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Recent deeper geophysical results better account for the tectonics in the Italian area

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Abstract
Results from extended DSS profiles (1956-1986) in Italy and surrounding land and sea areas offer good constraints for other geophysical and geological data. Integrated interpretations outline the main tectonic features. Collisional tectonics is predominant in the Alps, for which the Adriatic plate acted as hinterland against the European plate foreland. Main results: W-wards, NW- and N-wards oriented overthrusting on the European crust, bending of the lower European crust, European Moho to 70 km depth with the Adriatic mantle indented above, crustal doubling (Adriatic over the European one). In the Apennines, on the contrary, the Adriatic plate acted as a foreland, against the overthrusts generated by the Tuscanian and Tyrrhenian mantellic bodies, heated, elevated and migrated NE-wards and SE-wards, respectively. Also the Adriatic plate bends under this load-centripetally towards the Tyrrhenian sea, so that the Adriatic Moho from 35 km depth is presumed to descend through a flexure till 40-50 km below the Tuscanian and Tyrrhenian land areas. The external peri-Apenninic area is still in compression and includes thick sedimentary basins, from the Po-plain to Sicily. The internal area is in extension, overlapped by thin, stretched crusts of Ligurian and Tyrrhenian origin, whose remnants occupy most of both seas areas, with two areas of oceanic crust in the SE-Tyrrhenian. Rifting and opening is in action also in the Ligurian Sea and Sicily Strait.

Key words *Alpine orogeny – collisional tectonics – extensional tectonics – rifting*

1. The geophysical data

In the Central Mediterranean area recent (post-eocenic) tectonics has been (and still is) very active. In its Northern part, the continent-continent collision between Africa and Europe originated crustal and mantle overthrusts and indentations, thickenings and vertical movements both upwards and downwards. In its central part, lithospheric subductions, drifting and rotation (of Corsica-Sardinia) and the evolution of the Tuscany-Tyrrhenian mantellic bodies formed the Apennines and the Tyrrhenian basins. The extended and repeated covers (olistostromes) of Tyrrhenian origin obscured for decades the deep geology of the Italian Peninsula (fig. 1)

The tectonic evolution and the current situation can be inferred and understood from the extended geophysical data available. On the whole, they are the following.

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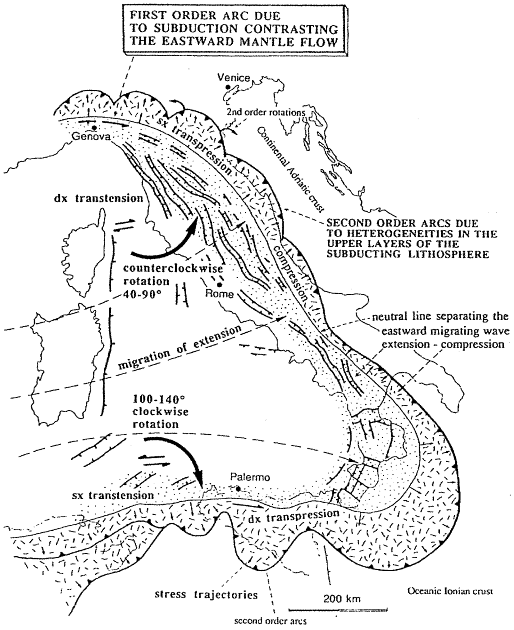

Fig. 1. Geodynamic model for the Tyrrhenian region schematized by Doglioni (1991).

1.1. *Near Vertical Reflections*

The CROP NVR (COCORP's type) profiles in the Italian land areas are relatively few: in practice, only those from the Western and Central Alps profiles are available (fig. 2). On the Apennines CROP-04 (1989/1990) has been observed which is in a delicate stage of processing, whereas the results of profile CROP-03 (1993) were discussed in a Workshop (1996) and are in print.

The same is true for the CROP sea profiles 1991-1994 and for the OGS Flexotir profiles (1969-1982; under revision).

1.2. *Deep Seismic Sounding*

The DSS profiles were realized within the frame of the European Seismological Commission, Explosion Seismology Group (1956-1982; fig. 3) and of the European Science Foundation, European Geotraverse (1983-1989, fig. 4). As known, when properly operated DSS permits the velocities and depths and spatial positions of the seismic discontinuities to be obtained. DSS offers therefore constraints on the other geophysical methods (including NVR, section 1.1) and renders the so-called «integrated geophysical interpretation» possible. Especially useful are the connected «Wide Angle reflections» (WA) for their high energy outputs.

In the area under discussion, these constraints are:

i) The detailed Moho topography, also where no Moho reflections are available from NVR (figs. 5 and 6).

ii) The crustal thickening and doubling in the collision zones, and the crustal thinning in the extensions areas (fig. 7), with the delimitation of the Tyrrhenian oceanic windows. All the Moho topography features and details are also important to understand the Bouguer (fig. 8) and the Heat Flow (fig. 9) anomalies.

iii) Under the Apennines the geologic basement has a high at ~ 6 km depth all along the Adriatic coast, and descends to 10 km towards the axis of the Adriatic sea (16 km in the Otranto Strait), to 12-17 km towards the Ligurian and Tyrrhenian coasts.

1.3. *The magnetic anomalies*

The aeromagnetic anomalies, available (AGIP+CNR) for all the land area and the seas around Italy, permit the computation of the magnetic basement depth (fig. 10). This is the level which limits bodies with a relatively high magnetic susceptivity, unlimited downwards, below which it is no longer possible to forecast sedimentary series. It has a behaviour similar to that of the geologic basement but it is a few kilometres deeper: a general weak descent from east (Adriatic coast) towards west (*e.g.*, from less than 9 km in the Gargano-Monopoli area to more than 13 km) with a beginning of rising towards the Tyrrhenian sea and a sudden strong rising along the Pontremoli-Civitavecchia line (fig. 10).

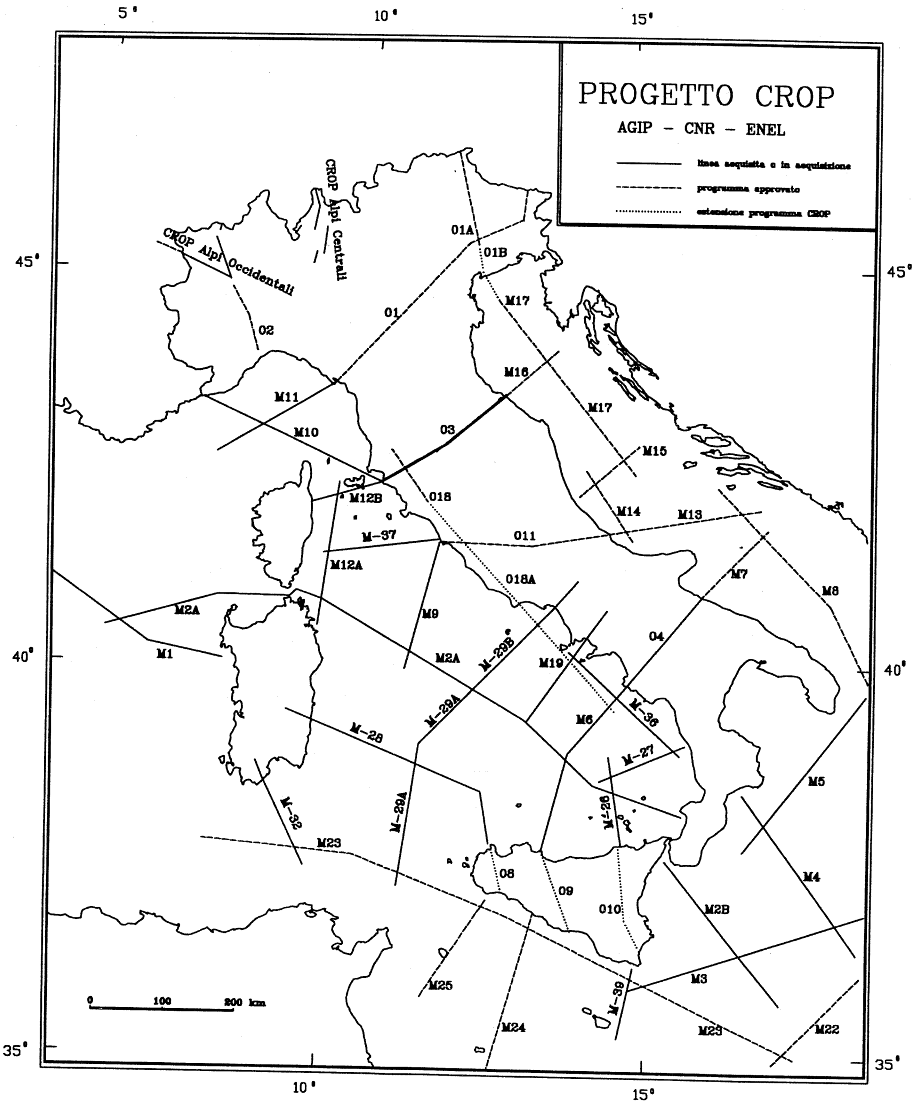

Fig. 2. The NVR CROP Program in Italy.

2. Main additional results

To the above mentioned results following be added:

Bending of the continental ramps – The bending of the continental ramps – disclosed in the Alps both for the European plate (foreland) and for the Adriatic plate (hinterland); and on the western side of the Adriatic plate acting there as foreland, against the centrifugal pushes from the Tyrrhenian area (hinterland) – can be considered mainly a consequence of the additional weight of the overlapping hinterlands.

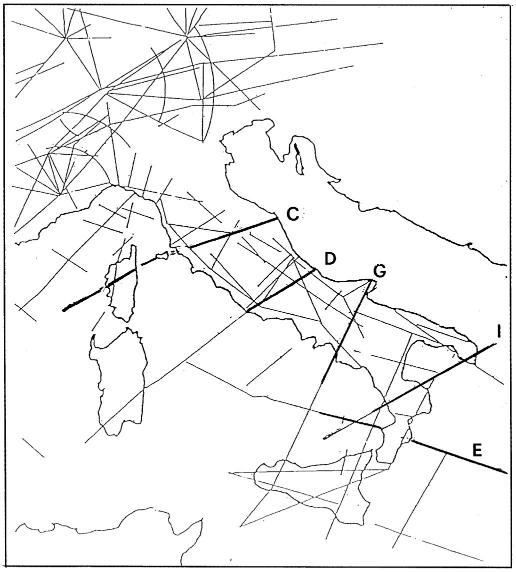

Fig. 3. The Deep Seismic Sounding (DSS) profiles in Italy and surrounding area (1956-1982; 21.160 km).

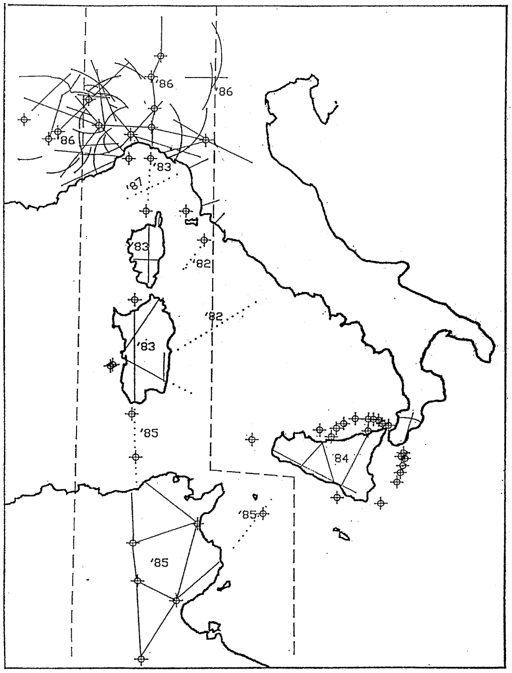

Fig. 4. The European Geotraverse, southern segment (EGT-S, 1983-1989; 3660 km).

In the Alps, no «Verschluckung» can be invoked for the formation of the actual «roots». They have in any case their maximum depth under Milano, in an asymmetric position (fig. 5).

The Po-plain gravity maximum – This can be principally attributed to the mantle dome under Milano (fig. 5).

Low-velocity zones – They were already discovered from the first DSS profiles in the Alps during the sixties. According to Kola's results (Pavlenkova, 1992), the LVZ in the crystalline basement can be attributed to the influence of fluids, in as much as they influence the microfracturing: in Kola, the beginning of disaggregation was discovered at −4500 m, with an increase in porosity (from 3 to 4 times), decrease in density (from 3.1 to 2.9 g/cc), decrease in seismic velocity. The lower limit of this disaggregation zone at −9000 m corresponds there to an increase in the seismic velocities: that is, not to the forecasted Conrad discontinuity, but simply to the end of the disaggregation zone with a return to rocks at normal density and end of inflow of thermal water in the well.

The super deep well has therefore confirmed that in the deeper upper crust high pressure fluids in the pores can explain the low values revealed for the seismic velocities and the increase in reflectivity.

The same results were found on the profile CROP.03 (fig. 11), where a strong seismic reflector from depths of the order of 10 km to the east was found to rise at a few kilometres towards the Tuscanian geothermal area. This reflector was already known in the Larderello and Monte Amiata area: named K-horizon, it was tested with the drill hole «San Pompeo-2», which at a depth of 3000 m discosed a very extreme fracturation of hydrothermally altered, microscists containing fluids at high temperature (> 420°) and pressure (> 240 bars). The K-horizon could more probably indicate the presence of deep brines or represent the top of granitic intrusions.

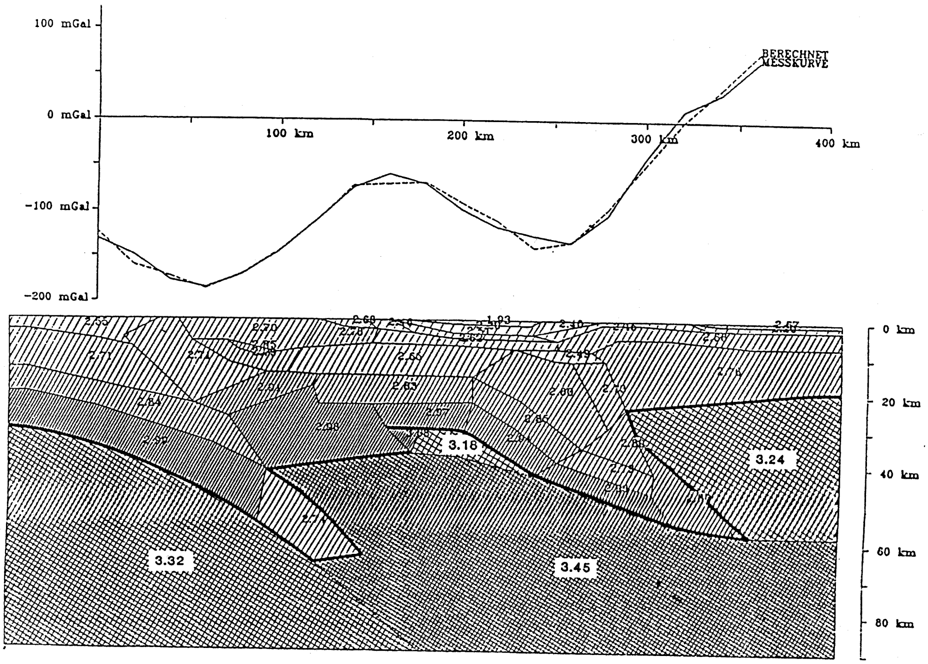

Fig. 5. The EGT-S ray-tracing model and the corresponding gravity model (from Buness, 1992).

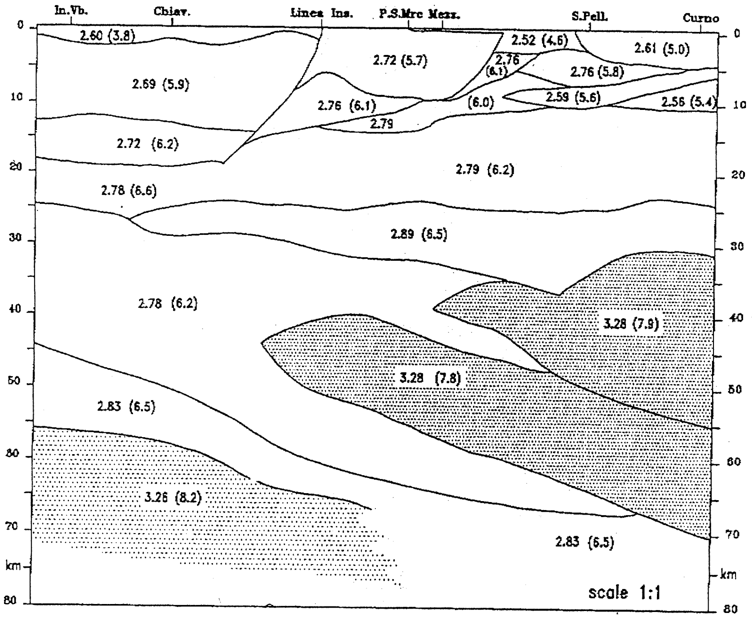

Fig. 6. The NVR NFP.2O-CROP profile in the Central Alps (1987-1988), integrated by EGT DSS-WA results 1986 (from Cernobori and Nicolich, 1994).

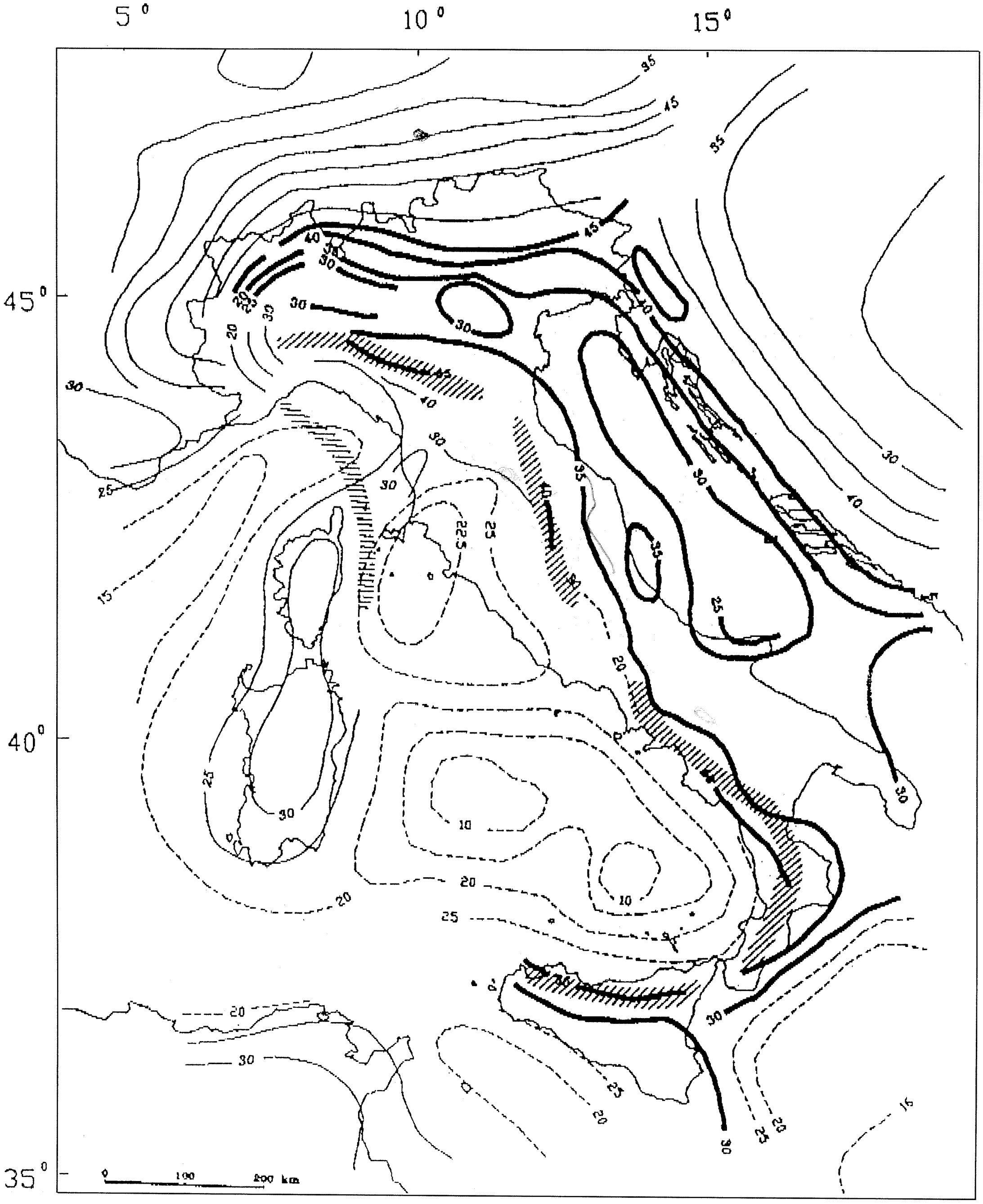

Fig. 7. The different Mohos in the Italian region from DSS (from Locardi and Nicolich, 1988; modified). Heavy lines = Adriatic Moho; thin lines = European; dashed lines = Tyrrhenian.

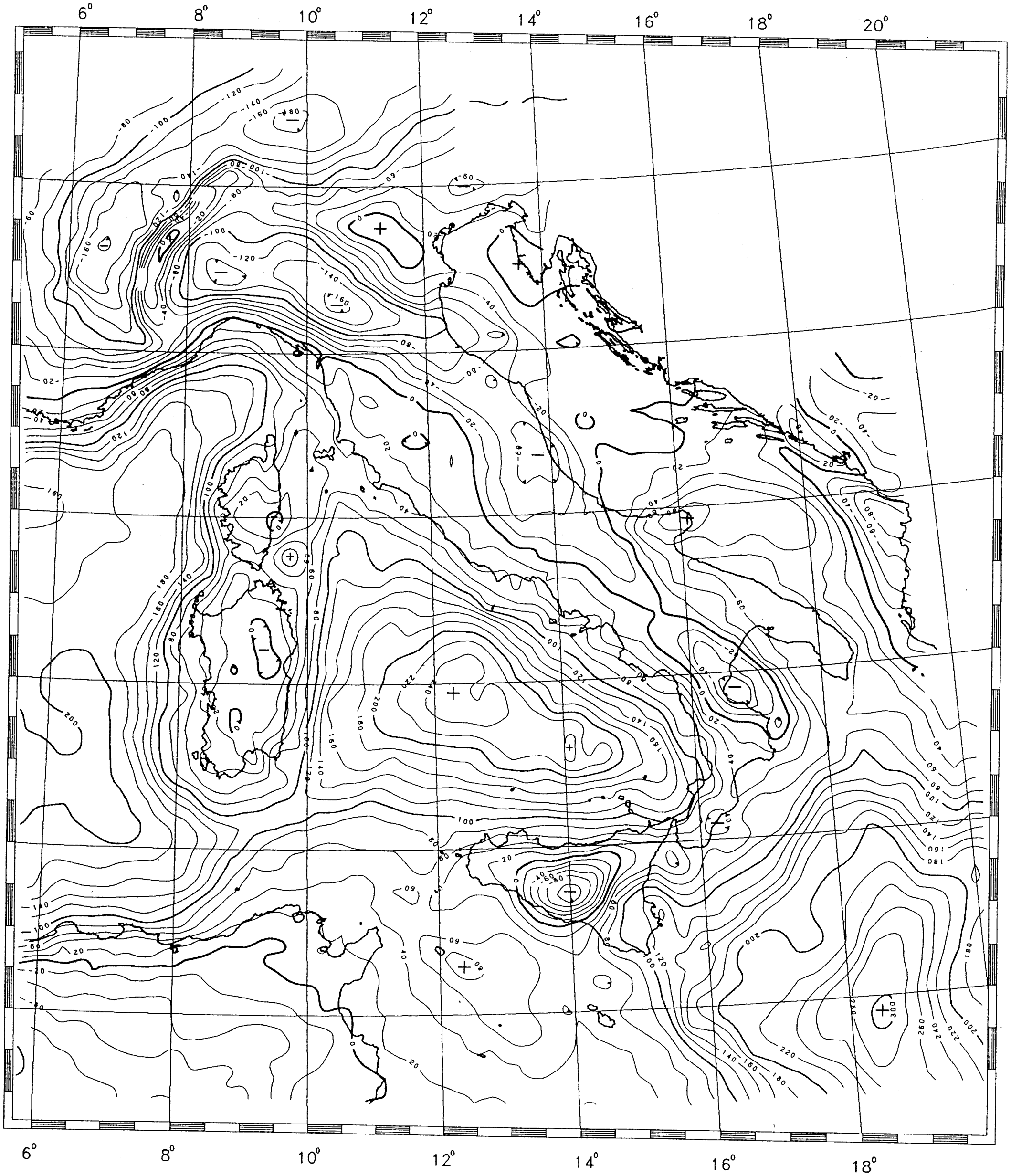

Fig. 8. The negative Bouguer anomalies also revealed the sequence of external peri-Apenninic sedimentary basins.

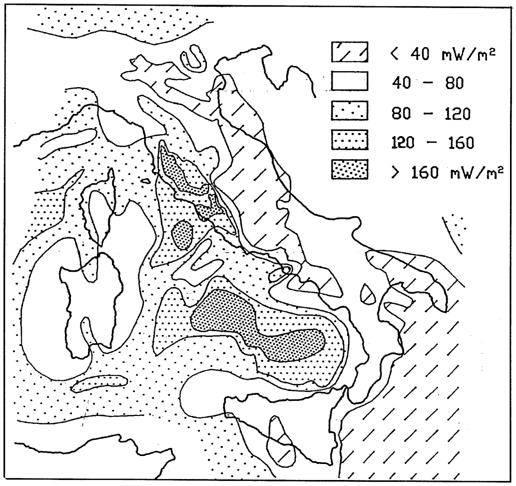

Fig. 9. The heat flow anomalies (from Mongelli *et al.*, 1992) are also correlated with the DSS results (see fig. 7).

The time sequence of the Corsica-Sardinia to Apennines drifting, in diverging directions (fig. 1), is very recent, and even ongoing: the current drift of the compressional fronts and of the fore-deep migration is 1.0-1.5 cm/yr NE-wards in the Northern Apennines (it is more than 5 cm/yr SE-wards in the Southern Apennines, Scandone *et al.*, 1990). Serri *et al.* (1993) succeeded in dividing the magmatic process in the Northern Apennines into 4 phases, progressively younger from west to east (~ 14.0 Ma; 7.3-6.0 Ma; 5.1-2.2 Ma; 1.3-0.1 Ma). These 4 phases correspond to the extensional periods recognized by geology throughout the region. The new model assumes that, before 15-14 Ma, the Adriatic plate underwent a delamination process, which permitted the upper parts of its lithosphere and lower crust to be subducted into the upper mantle.

Boccaletti *et al.* (1997) divide the region from the Tyrrhenian to the Adriatic Sea into 3 sectors (fig. 12): sector A affected by extensional tectonics; sector C affected by compressive tectonics; the intermediate one (B) affected normally by extensional tectonics, but – during greater velocities of the plate convergence – the compressive tectonics retreat interrupts both the sedimentation and the magmatic activities.

The centrifugal tectonic actions from the Tyrrhenian area are presumed to be caused by two ascending-descending mantellic bodies (Locardi and Nicolich, 1988, fig. 13).

Also recently, Frepoli and Amato (1997) found that the extensional zones of the Central-Northern Apennines and the compressive ones externally (*i.e.*, on the Adriatic plate margin) correspond to earthquakes with the same focal mechanism (fig. 14), in agreement with the above mentioned model. On the contrary, in the Southern Apennines the study of the focal motion and the drill-hole transitions confirms only the presence of E-W extensional motions.

The relocation of the epicenters in the Central and Southern Apennines area is illustrated in fig. 15. This map also clearly denotes the very strong correlation between seismicity maxima in the Apenninic area and the suture between the thin Tyrrhenian crust and the thick Adriatic crust revealed by DSS (fig. 16).

For Central and Southern Italy, the situation in the sedimentary cover is clearly illustrated by the AGIP Sections, based on detailed seismic (NVR) profiles and many drill-holes (Mostardini and Merlini, 1986). These data revolutionized the geological knowledge of the area. A typical cross-section is illustrated in fig. 17.

These overthrusts are responsible in the Apenninic area for the mentioned non correspondence of the surface to deep geology and the blind character of most of the areas to seismic prospecting. But after 20 years (1970-1990) of hopeless efforts with seismic 2D, an AGIP team (La Bella *et al.*, 1996) finally managed to understand that the poor quality of seismic response in an area of the Southern Apennines was mainly linked to surface geological conditions.

In the area of rugged topography indeed extremely heterogeneous lithologies outcrop,

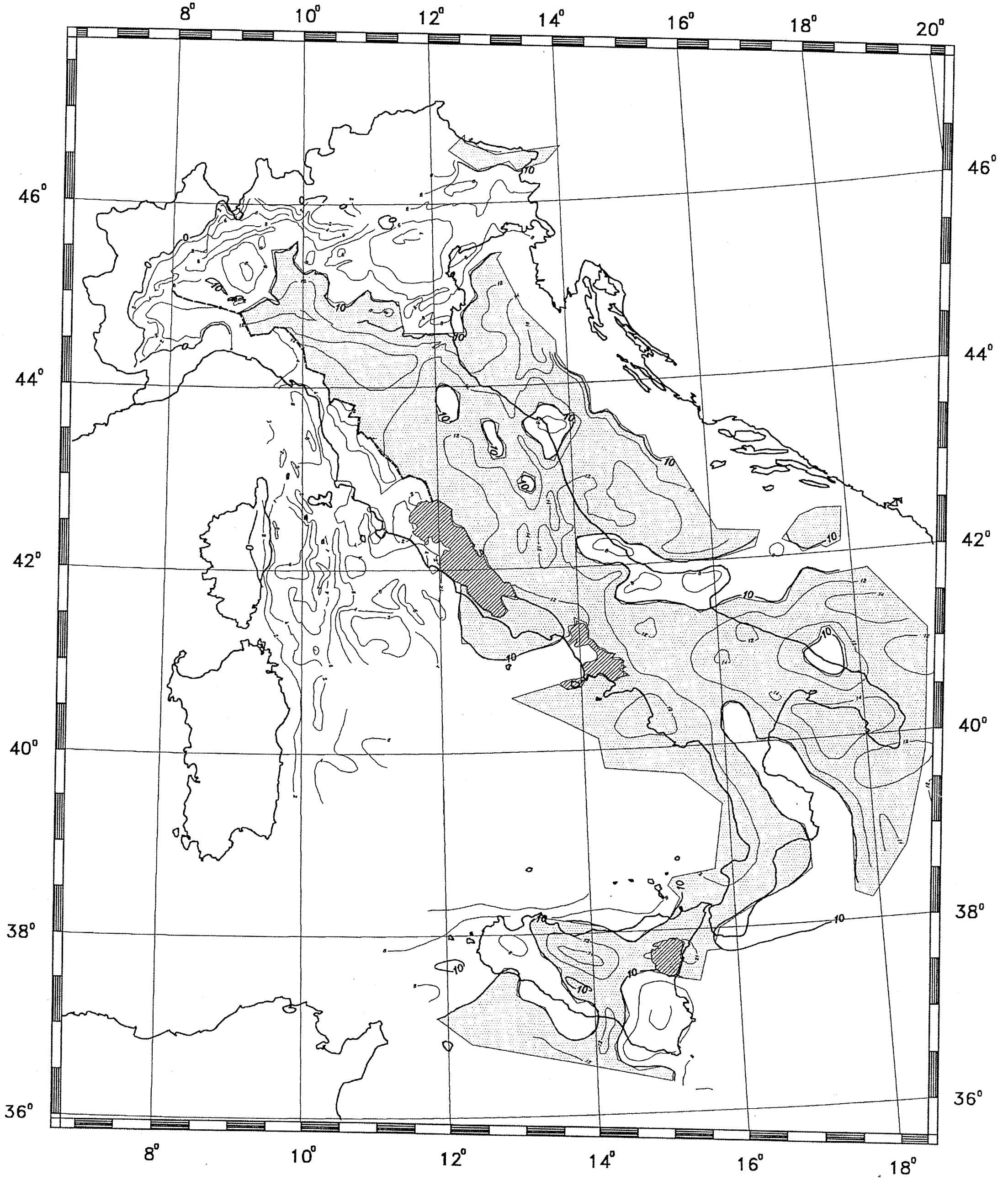

Fig. 10. Isobaths of the magnetic basement (equidistance 2 km; AGIP 1982).

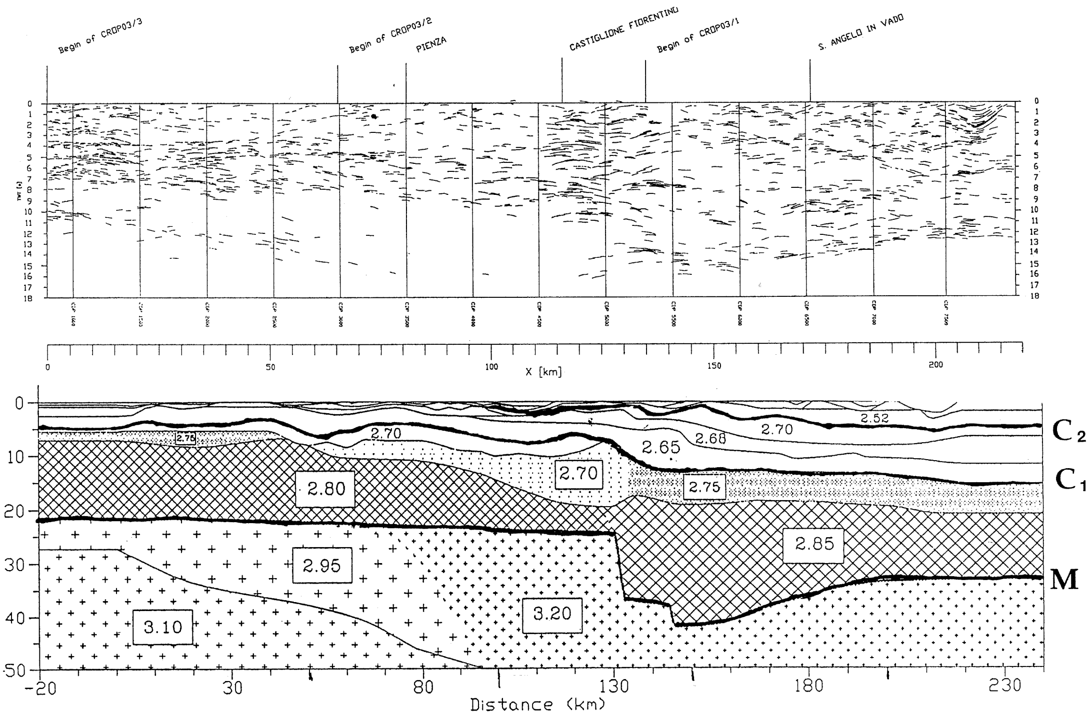

Fig. 11. CROP.03: seismic-gravimetric model (Nicolich *et al.*, 1997). To be noted: towards the west, a general rising of the markers and density decreasing; in the west the thinned crust; the great thickness of the lower crust and its repetitions upwards.

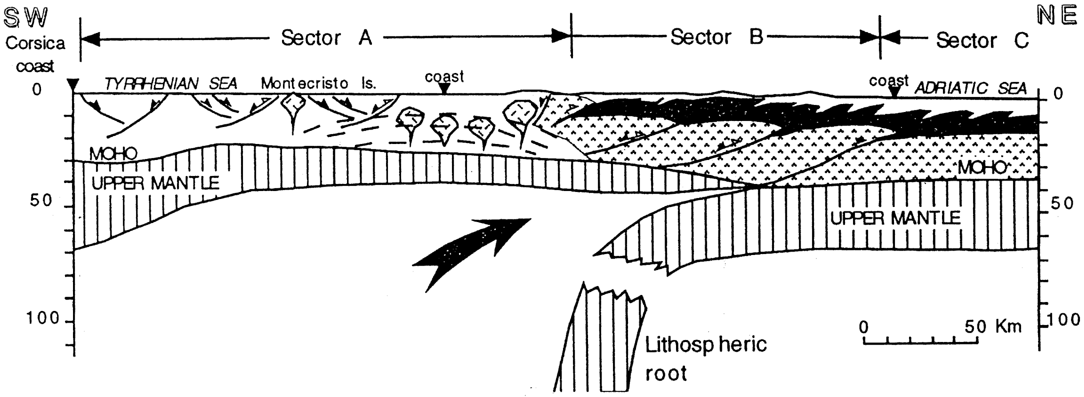

Fig. 12. Schematic crustal profiles from Corsica to the Adriatic sea (Boccaletti *et al.*, 1997) indicating the sectors of extensional tectonics (A), compressive (B) and alternative tectonics (C).

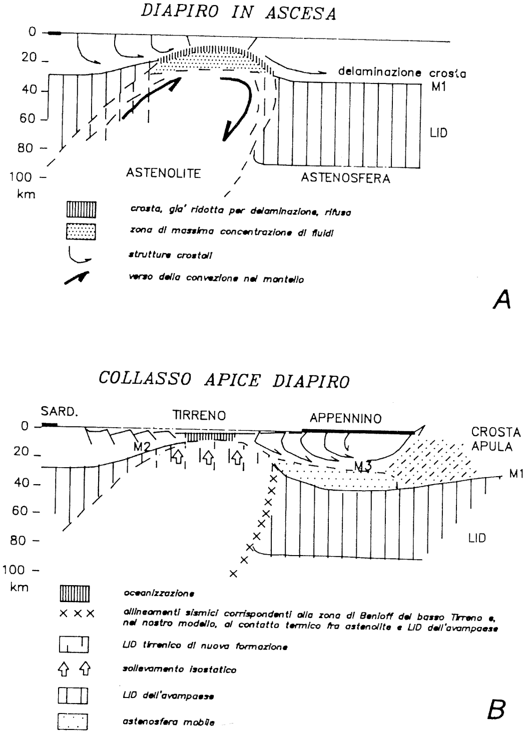

Fig. 13. Evolutionary scheme for the LID in the Southern Tyrrhenian area (from Locardi and Nicolich, 1988). A = ascending diapir (top = remelted crust, over the maximum fluid concentration zone); B = collapse of the top of the diapir (Tyrrhenian area: oceanic crust, over a newly formed LID in isostatic upheaval; Apennine area: sinking crust over a mobile asthenosphere and a foreland LID; XX = Benioff zone).

with strong variations in the subweather velocity to the reference datum; all the operational aspects of the job project have been therefore thoroughly analyzed and the best technical-operational compromises established.

This experimental survey confirmed that the use of an appropriate planning approach helped to resolve complex problems effectively. It demonstrated also that 3D seismic acquisition in mountainous areas is a technique which, if properly planned, can supply reliable data.

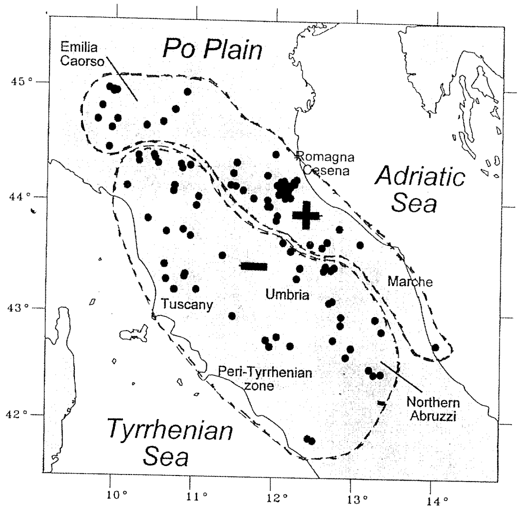

Fig. 14. The zones of extension (−) and compression (+) in the Northern Apennines, revealed by focal mechanisms and borehole stress distribution (Frepoli and Amato, 1997).

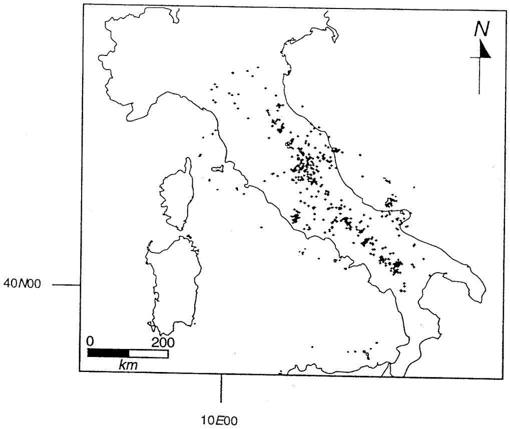

Fig. 15. Map of 600 events 1986-1993 relocated from travel time tomography (Chiarabba and Amato, 1996).

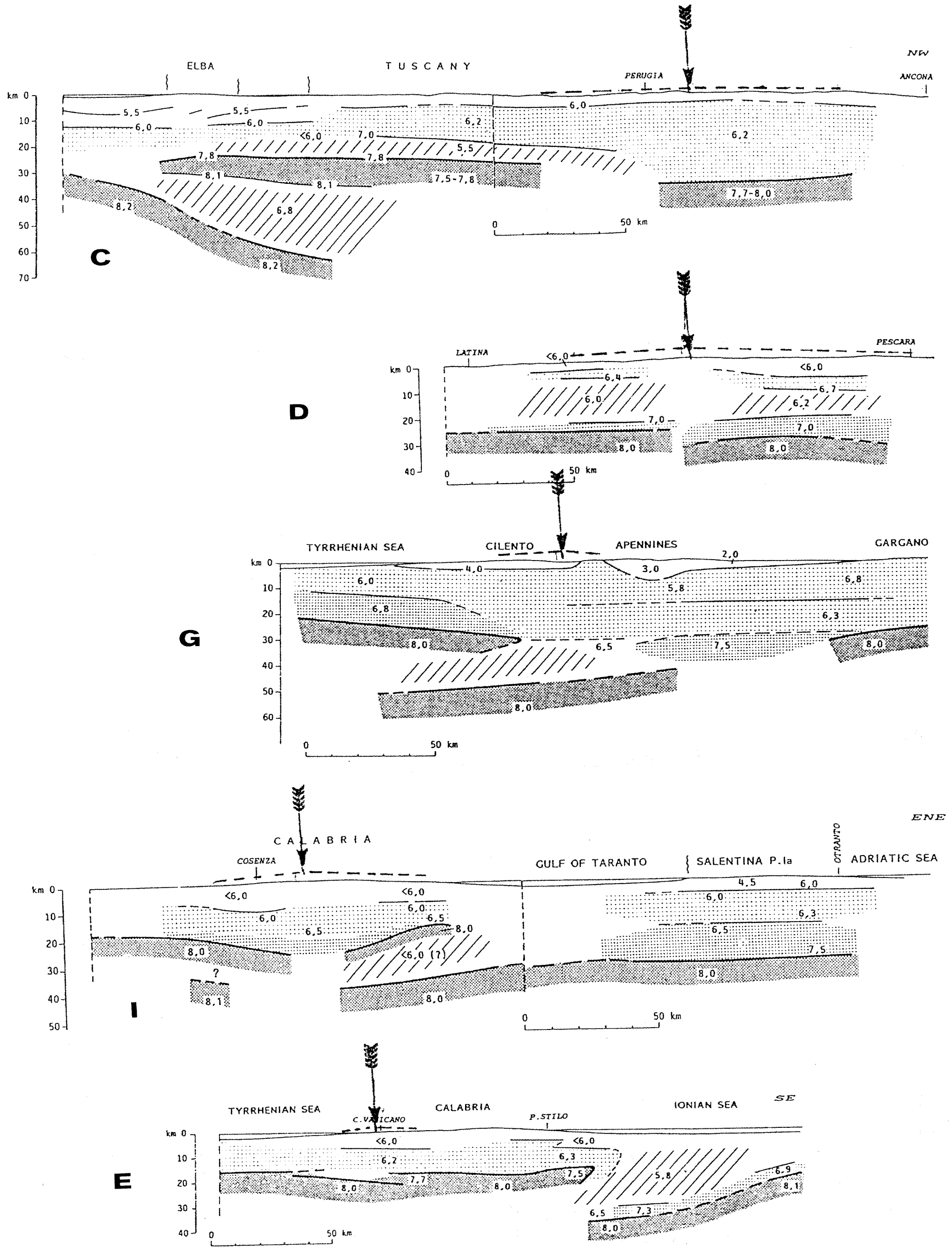

Fig. 16. Selected transversal crustal sections (thick in fig. 3) through the Italian peninsula, differentiated according to the longitudinal seismic waves velocity (in km/s; rev. Scarascia *et al.*, 1994). The crustal suture (arrows) corresponds to the maxima of seismicity at the surface (dashed lines; see also fig. 15).

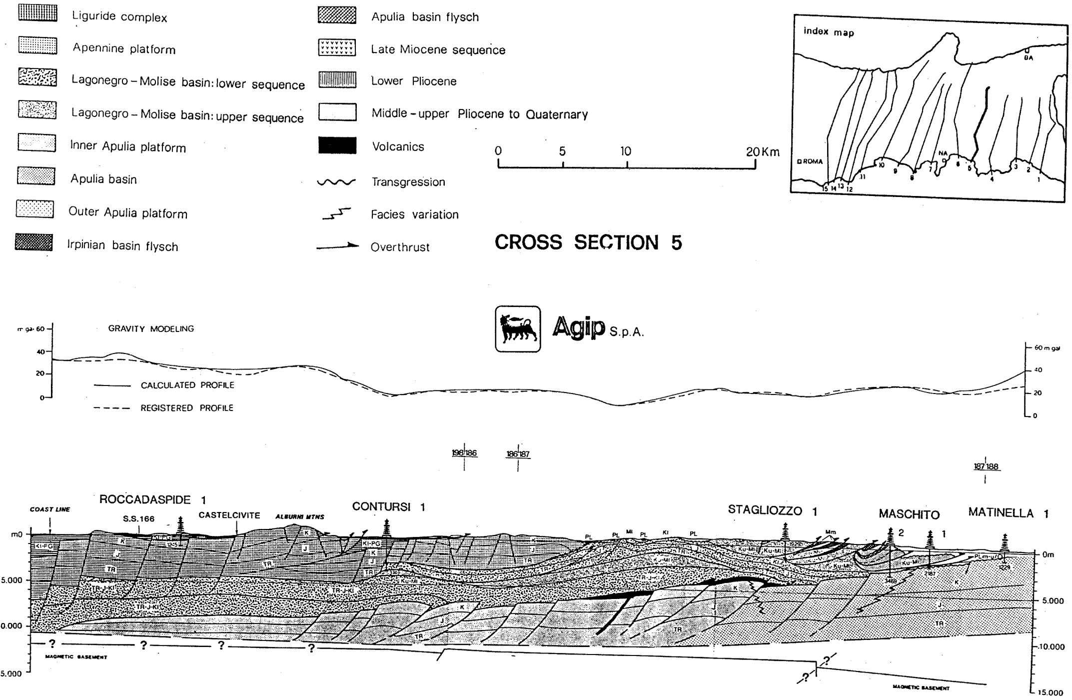

Fig. 17. A schematic cross-section (No. 5) in the Southern Apennines (thicker on the map from Mostardini and Merlini, 1986).

3. Conclusions

Both the Alps and Apennines thrust zones are young colliding systems, in which the basic principle of structural evolution is ramp-like tectonics.

In each system, three main units could be ascertained:

- The inactive foreland and the foredeep filled with young sediments.
- The central or axial zone with strongly folded and overthrust formations, being metamorphosed in many cases.
- The hinterland which with respect to the central zone behaves as a more or less rigid block (compressed in an earlier orogenic phase). The internal upper unit shows a crustal thickening by back folding and thrusting (*e.g.*, Southern Alps) or presents an extensional region with a thinned crust (*e.g.*, Tuscany).

From these compative studies the following conclusions can be given:

- All crustal sections through the young colliding systems studied here show a clearly expressed asymmetric lithospheric structure.
- Crustal thickening is mainly caused by stacking of sedimentary and crystalline formations.
- In the internal Alpine zone (and, less clearly, also in the Apennine zone) crustal doubling with or without mantle slices at the base of the upper unit are characteristic.
- Thus the deepest crustal formations are there found beneath the hinterland block.

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