BOLLETTINO DI GEOFISICA TEORICA ED APPLICATA VOL. XXXVI, N. 141-144 - MARCH-DECEMBER 1994

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CONSTRAINTS AND NEW PROBLEMS FOR GEODYNAMICAL MODELLING OF CENTRAL ITALY (CROP 11 CIVITAVECCHIA - VASTO DEEP SEISMIC LINE)

Abstract. The preliminary studies to the acquisition of the CROP Project deep seismic lines provide the opportunity for a full revision of geological and geophysical data available for Central Italy in the area along the CROP 11 profile and its off-shore prosecution in the Adriatic and Tyrrhenian sea. Furthermore, new data are reported, with special emphasis on the Apennine chain s.s.. Many of these data come from the co-ordinated work of a group based at the Dipartimento Scienze della Terra of La Sapienza University in Rome. Other data are derived from specific preliminary studies. The resulting regional framework is better defined and more complex than previous models. Some new evidence is considered here of regional importance and is briefly illustrated to show the various deformational styles present within the whole complex of the Apenninic chain. All of the reported field examples are associated with meso-structural analysis. A comparison of these results led to the identification of a specific sector with particular characteristics. New field data together with some general assumptions allow a tentative computation of the minimal percentage shortening of the central sector of the Apenninic chain; the derived value (about 57%) exceeds the expected value and should be further investigated. New constraints for a geodynamical model of Central Italy are suggested.

FOREWORD

Aquisition of deep seismic lines during the Italian CROP project has provided the opportunity for a review of geological data throughout the country. As it is well known, the connections between on-shore and off- shore CROP lines is a very important topic for future years. As a contribution to this, we present here a brief review of the new geological and geophysical data available for Central Italy, with special regard to the Apenninic chain. Most of data derive from a group project started more than ten years ago, while new data come from the official CROP 11 working groups since 1991.

The aim of this paper is not to present a new model, but to provide constraints and to discuss new problems in the preparation of previous CROP 11 results and, then, in the data interpretation.

A completely reviewed regional setting is presented here, followed by several field examples of new situations and new interpretations of previous data; a tentative computation of the minimum shortening of the Apenninic chain and the expected contribution of the CROP 11 seismic line to the solution of the major geological problems of Central Italy are also given.

Manuscript received, March 19, 1993; accepted, December 20, 1993.

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A deep seismic line (CROP 11) crossing the major geological features and addressing the geodynamical problems of Central Italy will be shot between Civitavecchia (Northern Latium, to the west) and Vasto (Southern Abruzzi, to the east) in the near future. In this large area of the Italian peninsula, some geophysical evidence suggests the existence of two different, important crustal domains, the Adriatic and the Tyrrhenian (for geographic locations see Fig. 1; for a brief summary see also Salvini and Tozzi, 1986; Funiciello et al., 1989 and Patacca et al., 1992b).

The Adriatic region (to the east) is characterized by a low-medium residual magnetic field (Arisi Rota and Fichera, 1987), low-medium Bouguer anomaly (except the Gargano zone; Morelli, 1975; Carrozzo et al., 1992) and low heat flow (Della Vedova et al., 1988); lithospheric and crustal (30-40 km) thicknesses are "normal" (Panza, 1984; Nicolich, 1989). Also, the "abnormal" magnetic anomalies are clockwise rotated (Fedi and Rapolla, 1987) and the Adriatic area shows a clear macroseismic "felt" area for the larger Aegean earthquakes (Margottini, 1982; Castenetto et al., 1984) and, finally, the ^{3}He/^{4}He ratio is very low (0.001x10^{-6}, Hooker et al., 1985).

On the contrary, the Tyrrhenian area (to the west) shows a high- medium residual magnetic field, high-medium Bouguer anomaly, very high heat flow; and lithospheric and crustal thicknesses are small (the latter less than 10 km). The "abnormal" magnetic anomalies are counterclockwise rotated, and the Tyrrhenian is not influenced by Aegean earthquakes. Finally, the ^{3}He/^{4}He rate is high (0.1-0.5x10^{-6}). For specific references see the aforementioned authors.

Basically, the Adriatic region is characterized by an old, inactive, not recently tectonized continental crust, and by a relatively simple surface structural geology, while the Tyrrhenian region has a new, very active, tectonized thinned ("transitional") crust.

A summary of the geophysical features of this central sector of the Italian peninsula is also reported in Ogniben et al. (1975), Gasparini and Praturlon (1981), Wigger (1984), Nicolich (1989), Lavecchia and Stoppa (1989) and, more recently, in Scarascia et al. (1992) in which a first attempt at a wide angle (DSS) profile interpretation in central-southern Italy is also shown. In that paper, the authors underlined the possibility of three different crustal types underneath this area: Tyrrhenian, Adriatic and Adriatic-like crust at around -25 km depth (Fig. 2).

Three main geodynamical units have been recognized for a long time in central-southern Italy on the basis of the geological data. From east to west the first sector is the Adriatic (1) poorly deformed intra-orogenic foreland. It is made up of several major blocks characterized by different senses and amounts of rotation from the Late Cretaceous up to the Pliocene. The blocks are separated by major discontinuities (e.g. Mattinata fault and Salento-Murge fault), mostly strike-slip in motion (Funiciello et al., 1989, 1992). The present- day ensialic post-collisional chain (2) is a thrust belt which developed from the Early Miocene to the Pleistocene as the result of a longer deformational history (Patacca and Scandone, 1989). The terrigenous deposits of an Upper Tortonian to Pleistocene foreland basin progressively migrating eastwards are incorporated in the chain. The Tyrrhenian basin (3) is now subject to strong crustal thinning, mantle uplift and large extensional processes, including great volcanic activity (Morelli, 1975; Finetti, 1982). Because of its peculiar characteristics it is an atypical back-arc basin in the plate tectonic sense (Doglioni, 1991). The present-day geodynamical framework is derived from the spatial-temporal migration of the foreland basin, a function of the sinking of the Adriatic lithosphere and of the Tyrrhenian basin opening (Patacca et al., 1992a).

MAJOR OUTSTANDING FEATURES IN THE CENTRAL APENNINES CHAIN

Presentation

The surface geological data (lithostratigraphical sequences, thickness of sedimentary series, structural features) reflect the dynamics of the different units, and also allow the recognition of several sectors characterized by different geometries and kinematics (Fig.1). In the western sector mainly pelagic sequences outcrop (Tolfa flysch, Tuscan nappe s.l., Sabina facies) with NW-SE and N-S trending structural axes. Deformation in that area is mostly ductile, and semi-

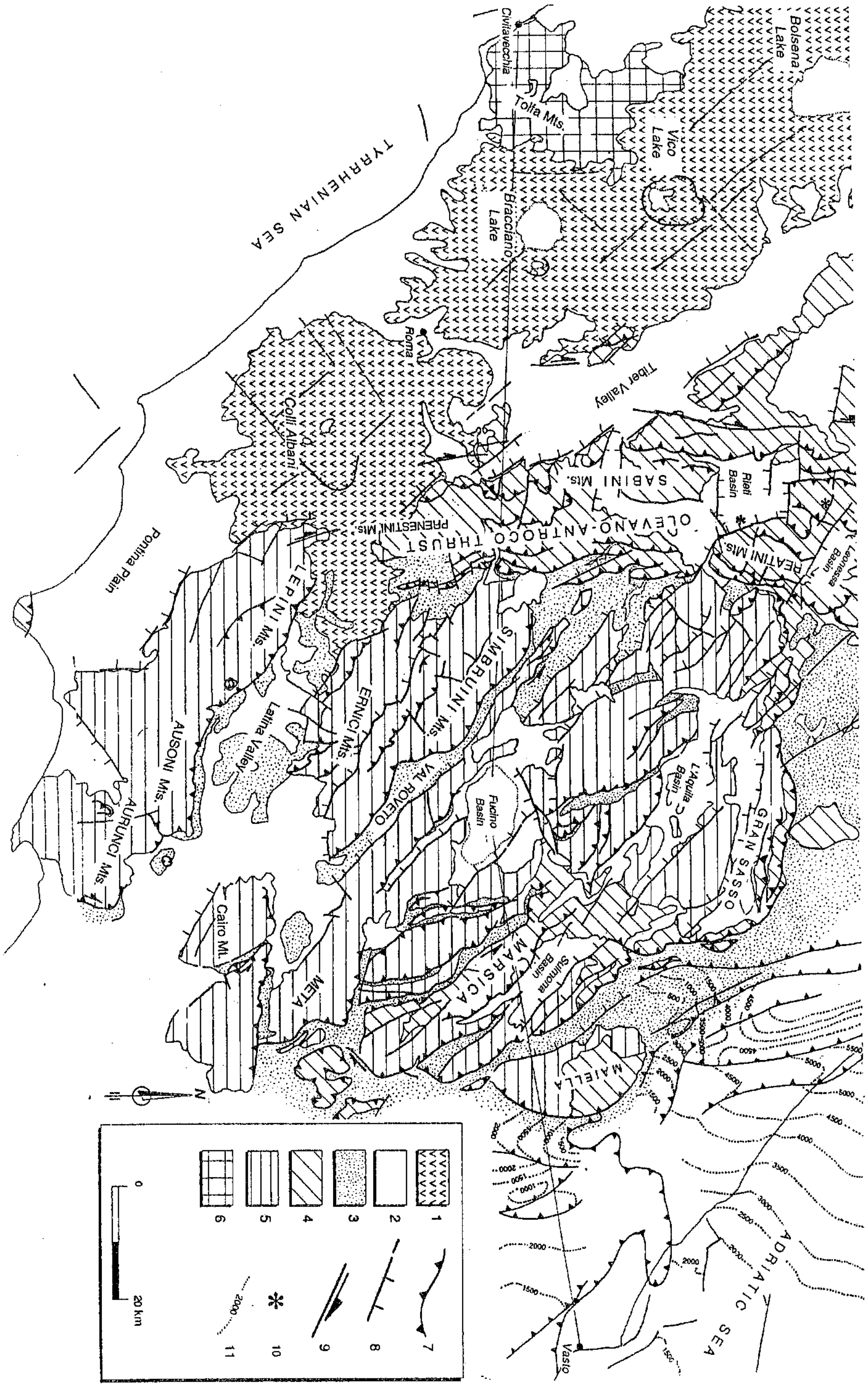

Fig. 1 - Tectonic map of central Italy (based on Bigi et al., 1988, Structural Model of Italy; greatly modified and re-drawn). Legend: 1- volcanic districts; 2- Plio-Quaternary marine and continental deposits; 3- terrigenous units (Upper Miocene-Pliocene); 4- slope and proximal basin sequences, including Sabina (Trias-Middle Miocene); 5- Latium-Abruzzi carbonate platform domain (Trias-Lower Miocene); 6- Tuscan units (Tolfa); 7- main overthrusts; 8- main normal faults; 9- major strike-slip faults; 10- intrapenninic volcanism (Cupaello, Polino, S.Venanzo); 11- base of Pliocene isobaths. The CROP 11 cross section line is also drawn between Civitavecchia and Vasto.

ductile due to the proximity of the brittle-ductile transition, and because of the rheology and attitude of the rocks. The central sector is characterized by typical carbonatic platform sequences (Latium-Abruzzi sequence, Maiella sequence) with NW-SE trending structural axes. Deformation here is mostly brittle (faults), mainly because of the higher competence of the outcropping rocks. The Olevano-Antrodoco line (Parotto and Praturlon, 1975) divides the two sectors. To the east, the Ortona-Roccamonfina tectonic line divides these sequences from pelagic to transitional successions.

The main characteristics of the stratigraphy of Central Italy are well known. Evidence of Tuscan-like series has been only recognized along the Tyrrhenian margin in the Tolfa area, and in the deep well of the geothermal field of Latera and Sabatini Mts. The transitional facies of the Sabina series (Parotto and Praturlon, 1975; Cosentino and Parotto, 1988) is widespread, cropping out all over the sector west of the Olevano-Antrodoco line. Mostly N-S elongated structural axes are common here in an imbricate geometry involving several tectonic units (Cosentino and Parotto, 1989; 1992; Cosentino et al., 1992).

Basement

The presence of a metamorphic basement under the Central Apennines chain, inferred mainly from geophysical data (mostly gravimetry, aeromagnetics, DSS) and by analogy with the northern sector of the chain, is generally accepted, although its role is still debatable. Depending on the various interpretations of the authors, its top is placed at a depth that varies between 9 and 16 km, gently dipping northeast (e.g. Mostardini and Merlini, 1986).

Whether part of the basement is involved in the chain formation process is still a major open problem (see paragraph below). Much evidence is in favour of such an involvement. Deep crustal cross-sections based on gravimetry, and located just north of the present area indicate that slices of metamorphic units are imbedded in the most allochthonous ones in SW Tuscany. Basement units outcropping in this region show Tertiary greenschist facies deformations associate with extensive shortening (Wise et al., 1983). In one locality (Roselle, Romani Mts.) there was field evidence for a thrusting of metamorphic basement over Ligurian (internal basin) derived sediments (Moretti, 1992).

Other indirect evidence come from the least shortening computation (see later): filling the entire chain volume down to the sole thrust (top of the basement) with sedimentary cover units only requires accepting a seriously abnormal shortening. Yet, several indications are very difficult to incorporate into this model in the studied area. Firstly, the outcrops of metamorphic units, a common feature along western Tuscany, abruptly disappear almost completely south-west of a NE-SW line located immediately south of the Romani Mts. The only exception is a 30 x 10m tectonic slice that outcrops on Zannone Island (Pontine Is., Pantosti and Velonà, 1986); this line could represent a step downthrowing the SE sector and burying at depth the deeper structural units. The major problem for this hypothesis is that also the most internal units, the Ligurian deep sea sediments with ophiolites, never outcrop southeast of this line. Since these, according to accepted models, should lie in the highest structural position, their disappearance is not likely compatible with the proposed relative motion along this line. The CROP 11 deep seismic line should shed new light on this important problem.

Main thrusts

The present geometry of the Central Apennine thrust belt is well known. Some of its main thrust surfaces have been analyzed, and the evolutiòn of this chain is in an ensialic context with an Adriatic-verging piggy-back thrust sequence. The timing of this sequence is well defined by the tectono-sedimentary events which controlled the evolution of the chain-foredeep system. The individuation of different foreland basins indicates the areas which, at different times, were involved in the orogenic system as foredeeps. The ages of the foredeep basins recognized in Central Italy show that in this area the build up of the outcropping Apenninic chain started in late Tortonian times and involved the outermost domains during middle Pliocene (Cipollari and Cosentino, 1992a; Patacca et al., 1992a). Besides the foredeep basin migrations, in the Central Apennines, several piggy-back basins have been recognized (Patacca et al., 1992a;

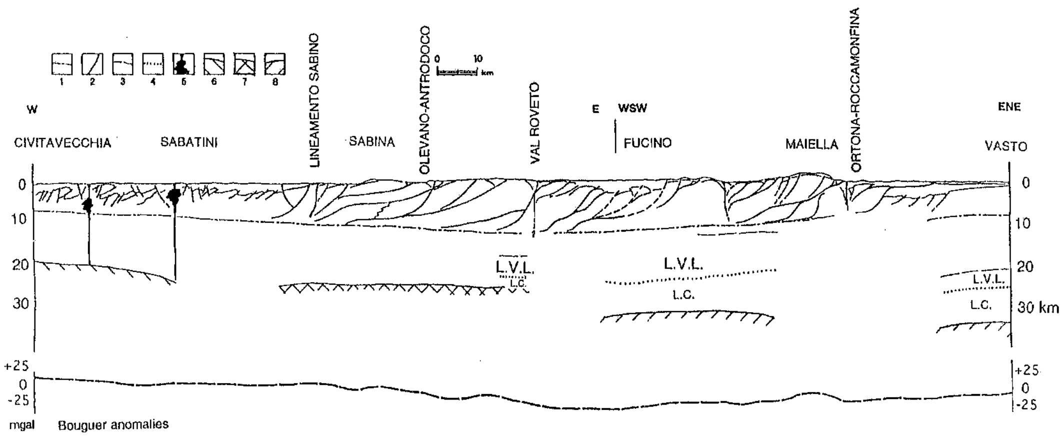

Fig. 2 - Hypothetical cross section between Civitavecchia (W) and Vasto (E), along the CROP 11 line. Most of geophysical data come from Carrozzo et al. (1992), Mostardini and Merlini (1986), Arisi Rota and Fichera (1987) e Scarascia et al. (1992); for tectonic data see the References. The three different crustal domains hypothesized by Scarascia et al. (1992) are here indicated. The main surface tectonic lines are also roughly underlined; among them, the Val Roveto line seems to correspond to a major step in the Moho. Only a very general sub-surface tectonic behaviour is here given. Legend: 1- aeromagnetic basement; 2- main faults; 3- top of low-velocity layer (L.V.L.); 4- base of low-velocity layer; 5- sub-surface magmatic chambers of Tyrrhenian margin; 6- Tyrrhenian Moho; 7- Adriatic-like Moho; 8- Adriatic Moho; L.C. is lower crust..

Cipollari and Cosentino, 1993). These basins allow us to define the different ages of mountain building, from inner to outer structural domains, and confirm the piggy-back character of the Apenninic chain thrust sequence. From the inner part towards the outer, the main thrust fronts are the Lepini Mts. thrust, Simbruini Mts. thrust, and Morrone Mt. thrust. During the latest compressional movements, out-of-sequence thrusts developed in areas already affected by compressional tectonics. The Gran Sasso front and the Olevano-Antrodoco thrust system are the major out-of-sequence thrusts recognizable in the Central Apennines (Ghisetti and Vezzani, 1988; Cipollari and Cosentino, 1992a; 1992b). The Olevano-Antrodoco line is an imbricate zone that involves, at the hanging-wall, the Sabine tectonic units, and piles them onto units derived from the deformation of the Latium-Abruzzi carbonate platform (Parotto and Praturlon, 1975; Cosentino and Parotto, 1989; 1992).

Back-thrusts

Although the main structural framework of the chain is a series of east- to north-east verging thrust sheets, showing a typical foreland dipping ramp-flat geometry which indicates the presence of duplexes, back-thrusts are a common features in the Central Apennines, either related to major flower structures (as in Marsica) or to frontal ramp tectonics of thrust sheets s.s. (as in the Simbruini Mts.).

In eastern Marsica, the existence of a regional back-thrust system was recently suggested (Corrado et al., 1992). This would be made up of the M. Turchio, the Morrone del Diavolo-Pescina and the Alto Sangro-Giovenco structures. Facies analysis in the area suggests that some of the regional tectonic lines have undergone oblique displacement, and sometimes pure strike-slip motion.

The structural characteristics, in addition to the kinematic complexity of some of the eastern Marsica structures, suggest that the eastern Marsica back-thrusting can be related to wrench tectonics along a NW- SE shear zone, located on the outer margin of the Latium-Abruzzi carbonate platform.

In the middle of the Latium-Abruzzi carbonate platform, west-verging thrusts have also been recognized in the Jenne zone (Simbruini Mts.), where the back-thrust is close to one of the major thrusts of the Apennines.

Other major lines

Several major tectonic discontinuities are easily recognizable in Central Italy on the basis of new field work and structural analyses (only a few are given, as examples in Fig. 3). Most of them show strike-slip characteristics; some are new and others are complex tectonic lines inherited from older deformative events and reactivated several times up to now. Strike-slip motions are common in the Central Apennines, but it is not yet always clear how to relate them to a specific tectonic phase. Some of these strike-slip faults show evidence of reactivaction in very recent times (especially along the Tyrrhenian margin) and are mainly N-S and NW-SE trending; E-W trending strike-slip faults in the chain are here mostly considered as tear-faults. Several field examples have been studied over the last ten years, coming from the carbonatic platform and from the Sabina facies.

The Sabina lineament is a N-S tectonic line active up to very recent times (Alfonsi et al., 1991; Faccenna et al., 1994). The deformative history of this line seems to be complicated by the variable geometry of the plane itself (strike-slip when sub-vertical, oblique-thrust when dipping) and by the different rock competences involved. Right-lateral strike-slip motion has been the most common all along this line, though it is probable that dip-slip normal motion was more common during Pleistocene times.

The Ancona-Anzio tectonic line is a major fault affecting the western edge of the Latium-Abruzzi carbonate platform (Parotto and Praturlon, 1975; Castellarin et al., 1978). The deformational evolution of this line seems to be complex: during the Jurassic it was probably an important normal fault dividing the Latium-Abruzzi platform from the Umbria-Marche pelagic domain. The Mesozoic step was probably reactivated as a right-lateral strike-slip fault during the Messinian and now should be buried beneath the Sabina nappe, whose frontal thrust is the Olevano-Antrodoco line (see also Salvini and Vittori, 1982; Cavinato et al., 1986).

The Filettino-Vallepietra line is an important fault in the Latium-Abruzzi carbonate platform, along which Cretaceous limestones tectonically overlie Triassic dolomites (Devoto, 1967; Naso et al., 1992). This younger-on-older contact is part of a wider transpressive fault zone, WNW-ESE trending, along which the fault plane is strike-slip when vertical, and oblique-slip or reverse when dipping less than 50°. Similar structural relationship were also described in other sectors of the Simbruini Mts., such as the Ortara Mt. line (Devoto and Parotto, 1966).

Along the Val Roveto Valley and the Atina gorge, new evidence of left-lateral strike-slip faults has been found (Funiciello et al., 1980; Cavinato and Sirna, 1992; Serafini and Vittori, 1988; Montone and Salvini, 1993). In the Val Roveto (NW sector) the complex kinematics of the fault systems produced the typical structures of wrench tectonics (ridge and pull-apart basin associated with positive and negative flower structures; Montone and Salvini, 1993). Along the Atina gorge, the kinematics of the strike-slip fault systems (thrust west- and north-verging, and strike-slip fault) can be related to an oblique/lateral ramp (Cavinato and Sirna, 1992).

The Ortona-Roccamonfina N-S tectonic lineament is a very complex and important discontinuity in central Italy. Several authors have shown the geophysical and general geological characteristics of this line (Locardi, 1988; Patacca and Scandone, 1989), but new field data has been collected only in recent years (Naso et al., 1989; Mattei and Miccadei, 1991; Di Bucci and Tozzi, 1992). The new data and a new interpretation of the older suggest the presence of a major NNE-SSW narrow deformational belt, with main right-lateral strike-slip motion, which has affected this region for a long time; this lineament is probably the reflex of a major deep lithospheric tear-fault related to the different retreat velocity of the Adriatic lithosphere here with respect to southern Italy (Cinque et al., 1993).

According to this evidence, we propose that a strike-slip tectonic phase with transpressive components has been active since the major thrust events, complicating the pre-existing geometries, introducing new deformation elements, and possibly causing fault block rotations (as also suggested in Mattei et al., 1992 and in Salvini, 1992).

Extension

Extensional tectonics are active along the Tyrrhenian margin, but extensional features can

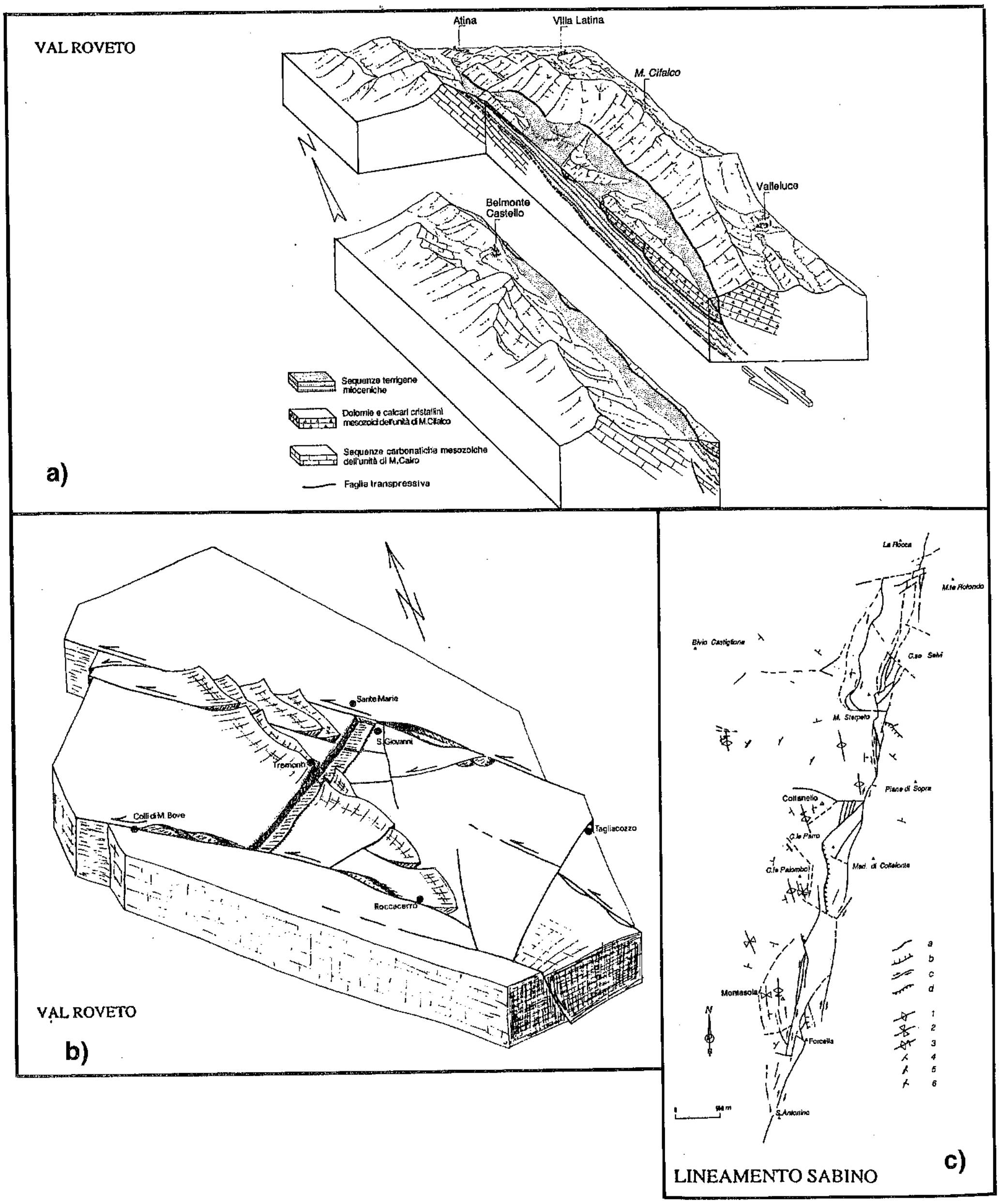

Fig. 3 - Three examples of the main strike-slip lines in Central Italy. The Val Roveto sinistral NW-SE trending fault is shown in A (Atina gorge, from Cavinato and Sirna, 1992) and B (Tagliacozzo-Monte Bove, from Montone and Salvini, 1993) where transpressive faults are underlined. In C, the N-S right-lateral Sabina lineament is shown, with main faults (a to d) and related folds (1,2,3), and bedding (4,5,6). From Alfonsi et al. (1991).

be recognized in the thrust belt core too. Relationships between extension and compression are still uncertain in Italy (see Malinverno and Ryan, 1986; Patacca et al., 1992a; Cinque et al., 1993). Furthermore, it is not yet completely clear which of the extensional deformative elements are related to the right-lateral N-S strike-slip tectonics which seem to affect the same Tyrrhenian margin. It is not even clear if one tectonic phase or more should be described: in fact, Tyrrhenian-linked structures (such as the grabens of Tuscany and volcanism of Latium) seem to have a wider wavelength than the intramontane basins, but we do not know if this is due to a different geotectonic position or to a different age. In the Southern Apennines, one new interpretation is based on two different steps; extension related to the Tyrrhenian rifting (1) should be older (till Lower Pleistocene) than extension related to the rebound of the Adriatic foreland (2) (Cinque et al., 1993).

The Tyrrhenian edge of the Central Apennines is characterized by structural elements produced mostly by the Quaternary evolution related to the basin, but it is also possible to recognize single (buried or outcropping) structures due to the geodynamical evolution of the Apennine chain s.s., and showing features tectonically consistent with those typical of the thrust belt.

Major pure dip-slip normal faults have been recognized along the Tyrrhenian margin, and most of the NW-SE main faults of the Apennine chain itself have also acted as normal faults (see also Salvini and Tozzi, 1986). Listric low-angle normal faults (LANFs) could always remain buried, because of the deeper structural levels affected with respect to the high-angle normal faults. The application of the LANF model to the Apennines, according to Basin and Range models, must be done carefully. In the Central Apennines, we have no clear field evidence of such faults, while they have been proposed for the Southern Apennines by D'Argenio and Ietto (1988) and Ietto et al. (1992). In the Northern Apennines, LANF-like faults have been proposed in recent years, generally included in a model of crustal delamination (Lavecchia, 1988). It is, of course, possible that most of the surface normal faults observed are part of major listric planes connected to lower detachment levels, but this does not imply large occurrences of LANFs at the surface.

Volcanism and tectonics

The potassic volcanic districts of Latium began their activity simultaneously after the Brunhes-Matuyama reversal (about 0.63 Ma, Villa, 1992, personal communication). Volcanic activity is synchronous also in the minor volcanic centers spread over the area.

Differences between districts located north of Rome and the southernmost ones are confirmed by stable isotope studies (Turi et al., 1991) and petrochemical considerations (Serri et al., 1991). Both demonstrate the key role of the Southern Latium sub-province, from the Alban Hills to Roccamonfina; here there is an evident depletion in the continental crust component, very strong in northernmost volcanoes, in favour of a mantle-like derived oceanic magma.

HKS types prevail in the huge quantities of the early products, the total volume being concentrated in the first volcanic phase.

This area seems to have a sort of continuity within the Tyrrhenian basin, where, at the N 41° parallel, there is a transition between the northern crustal volcanoes and the southernmost sub-crustal ones.

Furthermore, volcanotectonic features are synchronous and kinematically consistent with the youngest tectonic features of the sedimentary Plio-Pleistocenic and Meso-Cenozoic surrounding units described above.

Intramountain basins

Another important aspect is demonstrated by the intramontane basins, which show, from Late Pliocene to Recent, extensional features in the middle of the chain. The temptation to relate these basins to strike-slip tectonics is great, but no clear field evidence allows this kind of reconstruction, so that the origin of the Terni, Leonessa, Rieti, Fucino, L'Aquila, Sulmona, and the smaller Piana del Cavaliere and other basins is not yet known. The new data on the stratigraphical, tectonic and geomorphological features of the main intramontane basins (Rieti, Leonessa, Fucino, Sulmona) suggest that the Late Pliocene to Recent tectonic evolution was related to the combined effect of extensional and transtensional tectonics (Bosi, 1989; Bosi and Messina, 1992; Cavinato et al., 1989; 1993; Cavinato 1994; Miccadei et al., 1993; Michetti and Serva, 1990). During the Late Pliocene, the sedimentary processes (alluvial fans and fluvial-lacustrine deposits) in the intramontane basins were mainly related to the activity of the main boundary fault (N140°-N160°). This tectonic event was connected to the regional extensional tectonics along the peri-Tyrrhenian margin during the Tyrrhenian opening. The new acme in tectonic activity developed during the Middle Pleistocene (between 0.8-0.4 Ma, Cavinato et al., 1992); in this time-interval, the intense extensional tectonic events in the intramontane basins, which developed mainly along the boundary master faults, could have produced the ultramafic intrapenninic volcanism (S.Venanzo, Colle Fabbri, Cupaello, Polino, see also Lavecchia and Stoppa, 1989), a vertical tectonic uplift, the modification of the "paleosurface" (Bosi and Messina, 1992) and a general displacement of the Villafranchian deposits, sometimes with collapse structure (Cavinato, 1994). For now, it is difficult to say if these basins are linked to a limited extension, i.e., to a some block model rotation, or to more general extensional tectonics.

THE GEOMETRY OF SURFACE DEFORMATION

On field evidence, it is possible to divide the Central Apennines into at least four main mesostructural domains (Fig. 4):

1. *West of the Olevano-Antrodoco tectonic line.* Faults are here mostly N 10° and N 320° trending, and subordinately E-W trending. Slickensides are dip-slip on most planes, and strike-slip is evident on some N-S and NW-SE planes along particular ridges. Folding is associated with the thrusting and shows N 10° and N 310° hinges.

2. *The Olevano-Antrodoco line.* Faults are scattered N 10°, NW-SE and N 70°; slickensides show an E-W major motion, both dip and strike-slip; minor folding is also evident.

3. *East of the Olevano-Antrodoco line.* Faults are mostly N 310° and slickensides indicate a NE-SW motion along NW-SE planes.

4. *Coastal Tyrrhenian domain.* Faults are here mainly E-W and N 330° with sub-vertical motion. Locally, N-S strike-slip faulting is found.

A study of the extensional fracture field in the volcanic units along the Tyrrhenian coast line allows us to identify two main azimuths, E-W and N-S; NW-SE trends are present along the main N-S strike-slip fault zone (Faccenna et al., 1994).

Some general ideas can be derived from a statistical analysis of the mesostructural results. NW-SE fault planes are much more widespread over the Latium-Abruzzi carbonate platform (domain 3), while N-S trending planes are much more common in the western sector (and sometimes also in domain 4). E-W faulting is also common in the eastern domain (3) and along the coastal plain (4), probably as an effect of the Tyrrhenian opening, and as a relict of the old Adriatic foreland tectonics.

Dip-slip motions are generally prevailing N 40° in domains 1 and 2, and N 70° in domains 1, 2 and 3. The strike-slip component seems to decrease from west to east to south probably because of the position of the chain.

The presence of different, sometimes concomitant, paleostress trajectories proves the development of poly-deformational tectonics. This may be related either to abrupt changes in stress directions or to an extreme variability of stress trajectories, or more likely to the presence of block rotation kinematics. Under such an hypothesis, the two main directions of paleostress as found (N70°E versus N40°E) could indicate a 30° relative rotation between the Latium-Abruzzi platform domain and the Sabina domain. A lesser rotation (about 12°) within the Latium-Abruzzi platform domain was derived from a modelling of paleostress trajectories (Salvini, 1992).

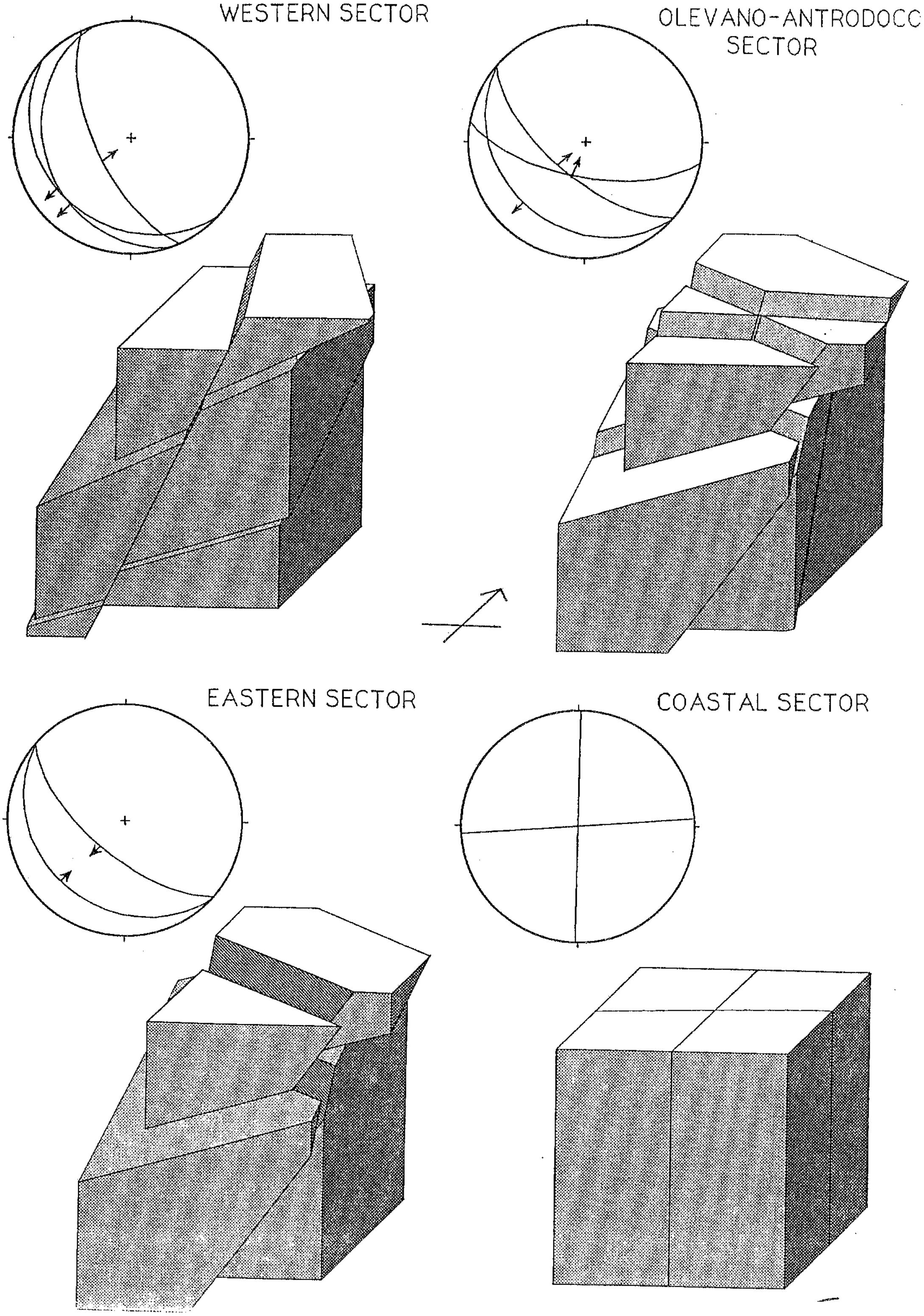

Fig. 4 - Domains (sectors) derived from structural analysis. Results are shown both as stereonets (Schmidt, lower hemisphere) and faulted blocks. Each fault line in the stereonets represents the main fault systems from large data set analyses (more than 20,000 brittle elements considered).

COMPUTATION OF THE MINIMAL SHORTENING VALUE

A speculative attempt at a first order approximation of the shortening during the Apennine chain formation process was made. Many authors have shown the intense shortening that accomplished the chain building processes in the Apennines (see References). However, these tectonic processes were so complex as to compell the authors to introduce several hypotheses into their modelling, thus reducing the possibility of extending their estimates through the entire chain.

To obtain first order regional constraints for the evaluation of the shortening, we computed the minimal shortening required to build up the present-day geometries of the chain, by assuming the tightest constraints, and hypothesizing an insignificant involvement of the "metamorphic basement" units, that is an insignificant flow of material through the sole thrust (although some evidence suggests a possible basement involvement hypothesis, see before).

According to this constraint, the sole thrust was positioned at around 9 km b.s.l. on the western side, following the minimal values proposed by Mostardini and Merlini (1986) from aeromagnetic and gravimetric data. Its dip was assumed as small as 2° (Woodward et al., 1989). Under the same principle, the front ramp was located in front of the northeasternmost outcropping thrust of Meso-Cenozoic detached successions. Again for the purposes of our computation, its dip was considered as small as 20°, following indications in the aforementioned literature. In this way, we considered the minimum value for the buried detached chain.

The cross-section itself was located in the region of the Central Apennines where the CROP 11 deep seismic profile will be shot. It was oriented exactly parallel to the regional shortening directions and positioned to minimize local complexities or different directions of movement. The section is thus oriented N 40°E, starts near Nettuno (Lat. 41°28'00" N, Long. 12°34'00"E Greenwich), and ends near Tocco a Casauria (Lat. 42°02'00" N, Long. 13°58'00"E Greenwich).

Southwestwards, the section begins at the coastline and crosses the coastal Plio-Quaternary marine deposits related to the extensional evolution of the Tyrrhenian Sea basin. These sediments were not considered in the computation. Since the maximum depth is estimated at about 1km below sea level (Funiciello et al., 1992), a strip with this thickness was eliminated in the outcropping areas of these deposits. A similar reasoning was used in the Latina Valley, where Plio-Quaternary outcrops together with Late Tertiary terrigenous deposits. The latter units, which constitute the dominant outcropping lithologies northeast of the section, were considered volumetrically insignificant within the thrust chain (see later).

The overthrust units were extrapolated above the present-day topographic level, i.e., the volume of the complete-sequence eroded portions of thrust units was ignored. The interval of sedimentary successions involved in the thrust chain deposited between Upper Trias and Miocene, and an average thickness of 3.3 km were used.

The original minimim length (L_{min}) of this sedimentary basin was computed from

$$L_{min} = A_{min}/T_{max} = 1155.73\ km^2/3.3\ km = 350.22\ km,$$

where A_{min} represents the minimum allowable area in the section representing the thrust chain, and T_{max} the maximum allowable thickness of the thrust successions. The amount of minimum shortening was then computed from

$$S_{min} = 100x\ (L_{min} - L')/L_{min} = 100x(350.22-151.25)/350.22 = 56.8\%,$$

where L' represents the present-day length of the cross-section.

It is interesting to note that, although the computation was done with a series of constraints to minimize the shortening, it come out larger than what is considered by many authors as the maximum observed (Bally et al., 1986; Woodward et al., 1989). Among the many models that can be invoked to justify this anomalous value, and apart from the possibility that significant volumes of extra-section terrigenous deposits are contained in the chain, three hypotheses or a combination thereof should be carefully considered.

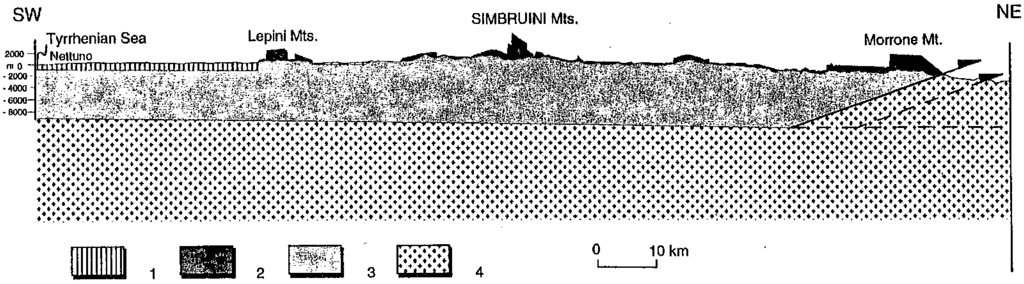

Fig. 5 - Sketch section for the computation of minimum shortening. Legend: 1- Plio-Pleistocene cover; 2- assumed minimal eroded portion of the Meso-Cenozoic chain; 3- buried Meso-Cenozoic chain; 4- footwall and foreland units.

- A two step evolution of the chain with opposite-vergence, as proposed by some authors (see for a review Ogniben, 1986). According to this evolution, a second orogenetic process (Apennine phase in Mio-Pliocene times) involved already-shortened units (during the Alpine phase in Eo-Oligocene times), reducing in this way the shortening produced by each phase to those predicted by in the literature.

- A significant involvement of pre-Triassic basement units, mostly of Hercynian age, in the building up of the thrust chain. The outcrop of metamorphic units in western Tuscany and on Zannone Island (southwest of our section) and their allochthony may represent evidence of this, together with the presence of tectonic repetition in the Paleozoic sequences drilled through by deep wells in the Tuscan-Umbrian Apennines.

- The presence of significant fragments of foreland units in the thrust chain. The present-day foreland is formed by a thick carbonatic platform (up to 6 km), Meso-Cenozoic in age. In this way, the extra length of the original section may be formed by units originally sited northeast of our section. Part of the transitional facies successions deposited between the carbonatic platform of the foredeep, and the pelagic to carbonate successions of the chain, would lie beneath the exposed units in an extremely favourable position for the development of structural oil traps.

EXPECTED CONTRIBUTION FROM THE CROP 11 AND CROP OFF-SHORE LINES TO A GEODYNAMICAL MODELLING OF CENTRAL ITALY

Even if many aspects of the geodynamical evolution of Central Italy are now clearer than in the past, several important questions do not yet have a satisfactory answer. An integrated preliminary study and interpretation of the CROP lines could help to improve future modellings starting from a more correct knowledge of the deep geometry.

The following geodynamic evolution seems to have been occurred in this region of Italy: a pre-Miocene subduction active somewhere in the present-day position of the central-southern Tyrrhenian sea, probably as indicated by the andesitic lavas of Sardinia; a continent-continent collision followed, and a post-collisional tectonic regime should have been active since then. The same old subduction is still a very questionable point: why do we not find real andesitic lavas in western Italy (only limited volcanoclastic deposits are known)? Why it is so difficult to reconstruct the geometry of the shear zones of a real accretionary wedge in the Apennines? Where are the real ophiolitic suites? And what about the limit of the presumed Apennine subduction with respect to the Alpine edge of subduction? If we postulate an active subduction now underneath the Apennines, we are not even sure that it is active in the Calabrian zone, and we have no positive evidence for the rest of Central-Southern Italy, while in the northern sector, Amato and Selvaggi (1992) recognize only a few deep earthquakes down to 90 km. Finally, it is not possible to exclude alternative hypotheses to the traditional plate tectonic subduction (e.g. accretionary orogeny).

The CROP lines should clarify the geometry of the continent-continent collision in Italy and give new indications, for instance, on the presence or not of decoupling phenomena as evidence of a post-collisional regime. We should have new interpretations of old data, but it will be still very difficult to directly associate the surface deformative pattern to a particular geodynamical regime.

Moreover, the already complex Italian deformational geometry is made more complex by rotations. In recent years, taking into account the rotations has become more and more important in all attempts to reconstruct the geometry of regions throughout the world (e.g., in Greece and Turkey, Kissel and Laj, 1988; in North America, Beck, 1988). In Central and Southern Italy, new paleomagnetic and structural data testify to the real occurence of important regional and block rotations. The ''stable'' Apulian foreland, for instance, has probably undergone at least two different senses and amounts of rotation since the late Cretaceous (Tozzi et al., 1988; Funiciello et al., 1989), while in the Central Apennines, Neogene block faulting rotations driven by strike-slip tectonics is a very important help for understanding the actual geometry (Mattei et al., 1992; Salvini, 1992). It ought to be clear that rotation is an obstacle to a correct restoration in balanced cross-sections only if we do not consider it. Thus a correct evaluation of sense and degree of rotation is necessary. Finally, it is of course important to correctly estimate how large is block rotation and how large is stress-field or local rotation.

A model of the geodynamical evolution of central Italy should consider the following points:

- lateral inhomogeneities in the crust and the presence of discontinuities such as Moho jumps and real deep mechanical shear (are they possible in the lower crust, as the first BIRPS results in the United Kingdom seem to suggest ?);
- Tyrrhenian dynamics of opening, thinning of the lithosphere, and the presence of a real transitional crust;
- Adriatic foreland geometry and kinematics: are the new structural (e.g., strike-slip wide faults) and paleomagnetic data (subsequent counterclockwise and clockwise rotations) consistent with the present-day model, or do we need a brand new model?
- geometrical relationships and age of compressional - extensional tectonics with respect to the strike-slip tectonics and rotations;
- possible block rotations in the Latium-Abruzzi carbonate platform and in the surrounding regions;
- importance of N-S and NW-SE strike-slip major tectonic bands;
- active stress field in the Central Apennines;

The geometrical definition that the CROP lines (and parallel research) should produce will be the starting point for considering the majority of the aforementioned items in a new light. For the off-shore CROP lines, the CROP 11 line should give a better definition of the foredeep structure and of the passage to the Adriatic foreland on the eastern side, while it should better characterize the thinned crust on the western side. One of the main objectives of CROP should be the study of the passage from a classic old continental layered crust (Adriatic) to an immature sub-orogenic crust (probably derived from the Adriatic crust), to a re-worked crust (Tyrrhenian edge), to a young semi-oceanic crust in the Tyrrhenian sea.

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