THE CRUST IN ITALY FROM SEISMIC PROSPECTING AND ADDITIONAL INVESTIGATING TECHNIQUES

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The near-vertical reflection seismic method was the most appropriate exploration tool utilized in the crustal exploration of Italy and neighbouring Seas with the CROP (CROsta Profonda) project and with similar programs. The method, subsequent to the improvements in data acquisition and processing with increased dynamic range of digital data and more powerful processing software, provides signal easily interpreted in geological terms. To complete the information needed for major geological synthesis a combination of different geophysical investigating techniques were required and added. Significant the wide-angle refraction/reflection method (WAR/R), which yield propagation velocities at depth with greater accuracy. Both reflection and refraction techniques, separately used, supply results which are different in nature though complementary.

Examples of the current interpretation and the open debates about the structure and geodynamics of the crust of the Italian area will be presented with regard to: first, the definition of the seismic nature of the Moho discontinuity, in terms of its position, topography, smoothness and continuity; second, the lower crust contribution in the complexities of the collision mechanisms; third, the presence of decoupling levels within the subducting lithosphere or the intracrustal ones, related to the Neogenic evolution, an insight into the processes that built the geological structures of the upper crust; fourth, what to do and future improvements to crustal exploration.

Active seismic prospecting can give major information in the first 50-60 km of the lithosphere, with limited data quality in the collision zones where the utilization of the receiver functions analysis can help in the precise indication of the positions in the crust-mantle transitions of the colliding plates. The tectonic melange may dominate the thickened crust after collision, making difficult to isolate the different bodies because the physical differences are small. Larger depths are investigated by earthquake hypocentre distribution or by tomographic analysis of teleseismic events, outside of my presentation.

Of interest, the acquisition of wide-angle reflection fans, successfully employed for imaging the complex geometries of the M-interface on collision belts once information was available about an approximate position at depth of the target.

The study of the crust started in Italy with controlled source refraction profiles in the Western Alps in 1956, in replay to requests for international collaboration among the confining countries. Analog recorders were used, and the spacing between stations, the number of the acquired profiles, were related to the availability of instruments and operators (students) from different participating countries. Reliable results were obtained only on the gross changes in crustal thickness and on the main velocity structures, but the data quality increased as years go following the technological evolution (from the initial coffins to the Coca-Cola cans of ALP-2000).

The deep seismic soundings covered the whole Italian Peninsula with profiles integrated with other pertinent geophysical methods. This activity was concluded with the long N-S transect of the European GeoTraverse (EGT) program in 1986 (Ansorge *et al.*, 1992).

We returned to the Alpine chain with reflection seismics updated technologies in joint international multidisciplinary programs, exploring Western Alps in 1985-1986, first with a French-Italian joint venture (CROP-ECORS), followed by a co-operation with the Swiss NRP20 project in the Central Alps. The Eastern Alps were explored from 1999-2000 by partner institutions of Italy, Austria and Germany acquiring data along the TRANSALP profile. In the mean time the CROP venture programmed acquisitions across the Apenninic chain; Sicily was explored in 2009, but with different funding following the CROP-11 solution.

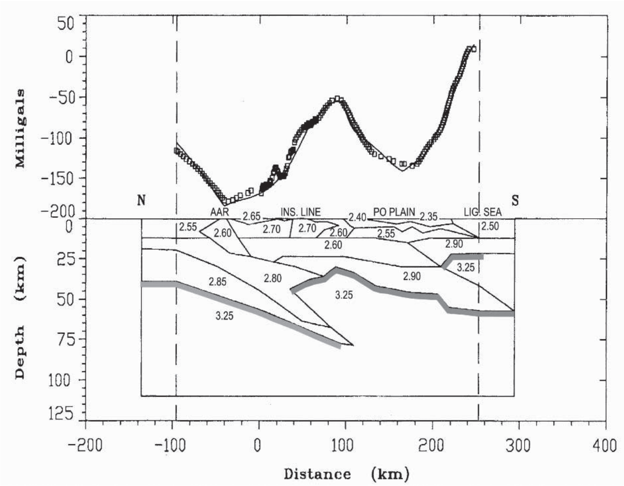

Fig. 1 – The gravimetric model (from Marson *et al.*, 1994) along the European GeoTraverse, crossing the Alps, the Po Plain and the Apennines, down to the Ligurian Sea. The model settles the European Moho at 60 km or more beneath the Po Plain with Adria Moho down-bended to about 40 km by the Apennines overthrust, Apennines here characterized by a vertical Moho uplift. Density values in gr/cm^3.

The deep exploration of the marine areas started in 1988 in the Provenzal Basin (again a CROP-ECORS joint venture) and after covered all the Italian neighbouring seas with CROP and with similar projects (ETNASEIS, SINBUS, PROFILES, IMERSE, ...).

The dynamite source was employed in several transects, but also heavy vibrators were used, for ex. in the narrow mountain valleys, but still adding explosive shots to aid imaging the deepest reflecting markers. The depth penetration of vibroseis signals is turned up to be particularly low in such areas where high-impedance rocks are exposed at the surface. The use of complementary wide-angle acquisitions continued about everywhere with in-line profiling or with fans or again designing cross-lines to enable 3D images extracted from a wide corridor centred on the main profile. The operative parameters employed in the acquisition were modified with the continuous improvements of the recording technologies and the gained experiences, varying the number of the active recording channels, the group intervals, the offsets; all parameters choice limited by the available funding.

The addition of the gravity information with the Bouguer anomalies can help to position the deep basins, the deep roots of the orogenies and of the high density bodies at shallow depths. Both the seismic and gravity interpretation take mutual advantage by iterative use of the two data sets and of the constraints posed to fulfill both observed data. The gravity field can be used to extend the interpretative models beyond the seismic profile and 3D gravity models have been presented to control the laterally variable crustal architecture. In Fig. 1 an example of a gravimetric model, which utilized the seismic information along a sector of the EGT transect from the internal crystalline massif in Switzerland to the Ligurian Sea, crossing the Milano belt, the western Po plain and the northern Apennine arc. The structural setting of the Adria domain results from the convergence of the plate margins producing a foreland-foredeep domain consumed by the advancing neighbouring chains with vertical offset of respective Moho's.

In Fig. 2 an example of wide-angle fan profiling, which were of primary importance for the interpretation of the deep interfaces disclosed in the reflection seismic sections of the CROP-ECORS project (Damotte *et al.*, 1990), revealing a dramatic imbrication of the upper mantle and crust. Organizing the sampling interval of reflectors along the cross sections and the shot-receivers distance in fan to have reflecting points around the critical distance corresponding to the common depth point of the near vertical reflection profile, the wavelet from the base of the crust is known to be very energetic and can be identified by the maximum amplitude signal. The root zone of the chain was outlined down to 55 km depth with the flaking of the lithosphere under the chain in the Briançonnais zone, while the hinterland Moho is raising stepwise from the Po plain up to about 13 km depth, the base of the outcropping rise known as the Ivrea lower crust body.

The exploration of the Alpine chain reached the peak with the TRANSALP transect, which utilized again multidisciplinary approaches: a) seismic multichannel acquisition with vibroseis and explosives, b) a 3D control of the deep structures utilizing a supplementary spread, c) wide-angle profiles, d) gravity measurements with compilation of a new map of cross-borders Bouguer anomalies covering NE-Italy, W-Austria and Bavaria, e) recording of seismological data with a permanent stations network.

Along TRANSALP profile the geophysical/geological models and the reflection seismic images with their well resolved small-scale heterogeneities (Lueschen *et al.*, 2006) have been extended on larger depths by teleseismic "receivers functions", P to S converted signals, illuminating the lithosphere from below which can give information on the main converter, the M-discontinuity, or on wide velocity gradient zone. An example is given in Kummerow *et al.* (2004), where the base of the crust and intracrustal structures in the Eastern Alps are recognized (Fig. 3), confirming the interpretation of the Transalp seismic sections (Castellarin *et al.*, 2006) with a south-dipping polarity of the Europe subducted mantle. It is not so immediate with the initially presented lower resolution teleseismic tomography procedures (Lippitsch *et al.*, 2003), probably with a poor control of the upper crust velocities and heterogeneities and construction of tomographic sections along direction where it is difficult to resolve the laterally variable structures (old, recent).

ALP 2002 experiment came again to WAR/R technique, but with many shots, several profiles and a large number of narrow spaced recording instruments, to complete the investigation of the Eastern Alps and Central Europe (Brückl *et al.*, 2010). The compression between Europe and the indenting Adria microplate generated the tectonic forces for the Dinaric orogeny, active from Cretaceous to Miocene, and for the extrusion and escape of the Eastern Alps towards the unconstrained Pannonian basin. Adria is moving towards north, obliquely thrusting

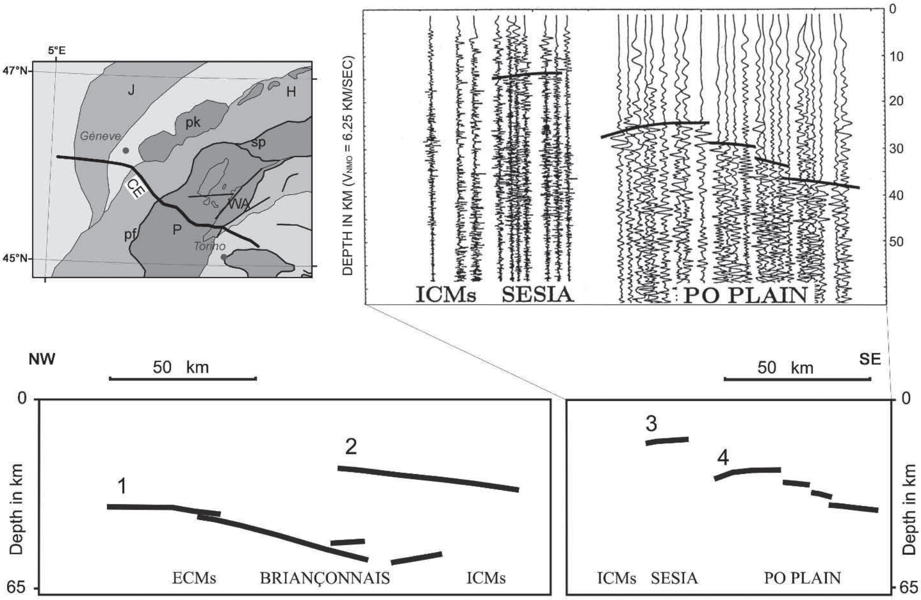

Fig. 2 – An example of the utilization of wide-angle fans with the crustal model and a stepwise M-discontinuity reflection images along a transect from the Po Plain to Gran Paradiso (from Thouvenot *et al.*, 1990, modified), intersecting Sesia-Lanzo zone and Canavese line, which marks the eastern limit of the chain (CE = seismic profile CROP-ECORS). Reflections are picked on the seismic section using a maximum amplitude criterion and traces correlation. ICMs = internal crystalline massif; ECMs= external crystalline massif. At the bottom the crustal scheme with main discontinuities across the whole Western Alpine chain: 1- European Moho, 2- Brianconnais Moho, 3 - base of the Ivrea body, 4- Adria Moho.

under the Pannonian fragment corresponding to the Dinaric chain. The upper crust is here characterized by the Dinaric thrusts (upper plate) moving westwards, opposed by the Istria massive Mesozoic shelf domain, the stable part of Adria that emerge from the Adriatic Sea. Europe is in the position of lower plate beneath Adria overthrust by a Pannonian fragment with vertical offsets of the respective Moho's, in the north; in front of the Adriatic coasts and beneath the Dinaric chain, the Moho surface seems to remain rather smooth and continuous from the foreland to the hinterland and down-bended towards the culmination of the Dinaric chain (Velebit mountains), suggesting that a major decoupling operates at or near the Moho between the Adria and Pannonian and the respective former mantle lithospheres (Šumanovac *et al.*, 2002). The lower crust of Adria probably plays a major role in the definition of the crust structure and evolution. The joint deep reflection seismic profiles with the WAR/R velocities could be the winning solution and give an answer to the role of the Adria indenter in a key area for crucial seismotectonic modelling.

The Adria collision with the Apennines developed from late Miocene to Quaternary. Unlike in the Alps, where a major lithosphere scale fault accounts for vertical offset of the Moho between the upper and lower plate, along the Apenninic chain facing the Adriatic Sea, the Moho surface remain rather smooth and nearly continuous, gently bended, from the foreland towards the Apennine chain and up to the hinterland mantle dome. A major decoupling is operating near the Moho and only the continental lithosphere of Adria seems to be currently involved in the subduction process presently active with a nearly south-eastward directed subduction plane, as proposed by Di Stefano *et al.* (2009) with earthquakes tomography analysis. These authors accept the upwelling of the asthenosphere and the related thermal softening of the crust on the Tyrrhenian side. Therefore the back-arc extension and the asthenosphere upwelling, in addition to the slab pull, constitute the major driving force in the Apennine-Adria collision.

The mobilized and uplifted asthenosphere, a not depleted mantle wedge, can be responsible of the lower crust lamination by magmatic intrusion. The mantle derived magmas releases heat at the base of the crust, induces anatexis in the overlying crustal rocks and produce granitoids melts, quickly migrating towards higher levels (Locardi and Nicolich, 2005). Wide-angle refraction/reflection acquisitions (Giese *et al.*, 1976) across the Tuscany Geothermal Province revealed a peculiar velocity structure with alternate velocity/density variations in the lower crust and a seismic waves propagation velocity not higher than 7.8 km/s, assigned to the Moho discontinuity. Crustal reflection seismic profiles give a well resolved image of the lower crust and of the brittle/ductile transition interval utilizing seismic attributes and the evaluation of strength (Accaino *et al.*, 2006).

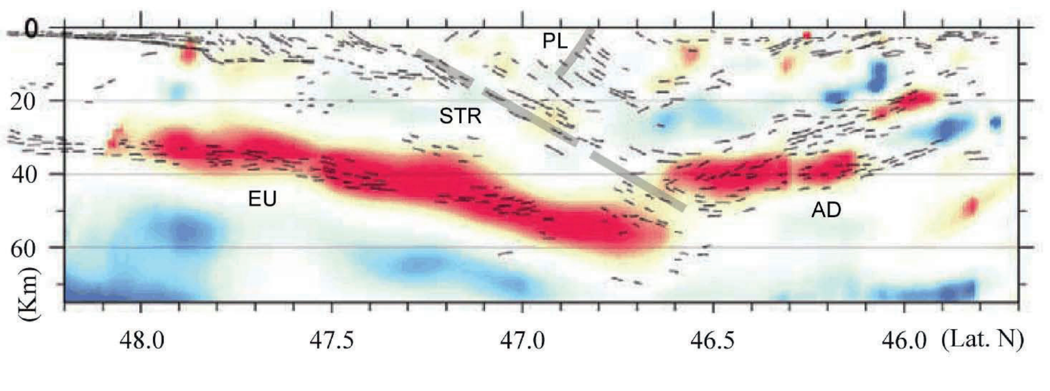

Fig. 3 – Receivers function and combined explosive and vibroseis depth migrated data line drawing along TRANSALP transect (from Lueschen *et al.*, 2006, modified). The presence of decoupling levels (the Sub Tauern Ramp: STR) within the subducted lithosphere poses an insight into the processes that built the geological structures of the upper crust. EU = Europe; AD = Adria; PL = Periadriatic Line.

The reprocessing of the CROP profiles in the region, let us to apply the wave equation datuming technique (Barison *et al*., 2011; Giustiniani *et al*., 2013) extracting information previously hidden by approximate static corrections and surface noise. From picked first arrivals, a tomography inversion created a near surface velocity model by iterative ray-tracing and travel time calculations. Then, the wave equation was applied to move shots and receivers to a given datum plane, removing time shifts related to topography and to near-surface velocity variations. Basically, WED is the process of upward or downward continuation of the wave-field between two arbitrarily-shaped surfaces; a process useful to attenuate ground roll, enhance higher frequencies, increase the resolution and improve the signal/noise ratio.

The new outputs show evidence of regional continuity of high amplitude horizons, a better fitting with the surface geological setting and with well data, resembling the local industry investigations; the results confirm the role of overpressured fluids, better define the tectonic setting as well as the contribution to the reflectivity of lithology and of hydrothermal fluids or thermo-metamorphic minerals.

The wave equation datuming is now applied to the SIRIPRO profile crossing central Sicily from the Tyrrhenian Sea to the Sicily Channel. This reprocessing requires large computers, parallel processors, because of the long listening times. The profile was acquired without additional complementary geophysical tools, like new wide-angle experiments, offshore-onshore continuation, … It shows the crustal flexure from the Hyblean foreland towards the Caltanisetta through, accompanied by crustal thinning: from an already thinned crust (around 30 km the Moho depth on coast of the Sicily Channel) to about 16-17 km thickness of the same interval beneath Caltanisetta. North of the collision zone the Maghrebides chain includes units of the African margin in a similar way to the crustal setting in the North-Algeria facing the Algerian basin. It is necessary to better resolve the structures of Maghrebides chain, north of the Caltanisetta through in the collision zone, where a Moho uplift is possible, as confirmed by the gravity anomalies and old deep refraction data. Again a bended continuous crust-mantle interface from hinterland to foreland is suggested, with delaminations and the decoupled mantle lithosphere still locally subducted and recycled in the asthenosphere, but more complex structures cannot be excluded. Moreover, contraction events are currently active at the toe of the North Sicilian margins, possibly accounting for the initiation of a new underthrusting/subduction zone along the southern margin of the Tyrrhenian basin, that will accomodate further convergence between Africa and Europe.

A crustal flexure has been observed moving from the Hyblean domain to the Ionian deep basin, where the crust-mantle transition interval is characterized by a curious high amplitude reflectors in the low frequency band (around 10 Hz). The crustal thinning from the Sicily channel to the Ionian basin across the Malta Escarpment is shown in reflection seismic profiles as well as the presence of a crustal transcurrent fault accounting for a major dextral lateral escape of the Calabria Block during the Plio-Quaternary opening of the Tyrrhenian Sea. The fault separates the eastward thinning continental crust from the deep Ionian domain, which crust is proposed as oceanic from many authors. The interpretation of the seismic data is still under debate and the presence of a wide oceanic domain or of an area still belonging to a distal portion of the North African continental margin cannot be confirmed or plainly denied. Following the exposed Tethian ophiolitic suture (in Albania, Western Greece, Crete, Western Turkey, …) the Tethian ocean has been already recycled within the asthenosphere. The Cretaceous rifting, presently recognized offshore Libia, is a possible origin of the thinning of the crust of a north African margin widely extended in the Ionian Sea with the presence of pull-apart basin up to oceanic openings; once more, the eclogitization of the upper mantle can account for the high velocities and high densities necessary to justify the positive Bouguer anomalies. The tectonic loading of the Africa foreland lithosphere by the Calabrian (and Aegean) arcs is not sufficient to account for the 4 km water depth in the Ionian abyssal plain. Other forces, like slab pull, lateral push of the asthenosphere upwelling in the Tyrrhenian and Aegean back-arcs are likely to account for the retreat of the deep mantle slabs and must therefore contribute to the decoupling operating close to the Moho. The decoupling of the crust is confirmed by the thrust-top pull-apart basins currently developing above the back-stop of the Hellenic Arc (Wardell *et al*., 2013; Barison and Nicolich, 2013).

The combined utilization of morphological analysis plus high resolution and deep penetration multichannel seismic jointly with OBS for wide-angle recordings and part of a permanent network of seismological station in connection with on land positioned recording points, is the optimum solution for the lithosphere exploration in subduction or collision zones. A first project was Etnaseis with marine and land synchronized operations (Laiglè *et al*., 2000). The SeaHellarc project followed these ideas studying the western continental margin of Peloponnesus. Thales project investigated the Lesser Antilles with European and French funding (Laiglè *et al*., 2013). This area was the target of a complete set of active and passive offshore seismic experiment: multichannel reflection seismic with air gun source organized in the Single Bubble mode, OBS WAR/R seismic profiles, OBS and land permanent seismological stations for earthquakes location, receiver functions analysis imaging the slab top and the LVL. The objective were the geometries of interplate boundary zone constrained from the subduction deformation front and the possible generation of mega-thrust earthquakes.

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