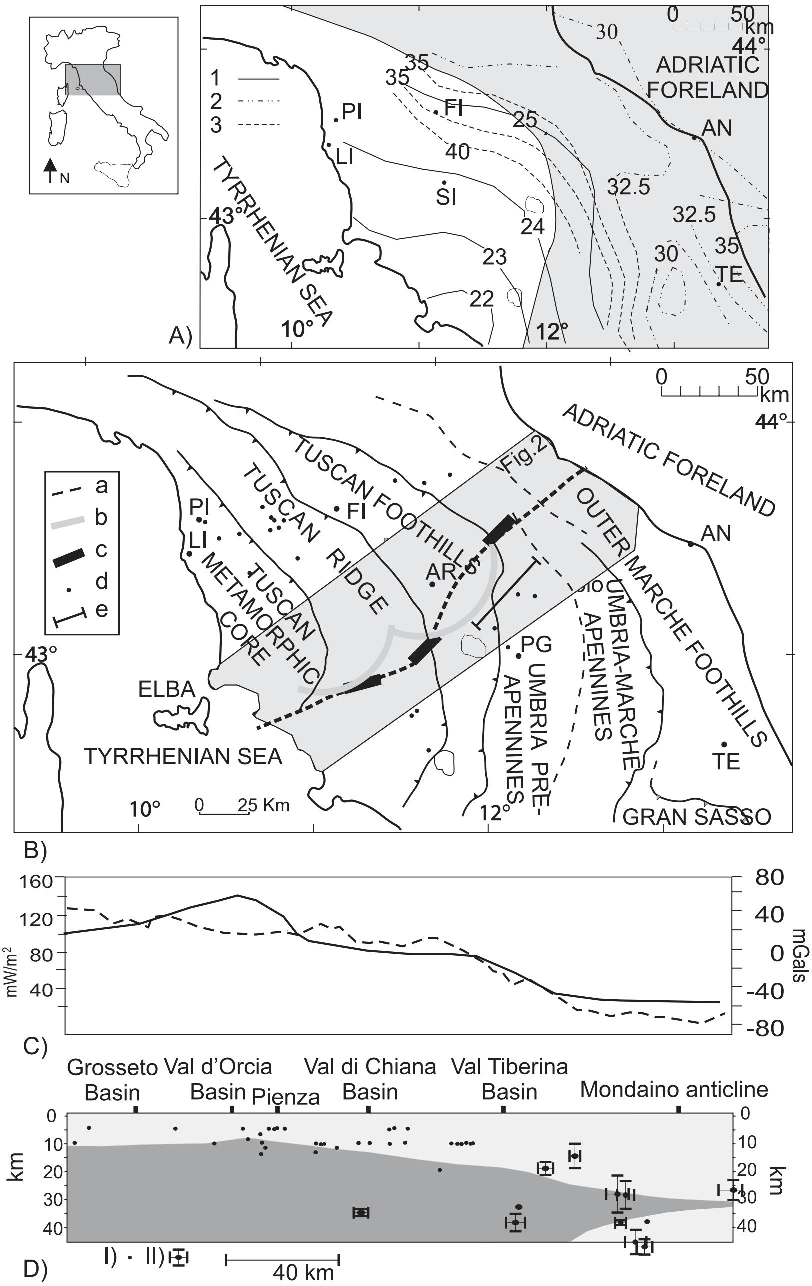

Fig. 1. Location map of the study area. (A) Tyrrhenian domain (white); Adriatic domain (gray). Depth contour map of the Moho discontinuity (modified after Scarascia and others, 1998). 1) depth contours in the Tyrrhenian domain; 2) depth contours in the Adriatic domain; 3) overthrusting front of the Moho discontinuity; (B) Simplified geological map of the Northern Apennines. a) CROP03 NVR seismic line, (b), mirror of the DSS-WAR (Deep Seismic Sounding-Wide-Angle-Reflection) seismic experiment (c) Expanding spread experiment, (d) Wells. e) section line of fig. 5B; (C) Surface heat flow (continuous line) (Mongelli and others, 1998) and Bouguer anomaly (broken line) along the CROP03 line (Marson and others, 1998) (D) Seismicity, brittle (light gray) and ductile (dark gray) field along the CROP03 profile (Pauselli and Federico, 2002). Relocated distribution of the seismicity after: I) I. N.G. V. (Istituto Nazionale di Geofisica) Database, period 1985–1995. II) Collettini and others, 1997. Error bars in the relocated depth.

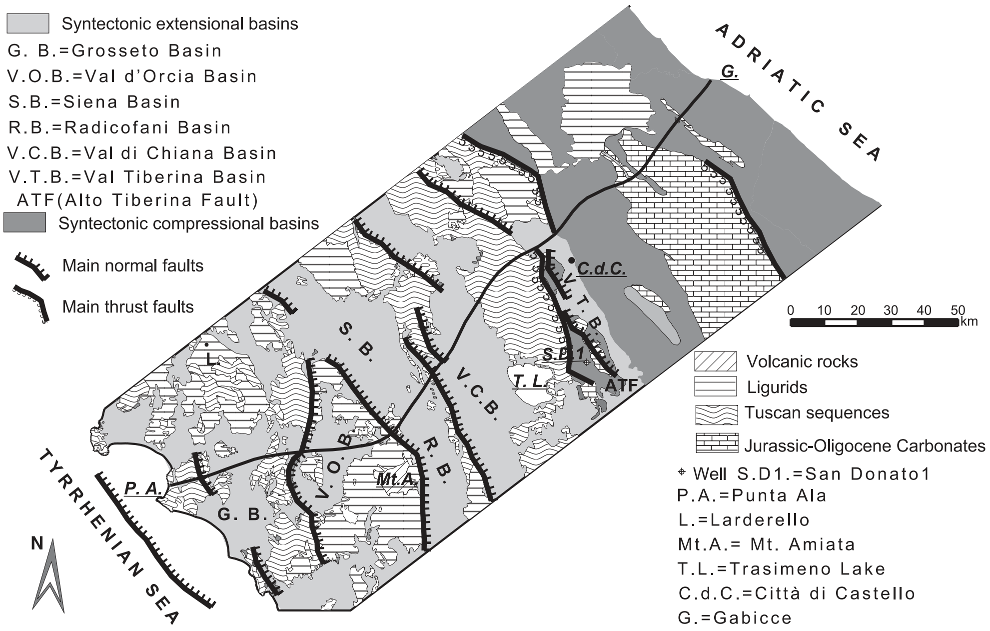

Fig. 2. Location map of the CROP03 seismic reflection profile, main geological units and main normal and thrust faults (modified after Pialli and others, 1998).

files and deep well data. The deep well data was produced by the Italian oil and energy companies ENI-Agip (presently ENI-E&P) and ENEL.

The detailed results of the project and several different interpretations of the profile (for example, Barchi and others, 1998a; Decandia and others, 1998) are described in a special volume edited by Pialli and others (1998). A new markedly different interpretation of the profile was more recently proposed by Finetti and others (2001) and is considered and discussed in this paper.

CROP03 NVR data are described and re-considered in detail, taking into account new data sources made available in the last five years (particularly from heat flow measurements, aeromagnetics, tomography, active stress determination and passive seismology). From this analysis a new interpretation of the crustal section is proposed. Shallow extensional and compressional structures that characterize the upper crust of the Northern Apennines are described, and seismic reflection data is presented to better define their geometry and evolution. Finally, the crustal structures are merged with the tomographic image of the underlying mantle in order to propose a geodynamic scenario of the Northern Apennines since the Upper Oligocene.

THE TWO DOMAINS OF THE NORTHERN APENNINES

The surface geology of the Northern Apennines has been extensively studied for over a century, and a large amount of stratigraphic and structural data have been collected (for a recent review see Vai and Martini, 2001 and references therein). In the last twenty years (particularly after the paper by Bally and others, 1986) these data were integrated with information derived from seismic reflection profiles and deep wells. This procedure provided the basis for a complete, though still controversial, interpretation of the structural setting to a depth of about 10 km.

The Northern Apennines are commonly interpreted to have formed as the result of the convergence between the already formed Alpine orogen and the continental

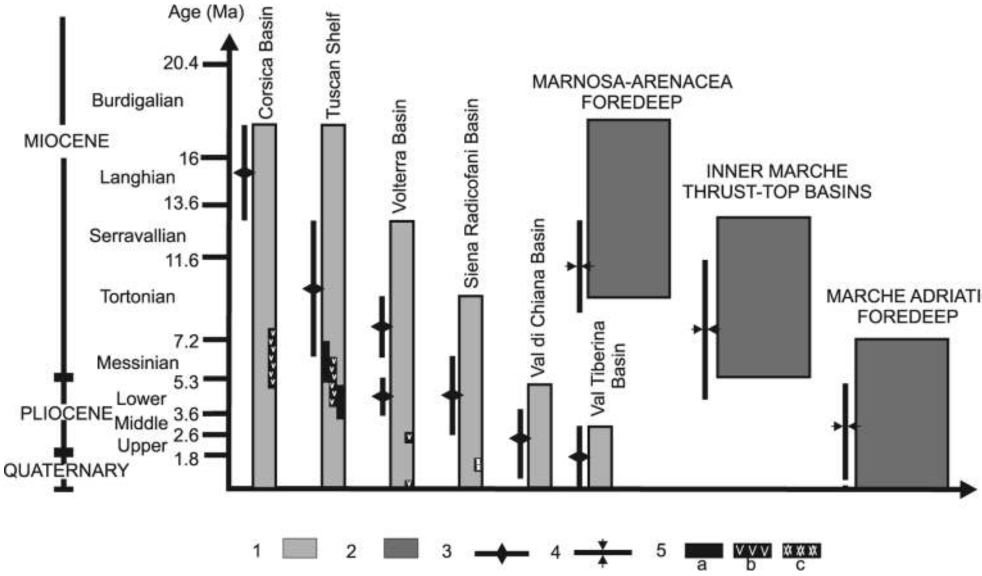

Fig. 3. Age of syntectonic 1) extensional and 2) compressional basins; 3) period of extensional phase; 4) period of main compressional phase (data from seismic reflection profiles Barchi and others, 1998a; Pascucci and others, 1999). 5) age of: a) plutonites, b) vulcanites and c) subvolcanic rocks (after Poli, 2004, ages after compilation of Serri and others, 2001).

crust of the Adriatic promontory of the African plate (for example, Doglioni and others, 1998). The convergence began during Late Oligocene – Early Miocene, along with the rotation of Corsica-Sardinia microcontinent. Convergence continued throughout the Cenozoic and is possibly still going on along the Romagna-Adriatic front (Frepoli and Amato, 1997), although the present-day activity of the easternmost compressive front is hotly debated (for example, Di Bucci and Mazzoli, 2002). The eastward moving Northern Apennines generated progressively younger foreland basins (foredeep and piggy back basins, Ori and others, 1986) that were successively incorporated into the collision zone, from Late Oligocene to the present (Merla, 1951; Ricci Lucchi, 1986).The Adriatic Sea represents the present-day active foredeep (fig. 3). A similar migration is observed in the Central Apennines (Cipollari and Cosentino, 1997). At the same time extensional deformation related to the opening of the Northern Tyrrhenian Sea propagated at the western side of the Apenninic belt, starting in Middle Miocene in the Corsica Basin. Extension continued in the Tuscan mainland during the Late Miocene-Middle Pliocene, affected western Umbria in the Late Pliocene and is presently going on in the Umbria-Marche Apennines ridge. This extension has produced progressively younger, continental and shallow marine "hinterland" basins (Bartole and others, 1991; Jolivet and others, 1998; Pascucci and others, 1999) (fig. 3). Magmatic activity associated with the formation of the extensional basins (fig. 3), also migrated eastward. The oldest magmatic activity is represented by the Sisco lamproitic sill (15 – 13.5 Ma) found in Eastern Corsica followed by the Montecristo, Monte Capanne (Elba island) and Vercelli plutons (7.3 – 6.2 Ma). Widespread instrusion of acid igneous bodies is documented in the Tuscan-Latium continental shelf (Porto Azzurro, Giglio, Gavorrano, Campiglia, Castel di Pietra, Monteverdi, *et cetera*) (Poli and others, 1989; Serri and others, 1990, 1993; Peccerillo and Panza, 1999).

The contemporaneous eastward migration of coupled compressional and extensional belts is one of the distinctive characters of the Northern Apennines orogen, as recognized early by Elter and others (1975). These features provide constraints for any geodynamic model of the orogen. The focal mechanisms of the earthquakes, as well as the analysis of the boreholes break-outs, confirm that extension is presently active in the western sector, whilst contraction is active in the Po Plain-Adriatic foreland (Mariucci and Muller, 2003; Montone and others, 2004).

As a result of the tectonic evolution described above, the Northern Apennines can be divided into two different structural domains, whose distinction is underlined by their peculiar geophysical and geological features: a western, "Tyrrhenian domain", where extensional deformation destroyed the pre-existing compressional belt; and an eastern, "Adriatic domain", where the compressional structures are preserved (fig. 1A).

The Tyrrhenian domain is characterized by a strong reduction of lithospheric thickness detected by passive seismology (Calcagnile and Panza, 1981; Suhadolc and Panza, 1989; Amato and Selvaggi, 1991; Selvaggi and Amato, 1992). A similar interpretation is supported by a study of thermal data in this region that locates the lithosphere-asthenosphere boundary (1600 K isotherm) at a depth of about 30 km (Pauselli and Federico, 2002). The overall thinning of the lithosphere is reflected in the high surface heat flow (>150 mW/m^2), and it provides an explanation of the positive Bouguer anomalies found in this domain (Marson and others, 1998) (fig. 1C). In addition, the "elastic lid" (the uppermost mantle between the Moho and the underlying low-velocity layer) is less than 15 km thick (Peccerillo and Panza, 1999; Pontevivo and Panza, 2002), which indicates a considerable amount of partial melting. A relatively shallow Moho is detected by refraction surveys at a depth between 22 and 25 km (De Franco and others, 1998). The study of the thermal field locates the brittle/ductile transition (as defined by Brace and Kohlstedt, 1980) at a depth of 10 to 12 km (Pauselli and Federico, 2002). As we were interested in the regional lithospheric behavior along the CROP03 profile low scale inhomogeneity in rheological parameters were neglected. This was done by selecting mean values for the rheological parameters of the upper crust, lower crust and the upper mantle. The depth of the brittle/ductile transition obtained using these parameters is in good agreement with the distribution of the earthquake's hypocenters, which are concentrated in the upper 10 km of the crust (Amato and Selvaggi, 1991) (fig. 1D).

The Adriatic domain is characterized by a lithospheric thickness of about 70 to 90 km, and the Moho is located at a depth of about 35 to 40 km (De Franco and others, 1998) (fig. 1A). The Bouguer anomalies are negative and there are relatively low values of the heat flow (between 70 and 40 mW/m^2). Shallow seismic events (less than 10 km deep), with strike-slip and thrust fault plane solutions, indicate active compression in the more external areas of the domain. Different seismicity is present below the main ridge of the Apennines at different depths. Moderate earthquakes related to extensional faults are found at upper crustal levels (7 – 15 km deep). A light to moderate seismicity, probably compressive in character, is localized in deeper, subcrustal levels (30 – 90 km) (Amato and Selvaggi, 1991). The brittle/ductile transition deepens from 12 km to about 25 km moving from west (Val di Chiana Basin) to east (active front of compression). The rheological behavior of the lithosphere in the easternmost part of the profile is more complex with rocks being brittle at a depth less than 25 km but also at depth greater than 34 km (Pauselli and Federico, 2002) (fig. 1D).

The marked geological and geophysical differences between the Tyrrhenian and Adriatic domains support the presence of contemporaneous coupled compressional and extensional behavior in adjacent zones, and they were produced by the peculiar tectonic setting of the Northern Appenines. The previously shortened Tyrrhenian domain has been affected by an extensional regime since 17 Ma, whilst the Adriatic domain, has been subjected to contraction. Three main hypotheses have been proposed to explain the contemporaneous eastward shifting of the compressional and extensional deformation that differ in how they interpret deep-seated crustal and upper mantle processes. The first hypothesis assigns the main role in the dynamics of the Apennines to extension. Extension is driven by the eastward shifting of an asthenospheric rising plume, and produces active rifting in the Tyrrhenian Sea (Lavecchia, 1988; Decandia and others, 1998; Lavecchia and others, 2004).

A second hypothesis calls for a quasi-continuous, eastward thrusting of the Apenninic crust and tends to minimize the role of extension (Bonini and Moratti, 1995; Boccaletti and others, 1997; Boccaletti and Sani, 1998). Finetti and others (2001) proposed a new, different, interpretation of the CROP03 profile and its offshore continuations towards the Tyrrhenian and the Adriatic Sea (lines CROP M-12A and M-16, respectively) that is compatible with this view, which is discussed in detail in the *Extensional Structures* section of this paper.

The third hypothesis invokes a combination of extensional and compressional mechanism and suggests that the eastward shift of the Northern Apennines orogenic system was driven by the roll back of a subducting slab, (Scandone, 1980; Royden and others, 1987; Doglioni 1991; Cavinato and DeCelles, 1999) or by delamination (Channel, 1986; Channel and Mareschal, 1989) of a crustal slice dipping westward into the upper mantle.

DESCRIPTION OF THE CROP03 NVR SEISMIC PROFILE

The CROP03 profile (fig. 4A) was acquired with a dynamite source, a symmetrical split spread with a maximum offset of 5700 m, a group interval of 60 m, 25 s records, and a theoretical fold of 3200 percent (Bertelli and others, 1998). The subsequent processing sequence included conventional steps for on-shore data processing. Processing parameters were chosen to image deep geological structures while not neglecting the near-surface ones. The aim was to reconstruct the geometrical features of the reflectors without carrying out any specific true amplitude control of the seismic signal. 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 highly dipping coherent noise. Predictive deconvolution was performed after shaping the signal to minimum phase to remove reverberations and to mildly boost the frequency spectrum. As a final step, post-stack time migration, up to 8 seconds, focused diffracted events and highlighted the geometry of the structures. The smoothed and optimized stacking velocity field was used as a migration velocity field. Detailed descriptions of acquisition parameters and of the processing strategies can be found in Bertelli and Mazzotti (1998) and Bertelli and others (1998).

The profile is here divided into three portions (fig. 4B) that are characterized by distinctive reflectivity patterns. The western and the eastern sectors correspond to the onshore portions of the Tyrrhenian and Adriatic domains, respectively. The intermediate sector is located in a transitional zone, between the Val di Chiana and Val Tiberina basins, where seismic refraction shows the presence of a doubling of the Moho at depth (Suhadolc and Panza, 1989; Ponziani and others, 1995; De Franco and others, 1998). For each sector, we will first describe the deep structures (Moho and lower crust), and compare them with seismic refraction results (De Franco and others, 1998) and with other geophysical surveys (Piana Agostinetti and others, 2002; Mele and others, 2003). We will then describe the shallow structures (upper crust and sedimentary cover) in the geological framework of the Northern Apennines.

In figure 4B, and in the following text, the main reflections of the NVR profile are numbered from 1 to 31. Further information from seismic refraction is labeled with

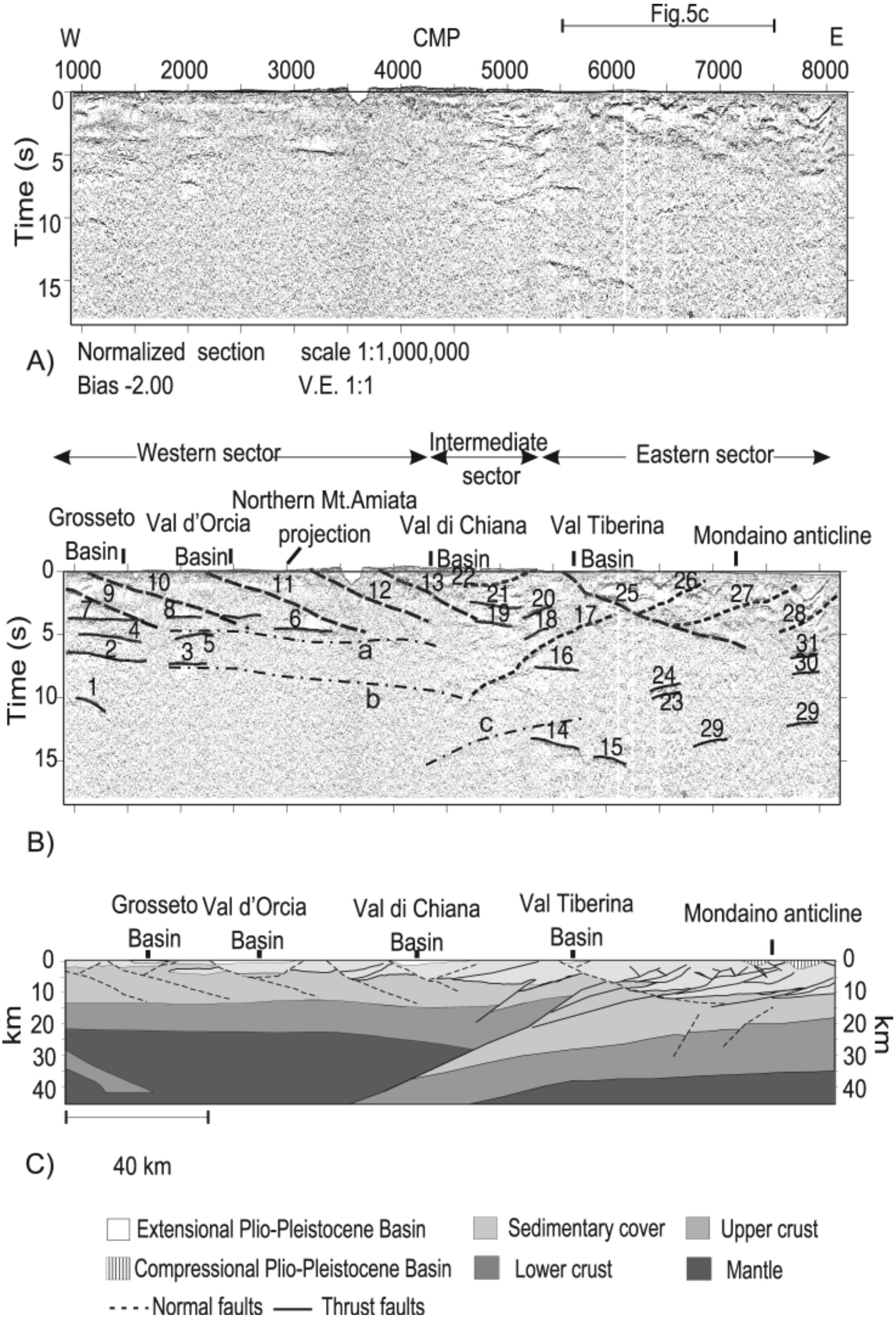

Fig. 4. CROP03 NVR Seismic Profile (A) Stack. (B) Main reflectors (numbered from 1 to 31). Seismic refraction data from De Franco and others, 1998: (a) Top of the lower crust; (b) Tuscan Moho; (c) Adriatic Moho. (C) Geological interpretation of the seismic reflection line CROP03.

lower case letters from a to c. The depth of all reflectors is expressed in seconds (Two Way Time, TWT).

Western Sector

At the western edge of the profile (fig. 4), below the Tyrrhenian coast, an alignment of strong reflections [2 and 3] localized at a depth of about 8 s are interpreted as the Tuscan Moho, as confirmed by the refraction survey [b], which detected a jump in velocity -V_P- from 6.7 km/s to 7.7 ± 0.2 km/s. A group of deep (10 to 12 s), east-dipping reflectors [1] is present below the Tuscan Moho. These sharp events are alternatively interpreted as a remnant of the European Moho, subducted during the Alpine collision (Barchi and others, 1998a; Doglioni and others, 1998; Finetti and others, 2001), or as an intra-mantle reflection near the top of the asthenosphere (Decandia and others, 1998).

The signature of the lower crust in this sector is highlighted by a fairly lateral continuous package of mixed, medium to high amplitude reflections between 4 and 7 s [4 and 5] whose top is also imaged by seismic refraction [a]. These signals deteriorate dramatically towards the east, where only some weak reflections of the original package can be seen. Very high-energy horizontal reflections [6] are present at about 5 s in correspondence with the northern projection of the Mt. Amiata geothermal field. Their seismic character (high amplitude, frequency content) demonstrates the similarity of this zone with other deep "bright spot" reflections acknowledged in other areas and interpreted as fluids at crustal depth (for example, Makovsky and Klemperer, 1999). The occurrence of this deep bright spot package of reflections in correspondence with the geothermal area of Mt. Amiata suggests a magmatic origin and the possibility that it could represent the top of a large intrusive body (Pialli and others, 1998; Magnani, ms, 2000; Acocella and Rossetti, 2002).

The compression-related, shallow structures of the western sector are poorly defined. The tectonic structures are deeply dissected by later extensional tectonic features (for example, Carmignani and others, 1994), so that the internal structures of the thrust sheets are not easily interpreted. Five clear east-dipping alignments [9 to 13] within the upper crust are recognized to a depth of 4 to 5 s. These alignments correspond to extensional master faults. The reflections link to the surface with the western side of the Upper Miocene-Middle Pliocene, continental to shallow marine, extensional basins of Grosseto [10], Val d'Orcia [11], Siena-Radicofani [12] and Val di Chiana [13], whose position is indicated in figure 2. With a similar attitude, the westernmost reflection [9] corresponds to the Zuccale fault (Keller, ms, 1990; Keller and Coward, 1996; Collettini and Barchi, 2004), exposed on the Elba Island, about 10 km west of the Tyrrhenian coast (fig. 1). Reflections 9 and 10 merge into a subhorizontal reflective zone at about 4 s [7-8], corresponding to the "K-horizon" (Batini and others, 1978) also resolved on many commercial seismic lines crossing the Larderello and Mt. Amiata geothermal fields. Interpretations of this horizon include a "bright spot" reflection due to fluid presence (Batini and Nicolich, 1984; Gianelli and others, 1988; Brogi and others, 2003) or detachment levels active during extensional tectonics (Bertini and others, 1991).

Intermediate Sector

This portion of the profile, situated between the Val di Chiana and the Val Tiberina basins (CMP 4500 – 5600), represents a highly reflective window where the overall signal increases and crustal slices show a distinctive seismic character, different from that of western Tuscany or of Marche. In this sector, the 1978 DSS campaign drew attention to the presence of a doubling of the Moho (Suhadolc and Panza, 1989; Ponziani and others, 1995) that has been confirmed by the CROP DSS experiment (De Franco and others, 1998) [b and c].

The prominent reflectivity below the depth of about 8 s is represented by three major alignments, one at about 8 s [16] and two between 14 and 16 s [14 and 15]. The interpretation of the almost flat reflection [16] is controversial, due to distinctly different velocity data obtained by different geophysical experiments (DSS, expanding spread, NVR). Considering a velocity of about 7.7 km/s assigned to this reflector by the refraction survey, De Franco and others (1998) interpreted it as the easternmost portion of the Tuscan Moho. In contrast, expanding spread and NVR experiments found significantly lower velocities (5.5 – 6 km/s). This result led Decandia and others (1998) to interpret this reflection as the easternmost edge of the "K horizon", considered to be the major extensional detachment of the Tuscany upper crust. Following Barchi and others (1998a) we interpret this reflector as the westernmost portion of the top of the Adriatic lower crust. High amplitude reflections [14 – 15] at about 15 s both dip towards the northeast. No other comparable reflectors are present along the profile at such a depth. Following studies of Zanzi (1998) the real significance of these high energy signals is actually ambiguous and more than one solution can be proposed. They could be either associated with a multiple reflection or they could be produced by the reflection of a lateral body rather than by a deep reflector. We further expect that appropriate tests designed and evaluated both geophysically and geologically will validate or exclude each alternative. Reflector [14] was interpreted by Barchi and others (1998a) and by Decandia and others (1998) as corresponding to the Adriatic Moho. However, the DSS campaign indicates in the same region a Moho discontinuity [c] gently dipping towards the west (Suhadolc and Panza, 1989; Ponziani and others, 1995; De Franco and others, 1998).

The crustal-mantle boundary in this area was recently imaged analyzing the teleseismic waveforms recorded by a regional array crossing the northern Italian peninsula (Piana Agostinetti and others, 2002; Mele and Sandvol, 2003). A different depth for the Adriatic Moho below the main ridge of the Apennines was obtained by the two groups. Mele and Sandvol (2003) obtained a value of $>$50 km whereas Piana Agostinetti and others (2002) obtained a value of about 35 km. The latter value is more consistent with the results of seismic refraction (Ponziani and others, 1995; De Franco and others, 1998). Notably, in this area a rather steep and continuous west-dipping reflection [17] separates the deep reflections [14-15-16] from the shallower structures. In our interpretation the event [17] represents the boundary between the Tyrrhenian and Adriatic crustal domains.

The group of reflections between 3 to 5 s [18 to 21] are interpreted as a deeply rooted antiformal stack, involving the Umbria-Marche phyllitic basement and propagating through the entire upper crust. The shallower portion of this structure was also encountered by a deep well (S. Donato1, fig. 2) located in this area (Anelli and others, 1994). At shallower levels, a west dipping, low-angle reflection [22] marks the eastward overthrusting of the Tuscan Units onto the Umbria-Marche domain (Damiani and others, 1991; Costa and others, 1998).

Eastern Sector

The seismic data from the lower crust in the eastern sector are scattered and less pronounced than in the western sector. The deepest recognizable reflection [29] is located at a depth of about 12 s, close to the eastern edge of the profile. This result along with results of seismic refraction DSS (Ponziani and others, 1995; De Franco and others, 1998) and of teleseismic waveforms (Mele and Sandvol, 2003), leads us to interpret reflection [29] as representing the Adriatic Moho [c]. Two marked reflections [30 and 31] that are located at the western edge of the profile, along with other west-dipping signals [23 and 24] that are traceable in the central part of the Adriatic domain, could be located at the top of or within the lower crust.

The sedimentary cover deepens in the upper part of the profile, from west to east (up to 5 s below the Adriatic coast) and is characterized by high energy and well organized reflections. The shallow structures of the Umbria-Marche fold and thrust belt are clearly recognizable in this sector, for the presence of a distinctive triplet of reflectors of good lateral continuity. These structures, after calibration with deep boreholes and commercial seismic lines, correspond to the boundaries between the major lithostratigraphic units of the sedimentary cover. The structures of the Umbria-Marche Apennines are discussed in detail in the next section.

The contractional structures are displaced towards the east by an east-dipping alignment that can be traced to a depth of about 5.0 s beneath the Umbria-Marche Apennines ridge [25]. This reflection reaches the surface at the western edge of the Tiber Valley, and corresponds to a well exposed east-dipping extensional fault system named the Altotiberina Fault (ATF). The Altotiberina Fault represents the easternmost master extensional fault of the Apennines (Barchi and others, 1998a; Boncio and others, 1998; Boncio and Lavecchia, 2000; Boncio and others, 2000; Collettini and Barchi, 2002).

Depth Converted Profile

The major features of the CROP03 profile are converted to depth in figure 4C. The seismic interval velocities adopted for depth conversion of the profile were derived from experimental studies (Batini and Nicolich, 1984; Burlini and Tancredi, 1998), from seismic refraction survey (De Franco and others, 1998), and from well data made available by ENEL and ENI-Agip (Bally and others, 1986; Barchi and others 1998a).

For the Adriatic Moho and lower crust we adopted the west-dipping geometry suggested by DSS and receiver functions, which also fit most of the reflections of the NVR profile (for example 23 24 29 30 31 in fig. 4B). This procedure forced us to ignore the ambiguous east dipping reflections 14 and 15.

EXTENSIONAL AND COMPRESSIONAL STRUCTURES IN THE NORTHERN APENNINES

We will describe in the following paragraphs the major extensional and compressional structures within the upper crust of the Northern Apennines, emphasizing the aspects where the contributions of the CROP03 profile have been most relevant to unraveling the structural setting.

Extensional Structures

Elter and others (1975) recognized that since the Miocene the Northern Tyrrhenian Sea and the western Northern Apennines (here named Tyrrhenian domain) were affected by extensional tectonics that continuously migrated eastward through time from Eastern Corsica to the Tuscany mainland. This view was successively confirmed by other researchers, who showed that the compressive structures of the Apenninic belt in Tuscany are no longer recognizable, because they are deeply dissected by the subsequent extensional structures (for example, Lavecchia and others, 1984; Carmignani and others, 1994). A similar eastward migration of the extensional tectonics was also recognized in the central Apennines fold -thrust belt (for example, Cavinato and DeCelles, 1999).

The results of the CROP03 project produced significant advances in the understanding of the extensional process, putting into evidence:

1) the strong asymmetric character of the extensional deformation, which appears dominated by a set of east-dipping, low-angle normal faults;
2) the depth of detachment of these fault zones, which is located at approximately 5 s (that is about 12 km);

3) the existence of a still active, east-dipping normal fault (ATF), affecting the westernmost part of the Adriatic domain.

The CROP03 profile imaged the extensional structures of the Tuscany mainland, providing evidence of the strong asymmetric character of the extension. The upper crust was thinned by a set of six major, east-dipping low-angle normal faults (Pialli and others, 1998; Decandia and others, 1998) and associated antithetic normal faults. We emphasize that the location of these fault zones is correlated with the occurrence at the surface of the continental and shallow marine syn-tectonic basins of the Tuscan region (figs. 2 and 4C). The age of the syn-rift deposits filling these "hinterland" basins supports the interpretation of a regular time migration of extensional deformation from west to east (for example, Pascucci and others, 1999; Collettini and Barchi, 2004) (fig. 3). The apparent geometry of the extensional faults and of the associated Neogene basins is further supported by many, onshore and off-shore seismic reflection profiles that demonstrate the extensional character of recent deformation (for example, Bartole and others, 1991; Pascucci and others, 1999; Cornamusini and others, 2002). Shallow extensional faults have been extensively mapped at the surface (for example, Zuccale fault, Keller and others, 1994; Collettini and Barchi, 2004) and intersected by deep wells in the geothermal areas of Larderello (Batini and others, 1985; Brogi and others, 2003) and Mt. Amiata (Calamai and others, 1970).

The low-angle normal faults along the CROP03 profile are interpreted to be detached at the top of the lower crust and to reach a depth of about 5 s (approximately 12 km) (fig. 4C). This is the same depth at which the thermal field is interpreted to localize the brittle/ductile transition (fig. 1D). The underlying lower crust has an anomalously reduced thickness (about 7 km) that possibly was produced by ductile flow. Summarizing, the Tyrrhenian domain is interpreted to have been extended by brittle/semi-brittle fault zones in the upper crust and ductile flow in the lower crust.

The younger and easternmost expression of extension of the Northern Apennines (ATF) is exposed in the Umbria region (Boncio and others, 1998, 2000; Collettini and Barchi, 2002). This structure rests on a thicker crust, and it reaches a greater depth (about 13 km), than the older and more western faults in the Tyrrhenian domain. This geometry is interpreted to represent incipient extension. A portion of the CROPO3 profile that offers a closer view of the ATF seismic image is shown in figure 5A. The trace of the ATF, represented by the eastward dipping alignment of the reflectors, corresponds at the surface to the western margin of the Val Tiberina Basin. The Val Tiberina Basin is filled by Upper-Pliocene-Quaternary deposits. The fault deepens towards the ENE below the Apenninic belt. An antithetic normal fault bounding the eastern part of the Val Tiberina Basin is also imaged in the data, in the shallower part of the profile. At depths ranging between 2.5 and 4 s (TWT) along the ATF fault trace, a lens-shaped, E-dipping package of reflectors suggests an extensional duplex made up of basement rocks. The ATF hanging wall corresponds to the previously formed (Late Miocene) compressional structures of the Umbria-Marche Apennines, dissected and down-thrown by normal faulting (figs. 2 and 5A). ATF geometry can be extended regionally through a network of good quality seismic reflection profiles (Barchi and others, 1999; Collettini and Barchi, 2002; Pauselli and others, 2002) and can be easily linked to the geological structures mapped at the surface (see Boncio and others, 2000 for a comprehensive review).

The relationships with the pre-existing compressional structures and the age of the syntectonic Val Tiberina Basin indicate that the fault activity took place from the Upper Pliocene to the present. Strong evidence for present-day activity of the ATF is furnished by microseismicity surveys operated by local networks along the fault trace. Two temporary microseismic networks operated in the Città di Castello-Perugia area in two time periods, 1986 and 2001 (Deschamps and others, 1989; Piccinini and others,

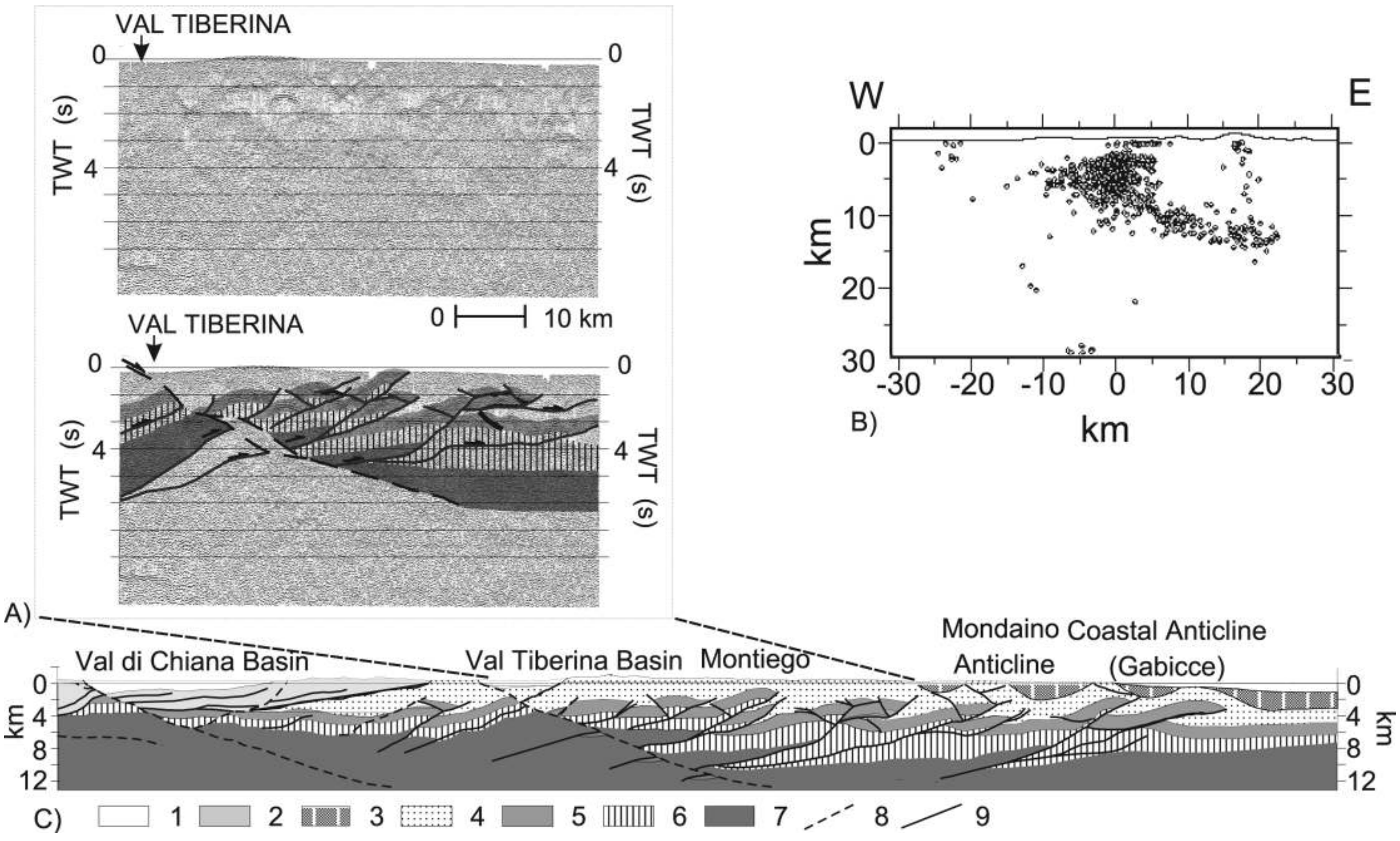

Fig. 5. (A) Portion of the CROP03 seismic profile (after Barchi and others, 1998a). (B) Vertical section of located earthquakes (after Piccinini and others, 2003); the trace of the section line is reported in fig. 1B. The topography is also reported. (C) Geological interpretation of the seismic reflection line CROP03, from the M. Cetona to the Adriatic Sea (modified from Barchi and others, 1998a), see location on fig. 3A. 1) Continental and shallow marine sequences; 2) Tuscan nappe Units; 3) Pleistocene Turbidites; 4) Miocene-Pliocene Turbidites; 5) Jurassic-Oligocene Carbonates; 6) Triassic Anidrites; 7) Upper crust; 8) Thrusts; 9) Normal faults.

2003). The two surveys show similar characters. Most of the seismicity fits the trace of the ATF, as depicted by depth converted seismic profiles, separating an active hanging wall from an almost aseismic footwall (fig. 5B). The focal mechanisms show extensional kinematics with NNW-SSE trending planes, parallel to the ATF, and the resulting stress tensor (with a vertical σ_1 and ENE trending σ_3) is consistent with both the presently active stress field (Montone and others, 2004) and with the Quaternary long-term stress field of the region (Lavecchia and others, 1994; Boncio and others, 2000).

In conclusion, since Miocene time, the western part of the Northern Apennines has been dominated by extensional tectonics. The amount of lithospheric thinning distinctly recognized by the CROP03 profile and suggested by other geophysical and geological data (such as high surface heat flow, magmatism, and positive Bouguer anomalies) indicates that the Tuscan region displays all the typical characters of an extensional belt, as defined by Lister and Davis (1989).

In recent years, some authors (Boccaletti and others, 1997; Bonini and others, 1999; Finetti and others, 2001) proposed a different interpretation, minimizing the importance of extensional deformation in the western Northern Apennines (Tyrrhenian domain). These workers suggested that the continental to shallow marine hinterland basins were formed by active thrusts, whilst normal faults are regarded as secondary effects, related to either collapse of the back-limb of the thrust anticlines or to local transtension along strike-slip, transversal fault zones. Extensional tectonics, in this view, started only recently (about 2 Ma), and produced only high angle normal faults affecting the pre-exisiting syn-compressional hinterland basins.

In our opinion, this interpretation is not consistent with an impressive amount of data, collected and interpreted by different authors, that converges on the concept that extensional tectonics have dominated the evolution of the Tyrrhenian domain since the Miocene. Interpretation that consider an extensional tectonics process a subordinate geodynamic event in the Northern Apennines evolution cannot account for:

1) the thinned crust existing below the Tyrrhenian domain;
2) the very high heat flow measured in the Tuscan region, which requires an advective process to allow the rapid propagation of the thermal anomaly from the asthenosphere to the surface;
3) the exhumed, low angle normal faults, which have been observed and studied in detail in Elba Island, as well as below the Larderello geothermal fields;
4) the evolution of sedimentary basins through normal faults extensively documented by both regional studies, mainly based on seismic reflection profiles and by surface geology data;
5) the absence of regionally documented thrust faults that unambiguously cut recent deposits or control sedimentation. Only minor (outcrop scale) compressional structural features have been observed in these deposits, which are related to the complex geometry of the normal faults (hangingwall anticlines and ramp synclines) or transfer faults that control the basin and normal fault segmentation.

Compressional Structures

The shallow structures of the eastern part of the section (Adriatic domain) correspond to the arc-shaped Umbria-Marche fold and thrust belt. This thrust belt has an eastward convexity and vergence, and represents the outer part of the Northern Apennines (Barchi and others, 2001). The good quality seismic data effectively image the style and timing of deformation of this compressional belt, which has not been deeply disrupted by extensional structures.

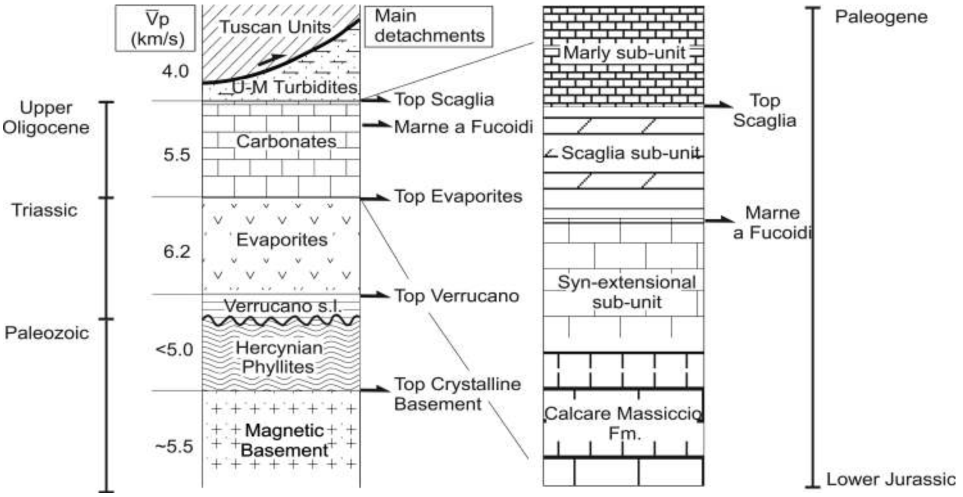

Fig. 6. Main lithostratigraphic units in the Northern Apennines (after Barchi and others, 2001).

A detailed interpretation of the shallow structures (above approximately 5 s TWT of depth) includes surface geology data (available from geological maps), commercial seismic profiles (both parallel and transversal to the CROP03 trace), and deep boreholes (fig. 2). The interpreted seismic profile was converted to the depth, using interval velocities derived from the boreholes closest to the CROP03 profile (Bally and others, 1986; Barchi and others, 1998b) in order to build up a geological section crossing the entire Umbria-Marche fold and thrust belt (fig. 5C).

The stratigraphy of the region has been described in detail in the literature and is schematically represented in fig. 6 (for example, Centamore and others, 1986; Ciarapica and others, 1987; Cresta and others, 1989, and references therein). From a mechanical point of view, the entire sequence can be divided into four main litho-structural units. From top to bottom the units are: turbidites, carbonates, evaporites and basement (*sensu lato*); the basement unit includes the Verrucano Formation and Palaeozoic phyllites (fig. 6). The mechanical boundaries among these units correspond to the main décollements and to the best seismic markers. This relationship has driven the geological interpretation of the profile.

The structural style of the Umbria-Marche fold and thrust belt has been controversial (Ghisetti and others, 1993) since the very influential paper by Bally and others (1986). The Bally and others (1986) paper was the first to use extensive seismic reflection data in the region. The proposed interpretations of the data to explain the deep structural style of the region can be divided into two main groups. The first group of authors interpreted Umbria-Marche Appenines as a typical thin-skinned thrust belt. In this interpretation, thrusts were developed in a regular piggy-back sequence. The main basal detachment corresponds to the Triassic evaporites (Bally and others, 1986; Calamita and Deiana, 1986; Hill and Hayward, 1988; Tavarnelli, 1997). The second group recognized the involvement of the basement in the major thrust sheets (Lavecchia and others, 1987; Sage and others, 1991; Barchi, 1991; Barchi and others, 1998b; Coward and others, 1999). Different models of basement geometry and depth have also been inferred from aeromagnetic data. The aeromagnetic map of Italy surveyed by Agip in the 1980's (Arisi Rota and Fichera, 1985) was used by Bally and others (1986) to support their thin-skinned model. A different geological interpretation of the same data-set, with the aid of gravity data, was later proposed by Cassano and others (1998,

2001) that included the involvement of the basement in the major thrust sheets. Recently Speranza and Chiappini (2002) have reinterpreted the magnetic data to support a thick-skinned tectonic model.

The CROP03 profile offers a valuable contribution to the question of basement involvement in the major thrust sheets, because the basement interpreted seismic reflections are clearly recognizable throughout the eastern part of the section. A detail of the profile, corresponding to the western part of the Umbria-Marche mountain ridge, is critical to interpret the structural style of the region (fig. 5C). Three prominent reflections can be recognized along this section. The reflections correspond to the Marne a Fucoidi Formation (close to the top of the carbonates), to the top of the evaporites, and to the top of the basement. The top of carbonate multilayer (Scaglia Variegata and Scaglia Cinerea Formations, Upper Eocene-Oligocene) and the Messinian reflector (recognizable in the easternmost sector of the profile) also can be traced locally.

Using seismic markers, the geometry of the major litho-structural units of Umbria-Marche fold and thrust belt can be interpreted. The geometry highlights the main characteristics of the structural style. The main features are:

1) Three fault ramps in the basement are present below the Umbria-Marche fold and thrust belt. These ramps correspond to the major thrust sheets, and produce basement deepening towards the east (see also fig. 5C for a regional view).
2) The Marne a Fucoidi reflections describe a set of large anticlines involving the carbonates and the evaporites whose geometry and wavelength resemble the typical Umbria-Marche folds cropping out in the main mountain ridge.
3) The shallower part of the section, above the Marne a Fucoidi seismic marker, is characterized by numerous reflections clearly imaging a complex pattern of short wavelength structures disharmonically overlying the carbonates.

A similar structural pattern characterizes the adjacent easternmost part of the profile (fig. 5C). This pattern supports a thick skinned style of deformation characterized by a system of multiple, superposed detachments, each of them generating structures differentiated by their wavelength in a hierarchical mode. The most important classes of structures seismically and geologically detectable are:

1) shallow imbricates, detached on the top of the carbonates and involving the turbidites that typically have a wavelength on the order of few hundred meters;
2) Umbria-Marche folds, detached at an intra-evaporites level and involving the carbonates, with structures that have a 5 to 10 km wavelength;
3) the main basement thrusts, corresponding to the major structural units of the region (having a 25–35 km wavelength) and that transfer the shortening from the upper crust through basement to the sedimentary cover.

This style of deformation is also supported by other studies mainly based on shallower commercial profiles (for example, De Donatis and others, 1998; Pauselli and others, 2002).

Compressional deformation is accompanied by the development of syn-tectonic basins (see Barchi and others, 2001, for a review). The age of the syntectonic deposits constrains the timing of deformation along the section (fig. 3). The timing of deformation reveal: (1) the general eastward migration of the contractional deformation from Late Burdigalian in the Tiber Valley zone to Pleistocene-present time at the Adriatic coast; and (2) the relatively long life of each structure that resulted in frequent synchronous thrusting (Boyer, 1992) of adjacent structures. The contemporaneous thrusting of adjacent structures also results in the development of small mobile basins located between the growing ridges that were superimposed on regionally extended foredeep basins (Ori and others, 1986).

The total shortening of Umbria-Marche fold and thrust belt, interpreted along a regional geological section extended offshore to the Adriatic undeformed foreland, is approximately 60 km. Sixty km corresponds to about 30 percent (Barchi and others, 1998b) shortening. This value is an important constraint for the attempts of crustal balancing and for the reconstruction of the geodynamic setting of the region.

CRUSTAL STRUCTURE AND GEODYNAMICAL INTERPRETATION

Summarizing, the Tyrrhenian and Adriatic domains exhibit a distinct pattern of reflections at all crustal levels (fig. 4). The Tyrrhenian lower crust is characterized by several discrete sub-horizontal reflections, some of them laterally continuous for as much as 10 km, wheras the Adriatic lower crust possesses a weak and diffuse reflectivity without any prominent reflections. The upper crust of the Tyrrhenian domain is dominated by extension whilst the Adriatic domain shows a well-structured upper crust with well imaged thrusts and folds (Barchi and others, 1998b). The NVR profile highlights the presence of an intermediate sector, between these two domains, consisting of a highly reflective window, which includes some diffraction hyperbola down to a depth of 10 s.

The Moho in the Tyrrhenian domain is shallow (<25 km), gently deepening towards the east. The Moho in the Adriatic domain in contrast is deeper (>30 km), gently west-dipping. In addition the refraction data indicates a relatively slow Moho (7.7 km/s) in the Tyrrhenian domain and a faster Moho (about 8.0 km/s) in the Adriatic domain. Seismic refraction data (Suhadolc and Panza, 1989; Ponziani and others, 1995; De Franco and others, 1998) indicate a localized doubling of the crust for about 30 km, below the Val di Chiana-Val Tiberina region. The Moho doubling is poorly imaged by the NVR profile, but the corresponding region possesses a distinctive reflection pattern, in which reflections suggest that a major west-dipping crustal shear zone can be traced. Just below the doubling of the crust, detected by the refraction data, tomographic images obtained by different authors with different methods (Amato and others, 1993; Spakman and others, 1993; Selvaggi and Chiarabba 1995; Piromallo and Morelli, 1997; Ciaccio and others, 1998; Lucente and Speranza, 2001) show a pronounced high-velocity anomaly. This anomaly is interpreted as a submerged crustal slab possibly linked to the crust of the Adriatic domain. The shape and position of the velocity anomaly are slightly different in the different studies, possibly due to insufficient areal distribution of the seismic stations. The most relevant differences pertain to the length of the slab and its continuity. The submerged crustal body extends down to 200 km, according to Ciaccio and others (1998), whereas it is interpreted to extend to a depth of 670 km in the study by Lucente and Speranza (2001). An even greater continuity is imaged by Faccenna and others (2001). The slab is considered continuous by Amato and others (1998), Ciaccio and others (1998), and Lucente and Speranza (2001). Spackman and others (1993) however, consider the continuity of the slab to be interrupted, which suggests slab detachment has taken place. Their study images relatively low velocities between 150 and 200 km. The anomalous high S-wave velocity at depths exceeding 50 km confirmes the presence of lithospheric roots below the intermediate sector (Calcagnile and Panza, 1981; Du and others, 1998; Pontevivo and Panza, 2002). These roots are also marked by rare, but regularly recorded, seismic activity (Amato and others, 1997) that reaches a maximum depth of 90 km below the Val Tiberina Basin.

The presence of a submerged crustal slab detected by tomography and the deep seismic activity in the intermediate sector both support a geodynamical interpretation in which the pattern of coupled compression and extension, continued since the Middle Miocene, was driven by sinking and retreating of a westward dipping Adriatic crustal slice. A schematic model is shown in figure 7. The proposed model assumes that in the late Oligocene-early Miocene the collision between the Alpine orogen and the

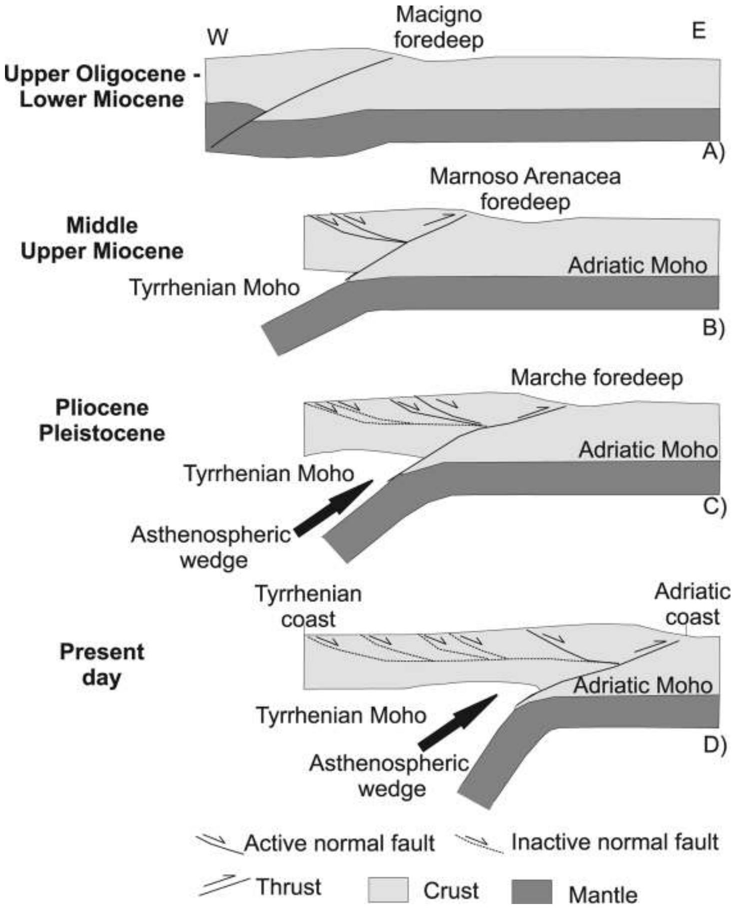

Fig. 7. Schematic model for the Upper Oligocene to recent evolution of the Northern Apennines, indicating the hypothesized delamination of the continental margin mantle lithosphere.

continental crust of the Adriatic promontory (African plate) shortened and thickened the lower and upper crust, depressing the Moho and raising the surface topography isostatically (fig. 7A). The overthickened crust started to delaminate in the Middle Miocene due to the lithospheric mantle negative buoyancy with respect to the underlying asthenosphere (Bird and Baumgardner, 1981) (fig. 7B). The delamination resulted in a mechanical thinning of the lithosphere beneath the orogenic belt (Nelson, 1982) and high tensional stress on the crustal lithosphere in the zone of convergence and compressional stress in areas away from the collision zone (Channell and Mareschall, 1989). The subsequent sinking and retreating of the lithospheric slice produced a wave of compressional deformation propagating toward the Adriatic foreland and generating foredeeps that were progressively incorporated in the tectonic pile. The delaminated crust in the western sector was underplated by an asthenospheric wedge progressively welling up into the gap opened in the lithosphere during the delamination (fig. 7C). As a consequence, a new Moho was formed in the western domain and the lower part of the crust was heated, thinned and invaded by intrusive bodies. The ongoing lithospheric thinning process also resulted, at the surface, in the formation of extensional basins bound by the east-dipping normal faults affecting the upper-middle crust and migrating through time from west to east. Compression (thrust belt and associated foredeeps) was followed by extension (normal faults and related basins) in any position along the section. The most recent expression of the extensional process (that is, Alto Tiberina fault) affects the intermediate sector of the profile (Umbria region) where extensional tectonics is still active and stronger seismic activity is concentrated because the process of crustal thinning has not yet been completed. The brittle/ductile transition in the intermediate sector (fig. 1D) deepens towards the east from 12 km to about 25 km, indicating that the zone is progressively going from a compressed state to an extended state.

The total amount of Neogenic-Quaternary extension is not easy to constrain due to the lack of good geological or geophysical markers. Collettini and others (2006) estimated the displacement of some major east dipping shear zones was in the range of 6 to 10 km. Applying this value to the entire extended crustal sector, between northern Corsica and the Tiber Valley, a total extension of 60 to 70 km can be estimated (β about 1.4). This value is comparable to the amount of shortening experienced by the Adriatic domain (Umbria -Marche units) in the same time period, which is about 60 km (Barchi and others, 1998b). The total shortening of the Northern Apennines also comprises the shortening of Ligurian and Tuscan Units produced during Oligocene and Lower Miocene, which is not easy to constrain. However, assuming that the rate of convergence has not dramatically changed the total amount of shortening can be estimated to be 120 to 150 km. The relatively low value of the total shortening does not agree with the existence of crustal slab 670 km long as deduced by the interpretation of tomographic data by Lucente and Speranza (2001) but is consistent with the depth evaluated by Ciaccio and others (1998).

CONCLUSIONS

The CROP03 seismic reflection profile has been described and re-interpreted in detail, taking into account new geophysical data and interpretations made available in the last five years. In particular, information from refraction data (De Franco and others, 1998), gravimetric data (Marson and others, 1998; Cassano and others, 1998, 2001), tomographic data (Ciaccio and others, 1998; Faccenna and others, 2001), results of teleseismic waveforms, (Piana Agostinetti and others, 2002; Mele and Sandvol, 2003) and the interpretation of other seismic reflection profiles (for example, Pascucci and others, 1999; Cornamusini and others, 2002) are used to better define the crustal structure of the Northern Apennines. Numerous aspects of the CROP03 profile were useful in a geodynamic interpretation for the crustal setting of the Northern Apennines. They were:

1. The Tyrrhenian domain is dominated by extensional tectonics at any crustal level. It is extended by brittle/semi-brittle east-dipping normal fault zones in the upper crust that cut the earlier compressive structures. Extension in the lower crust is accomplished by ductile flow. The east-dipping normal faults in the upper crust are detached at a depth of about 5s (approximately 12 km), possibly at the top of the lower crust. The interpreted thermal field localizes the brittle/ductile transition at the same depth (Pauselli and Federico, 2002). The underlying lower crust has an anomalously reduced thickness (about 7 km), possibly produced by ductile flow. The extensional tectonics of the Northern Apennines are still active in the Umbria region where the younger and easternmost extensional fault of this extensional system (ATF) is exposed. Here the brittle/ductile transition is much deeper than suggested by the seismic evidence of the fault (Pauselli and Federico, 2002).
2. In the Adriatic domain the pattern of shallow contractional structures is well preserved. The good quality data of this part of the profile has allowed the interpretation of the style and timing of deformation of the Umbria-Marche

fold and thrust belt, as well the evaluation of the total shortening. The calibration with surface geologic data has allowed the interpretation of a total shortening of approximately 60 km (30%) for the whole Umbria-Marche sector (Barchi and others, 1998b).

3. The Tyrrhenian and Adriatic domains, with distinctive geological and geophysical characteristics, exhibit a distinct reflectivity pattern at all crustal levels. The Tyrrhenian lower crust is characterized by several, discrete sub-horizontal reflections, some of them laterally continuous for as much as 10 km, whereas the Adriatic lower crust is characterized by a weak and diffuse reflectivity and no prominent reflections.

The NVR profile highlights the presence of an intermediate sector, between these two domains, consisting of a highly reflective window, which includes some diffraction hyperbolae down to a depth of 10 s. Tomography and the deep seismic activity indicate the presence of a submerged crustal slab in this sector supporting a geodynamical interpretation in which the coexistence at any time and at any position of continuous eastward migration of both extensional and compressional structures was driven by sinking and retreating of a crustal slice dipping westward into the upper mantle. The value of the total shortening of the Umbria-Marche fold and thrust belts obtained by Barchi and others (1998b) constrains the depth of the supposed retreating crustal slab to less than than 200 km, consistent with the depth evaluated by Ciaccio and others (1998). In this geodynamical framework the relatively slow Tyrrhenian Moho (7.7 km/s) detected by seismic refraction (De Franco and others, 1998) at a depth less than 25 km, and the faster Adriatic Moho (8.0 km/s) detected at a depth greater than 30 km, is seen as a consequence of the retreating processes. The delaminated crust in the western sector was underplated by an asthenospheric wedge, progressively welling up into the gap opened in the lithosphere during the delamination, that thinned the Tyrrhenian lower crust and restructured almost completely the Tyrrhenian Moho.

The intermediate sector of the Northern Apennines is considered as a transitional area between the western extensional sector and the eastern compressional sector of the orogen. This interpretation is consistent with the geological and geophysical characteristics of this area: (1) the variable depth of the brittle/ductile transition (going abruptly from a depth of about 10 to 12 km, that characterizes the western sector, to a depth of about 30 km of the eastern sector), (2) the presence of a highly reflective window, and (3) continuing crustal thinning in the presence of extensional active tectonics (ATF).

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