

## Seismic lines CROP-ECORS across the Western Alps

### *Le linee sismiche CROP-ECORS attraverso le Alpi Occidentali*

BERNABINI M.<sup>(1)</sup>, NICOLICH R. <sup>(2)</sup>, POLINO R. <sup>(3)</sup>

**ABSTRACT** - This was the first plan in Italy for deep crust reflection seismic data, acquired across the Western Alpine chain following the invitation for a joint venture from the group ECORS-France. The Italian share was founded by CNR (National Research Council), included in a "Strategic Project", with a contribution of ENEA (Alternative Energies National Agency), but the project remained under the umbrella of the newly established CROP Syndicate (Progetto Crosta Profonda), including at that time the following partners: AGIP (the National Oil Company), CNR, ENEA and ENEL (National Electricity Board).

This was a significant opportunity to gain experience in the programme preparation, definition of the data acquisition procedures, of the data processing, data interpretation and in the presentation of the scientific results. The effort was done within an international working team where geological and geophysical expertise, with members of various academic and industrial backgrounds, was present and this factual international cooperation represents an unsurpassed model.

The most important choices regard the updated prospecting techniques with a combination of dynamite and vibroseis seismic sources, the employment of helicopters for drilling and recording in high mountain rugged terrains, the crucial wide-angle experiment and the complementary gravimetric and magnetic surveys. The scientific results of this first profile across the Alpine chain have moved the attention of the scientists and primarily of the Alpine geologists.

**KEY WORDS:** Western Alps, reflection seismic, deep crust, wide-angle reflections, structural geology

**RIASSUNTO** - Questo è stato il primo passo effettuato in Italia per l'acquisizione di dati di sismica a riflessione crostale, assecondando l'iniziativa del progetto francese ECORS. La parte italiana della traversa è stata finanziata dal CNR nell'ambito di un "Progetto Strategico", con un contributo di ENEA. Esso in ogni modo rimane parte integrante dell'allora neo costituito Consorzio CROP (Progetto Crosta Profonda) con partners l'AGIP, il CNR, ENEA ed ENEL. L'esperienza acquisita è stata fondamentale per la definizione dei criteri nelle procedure di valutazione dei problemi, l'acquisizione, l'elaborazione ed interpretazione dei dati, la diffusione dei risultati scientifici, in un contesto di mutua e fattiva collaborazione fra geologi e geofisici del gruppo di lavoro, rappresentanti nazioni e scuole diverse e con competenze acquisite sia nel mondo accademico sia in quello industriale. È un modello operativo che rimane ancora insuperato. Significative le tecniche di prospezione impiegate, l'uso di elicotteri per la perforazione e l'acquisizione in territori inaccessibili d'alta montagna, la combinazione di operazioni con esplosivi e con sorgenti vibroseis, l'innovativa e determinante prospezione wide-angle e poi ancora i complementari rilievi gravimetrici e magnetici. Essendo il primo profilo attraverso le Alpi, ha suscitato subito l'interesse degli scienziati e dei geologi alpini in particolare.

**PAROLE CHIAVE:** Alpi Occidentali, sismica a riflessione, crosta profonda, riflessioni a grande angolo, geologia strutturale.

<sup>(1)</sup> Dip. di Idraulica, Trasporti e Strade, Area Geofisica, Università "La Sapienza", Via Eudossiana, 20 - 00184 Roma.

<sup>(2)</sup> Dip. di Ingegneria Civile, Sez. Georisorse e Ambiente, Università di Trieste, Via Valerio 10 - 34127 Trieste.

<sup>(3)</sup> CNR-Istituto di Geoscienze e Georisorse, c/o Dip. di Scienze della Terra, Università di Torino, Via Accademia delle Scienze 5 - 10123 Torino.

## 1 - FOREWORD

The first crustal seismic profile across the Alps was planned within a cooperation between the CROP (Italian) and ECORS (French) Projects. The primary objective was to acquire deep seismic data along a complete Alpine section. From among the various options restricted by the complex superficial structures and permitted by the logistic difficulties, the choice fell on that which unites the molasse foreland near Geneva with the Po plain molasse, crossing the Prealps, the Vanoise, the Gran Paradiso and the Canavese (southern Alps) zone (fig. 1).

During 1985 a working team was constituted for the preparation of a detailed programme. It was also in charge of the data interpretation and distribution of the scientific results

The seismic refraction and wide-angle reflection preliminary survey was acquired in 1985 with a financial contribution, for the Italian part, from CNR. The French-Italian profile, ALP1 reflection seismic profile, 214 km of seismic lines, from the Po Plain to the Plateau des Glières, was acquired in 1986 and completed in 1987. The Italian share was founded by CNR with a financial contribution of ENEA.

Other profiles followed and all were founded by the ECORS group:

- a) the French Alps profile (ALP2), from the Plateau des Glières to the Rhone river, 49 km long, in 1986;
- b) the Jura-Bresse profile, from the Rohne River to Tournus, 114 km long, in 1987.

All the data were reported in the Final Report (ROURE *et alii*, 1996).

## 2 - WIDE-ANGLE AND NEAR VERTICAL REFLECTION DATA.

A wide-angle seismic profiling experiment (DSS) was undertaken in 1985, which allowed drawing a cross-section of the Moho across the western Alps (ECORS-CROP DEEP SEISMIC SOUNDING GROUP, 1989a). Five shots of 1 metric ton of explosive were recorded on fans and lines across the chain (fig. 2). A tight sampling of this deep reflector shows abrupt changes in its depth and dip. The root zone of the chain (the zone of maximum crustal thickness) was well defined, with a 55-km-deep crust-mantle boundary. The Moho under the western Po plain was also clearly seen, and a shallow reflective structure is mapped under the Briançonnais zone in the 25-30 km depth range. This structure, if interpreted as lower-crust or upper-mantle

material, would support the hypothesis of a flaking of the lithosphere under the western Alps (ECORS-CROP DEEP SEISMIC GROUP, 1989b). The technique of wide-angle seismic reflection has enabled to locate the Moho providing also information on upper- and mid-crust main reflectors, becoming the constraints for the interpretation of the vertical seismic (THOUVENOT *et alii*, 1990). The projections at depth of the two data sets and their correlation were granted by the high degree of cylindricality of the gravity anomaly in this segment of the Alps (REY *et alii*, 1990). This was also one of the principal reasons for the selection of the transect-line.

Two NVR profiles were recorded on the two sides of the chain in 1986. On the Italian side, between October and December, OGS (Osservatorio Geofisico Sperimentale) acquired a 93.2 km long seismic line along the whole Valle dell'Orco from Lago Serru (2500 m) as far as Castellamonte and then SE along the valley to the Apenninic overthrusts near Lamporo (NE of Chivasso). On the French side, the line recorded in September by CGG (Compagnie General de Géophysique) extends from the Val d'Isère to Petit Bornand across the Cormet de Roselend, the Col des Saisies, and the Col des Aravis for a total length of 101.52 km. The acquisition geometry was similar for the two lines: 120 traces with 80 m spacing, a vibroseis source (five heavy trucks, VVCA, operated by Prakla-Seismos in Italy) with an asymmetric sweep 9-39 Hz, summing 8 sweeps for each shot point, and a 60-fold coverage. Along both lines, a supplementary single- to two-fold dynamite section was also produced.

The gap of about 7 km between the two vibroseis lines was filled in October. This was a complex operation, both due to the environmental conditions (altitude between 2,000 and 3,000 m) and because two different equipments and recorders were used in two different valleys, necessitating a synchronization of the firing equipments and the two laboratories via radio with a repeater installed at Colle della Losa (2,990 m). The line, shot entirely with explosive (15 shots with charges from 30 to 250 kg) and using only helicopters, was recorded with 250 channels at a spacing of 80 m for a total length of 20 km ensuring an overlap with the normal lines (DAMOTTE *et alii*, 1990).

In the context of the CROP-ECORS Project, a recompilation of the existing gravimetric data was made in order to have a homogeneous cover of the whole region containing the line; moreover an aeromagnetic profile approximately coincident with the seismic line was commissioned (BAYER *et alii*, 1989; REY *et alii*, 1990)

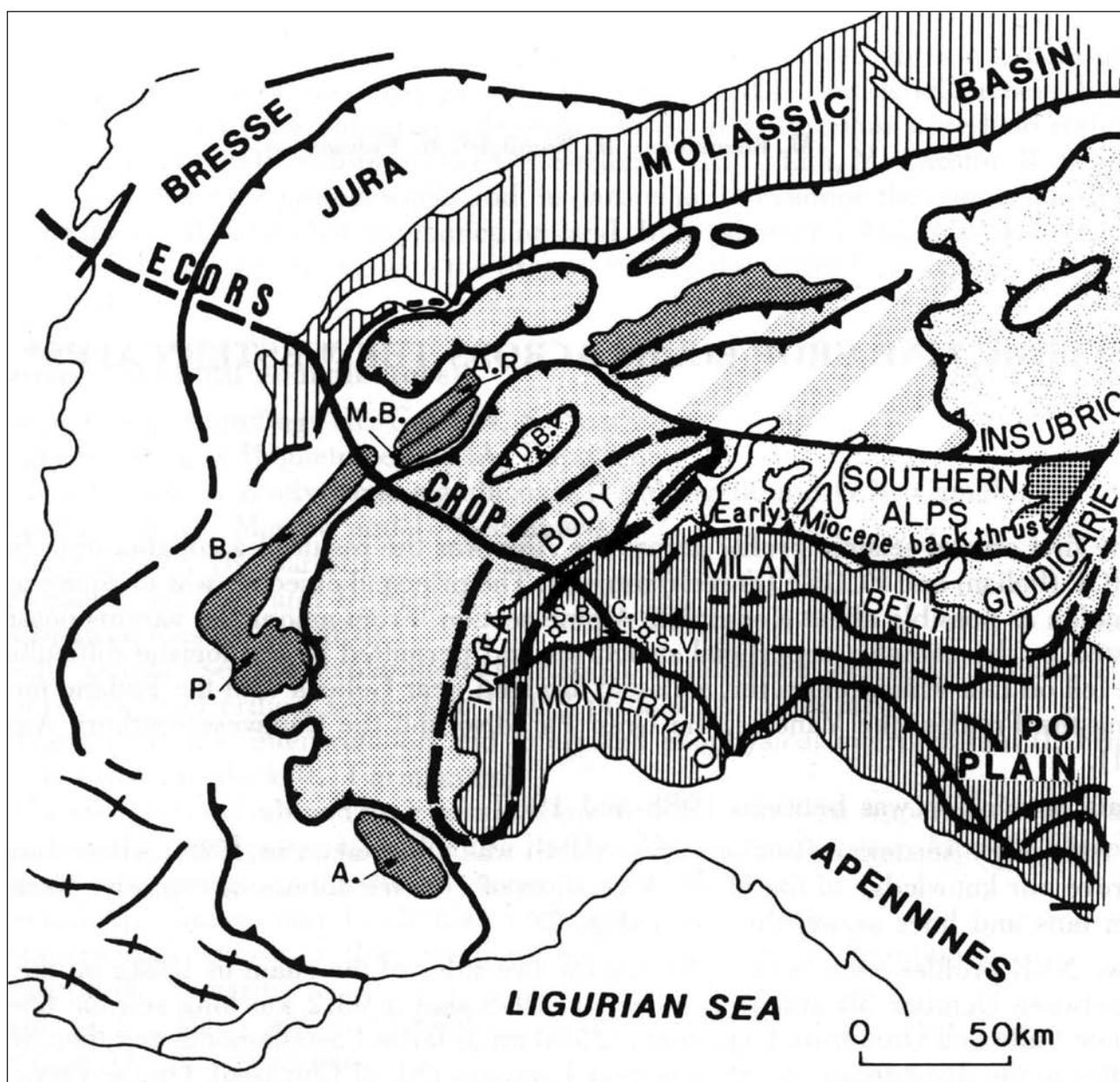


Fig. 1 – Location of CROP-ECORS profile and main geological structures  
 – Localizzazione del profilo CROP-ECORS e principali strutture geologiche interessate.

## THE GEOLOGICAL OBJECTIVES AND THE SCIENTIFIC RESULTS

- The principal problems facing the project leaders, which it was hoped, will be better understood were, from west to east (The ECORS-CROP Alpine Seismic Traverse, ROURE *et alii*, 1996):
- the origin of the Bresse Graben sinking mechanisms;
- thinning mechanism of passive margin, reactivation during collision of the faults linked to this distension and their interaction with older brittle systems;

- flexure of the European lithosphere at the front of the crustal thrusting,
- the probable crustal doubling at the external crystalline masses, the magnitude of their movement over the foreland, and the origin of the vertical faults and of those reversed towards the inner part of the arc;
- the possible presence at a depth of about 15 km of a low seismic velocity zone, which could correspond to a zone of lower viscosity which allows movements between the upper and lower crust;
- the significance of the large surface fractures of the axial part of the chain (Pennidic Front, Viu-Locana

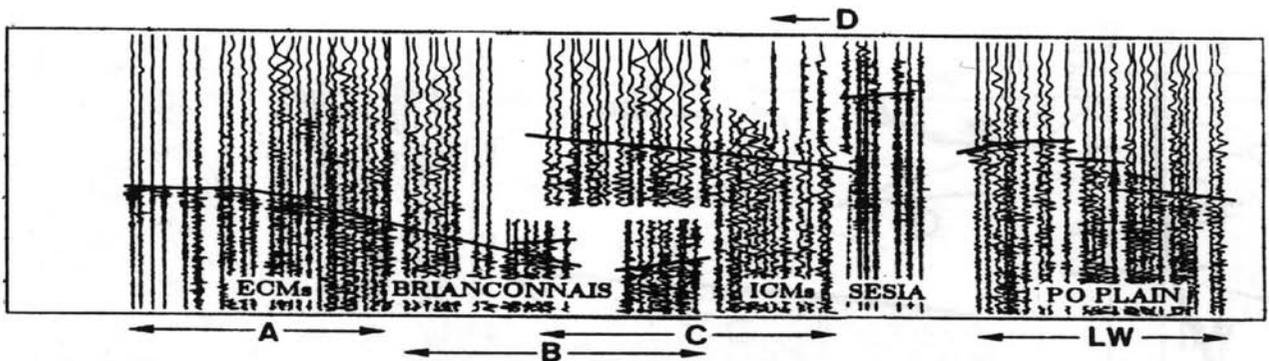


Fig. 2 – Position map of wide-angle reflection seismics. A, B, C, D, LW: shot points; dots indicate the geophones; thick lines indicate subsurface coverage. Above is a synthesis of the seismograms with the Moho-like surfaces imaged during the experiment indicated.

– Pianta di posizione della sismica DSS; A, B, C, D, LW: punti di scoppio; i punti indicano la posizione dei geofoni, le linee ingrossate la copertura subsuperficiale. In alto una sintesi dei sismogrammi registrati con l'immagine della superficie di Moho come risulta rappresentata dall'esperimento descritto.

fracture zone, system of Insubric faults) and their continuation in depth in order to answer the problems posed by the collision of the European and Insubric plates: the suture between the plates coincides with the Viu-Locana line, i. e. the eastern limit to the ophiolites, or with the Insubric Line with eastern limit of high pressure metamorphism?

- the significance of the Ivrea Zone: edge of the colliding Insubric plate or independent unit created during the uplifting of the chain?
- relationships between the ultrabasic masses and eclogite metamorphic units and/or deep crustal units.

Thus one can see how these points were linked to an imprecise knowledge of the deep structures, and, on the other hand, how innovative a picture of the crust emerges from the investigations undertaken during the Project.

The most important characteristics of the crustal images resulting from this operation are the following (BAYER *et alii*, 1987):

- west-vergence of the principal lithospheric discontinuities;
- involvement of the mantle in the tectogenesis (fragments of mantle are seen at various crustal levels in the chain).

The picture poses important constraints for:

- locating the principal lithospheric discontinuities;
- locating the suture between the European and Insubric plates;
- defining the geometry of the principal superficial crustal discontinuities (Penninic Front and Insubric Line);
- revealing the structure of the roots in the axial metamorphic chain;

- establishing the importance of the depth of the decollements in the Mesozoic folds.

The line-drawing of the crustal seismic profile (fig. 3) gives information on the current geometry of the chain (NICOLAS *et alii*, 1989, 1990). Extrapolation in depth of the structural domains and principal discontinuities, taking account of the geological constraints, allows a definition of crustal and lithospheric blocks of independent evolution. In the diagrammatic representation of the seismic line in fig. 3, the following are evident: 1) the decollements in the subalpine folds; 2) the highly reflective seismic character of the deep crust under the part not involved in the continental collision of the European plate; 3) the west-verging overthrusts in the crust in the external part of the chain; 4) the deep geometry of the Penninic Front; 5) the peculiar reflective character of the zone of nappes piling in the metamorphic chain; 6) the correspondence between the image from vertical seismic and the surface interpreted as Moho from the wide angle refraction seismics (amongst others, the top of the Ivrea geophysical body is well evidenced); 7) the involvement of the Insubric basement in the retro-vergent overthrusts of the chain's internal part; 8) the elongation as far as this profile of the Apenninic Mio-Pliocene foreland.

Figure 4 gives a crustal profile, which includes the depth converted seismic data (NVR and DSS), the gravimetric and magnetic modelling, and, obviously, the constraints of surface geological work.

The letters A, B, C, D, LW indicate the DSS seismic markers and corresponding bodies interpreted as crust-mantle transition (Moho). What is considered European Mantle (A, B, and C) is indicated in dark grey, while the Insubric in light grey (D, LW).

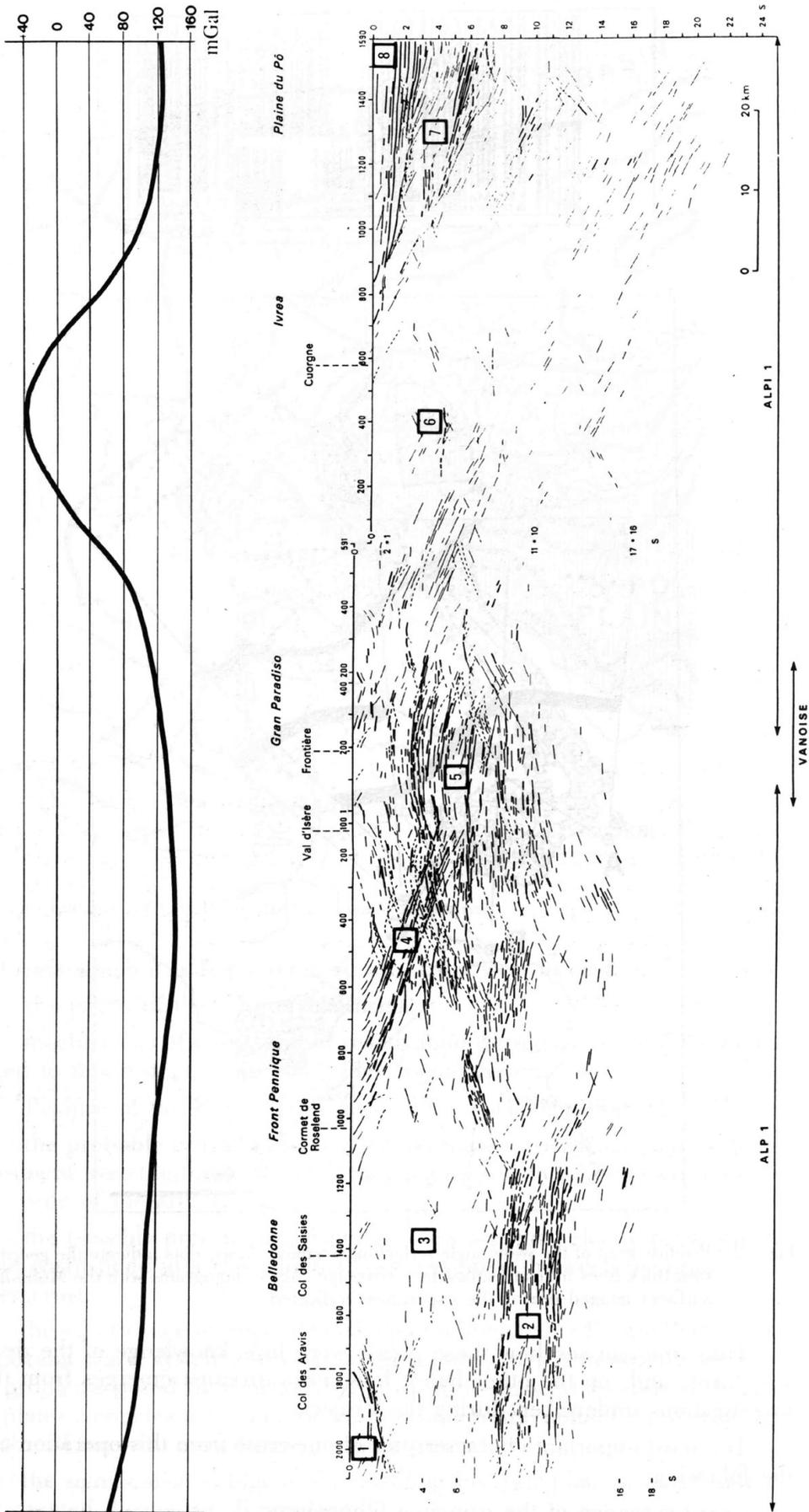


Fig. 3 – Line-drawing of the crustal seismic profile CROP-ECORS “Western Alps” and related gravimetric profile. The width of the lines indicates the degree of confidence in the reflectors. Explanations are given in the text.

– “Line-drawing” del profilo sismico crostale CROP-ECORS “Alpi Occidentali” e relativo profilo gravimetrico. Lo spessore del tratto indica il grado di confidenza dei riflettori. Spiegazioni nel testo

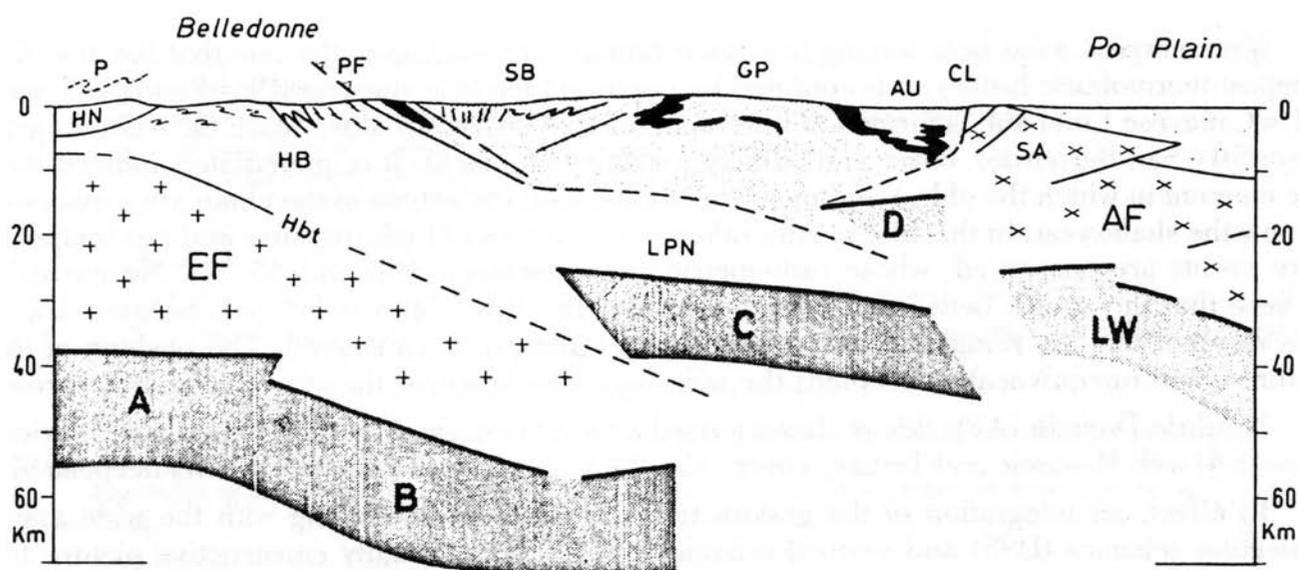


Fig. 4 – Schematic crustal profile along the CROP-ECORS traverse.  
– Profilo crostale schematico lungo la traversa CROP-ECORS.

European foreland (EF): this is the youngest element of the chain, and is formed of European crust, which runs under the already formed chain; it is recognizable in the seismic data to a depth of 55 km.

Deformed European Margin: this is a composite block of surface folds (HN = Helvetic folds), of superficial basement folds (HB = Helvetic basement), and of deep basement and cover folds (LPN = lower Penninic folds) overlying the European foreland along a discontinuity of crustal dimensions (Hbt = Helvetic basal overthrusting). This structural domain lies on a fragment of European mantle (C), which has been involved with the chain during its more recent history.

Metamorphic axial belt: among the outcropping elements, this is the one that has had the deepest thermobaric history. It is confined by important tectonic surfaces (PF = Penninic Front; CL = Canavese Line) and is formed of basement folds (AU = Austroalpine, Sesia; GP = Gran Paradiso; SB = San Bernardo), cover and ophiolitic nappes (in black). It is immediately noticed how the element in which the oldest and most violent thermobaric events of the chain are conserved is now the shallowest. In this block, mineralogical associations of high pressure and low temperature events are conserved, whose radiometric age is between 130 and 45 My. Moreover, it is here that the suture between the European and Insubric plates is located, because it's in this element that the remains of the ocean between the two are conserved. The position of the suture is not unequivocally accepted; the most logical is however the current Penninic Front.

Insubric Domain (AF): this is characterized by south-verging Southalpine crustal imbrications (SA) with Mesozoic and Tertiary cover.

Also the Insubric upper mantle (D, LW) deepens SE.

In effect, an integration of the gravimetric and magnetic models with the wide-angle reflection seismic (DSS) and vertical seismic (NVR) gives a highly constructive image necessary for all crustal interpretations of the western Alpine chain. In particular, it demonstrates the importance and interest of bringing together several different geophysical and geological techniques for investigating the chain and interpreting a vertical deep reflection profile (POLINO *et alii*, 1990; ROURE *et alii*, 1989, ROURE *et alii*, 1990).

## CONCLUSIONS

In conclusion, the most innovative results are 1) the presence in the chain at different structural levels of mantle fragments which demonstrate that the mantle was also involved in the orogenesis; 2) the predominant west-vergence of the major crustal (and lithospheric) discontinuities confirms that the European plate subducted to the SE under the Insubric; 3) the absence of a direct connection between the ophiolitic nappes and suture zone is a confirmation that the metamorphic axial zone is the "fossil" of an older precollisional chain with structure profoundly modified by the syncollisional deformations which produced the present geometry (see also the Final Report of the ECORS-CROP project, BAYER *et alii*, 1996).

## REFERENCES

- BAYER R. ET EQUIPE DE PROFIL ALPES ECORS-CROP (1987) - *Premiers résultats de la traversée des Alpes occidentales par sismique réflexion verticale (Programme ECORS-CROP)*. C.R. Ac. Sc. Paris, **305**, II: 1461-1470.
- BAYER R., CARROZZO M.T., LANZA R., MILETTO M. & REY D. (1989) - *Gravity modelling along the ECORS-CROP vertical seismic reflection profile through the Western Alps*. Tectonophysics, **162**: 203-218.
- DAMOTTE B., NICOLICH R., CAZES M. & GUELLEC S. (1990) - *Mise en oeuvre, traitement et présentation du profil Plaine du Pô - Massif Central*. In: ROURE F., HEITZMANN P. & POLINO R. (Eds.): "Deep Structure of the Alps". Mém. Soc. Géol. Fr., Paris, **156**; Mém. Soc. Géol. Suisse; Zürich, **1**; Vol. spec. Soc. Géol. It., Roma, **1**: 65-76.
- ECORS-CROP DEEP SEISMIC SOUNDING GROUP (1989a) - *A new picture of the Moho under the Western Alps*. Nature, **337**: 249-251.
- ECORS-CROP DEEP SEISMIC SOUNDING GROUP (1989b) - *Mapping the Moho of the Western Alps by wide-angle reflection seismics*. Tectonophysics, **162**: 193-202.
- NICOLAS A., POLINO R., HIRN A., NICOLICH R. & ECORS-CROP WORKING GROUP (1990) - *ECORS-CROP traverse and deep structure of the Western Alps*. In: ROURE F., HEITZMANN P. & POLINO R. (Eds.): "Deep Structure of the Alps". Mém. Soc. Géol. Fr., Paris, **156**; Mém. Soc. Géol. Suisse; Zürich, **1**; Vol. spec. Soc. Geol. It., Roma, **1**: 15-27.
- NICOLAS A., HIRN A., NICOLICH R., & POLINO R. (1990) - *Lithospheric wedging in the Western Alps inferred from the ECORS-CROP traverse*. Geology, **18**: 587-590.
- POLINO R., DAL PIAZ G.V. & GOSSO G. (1990) - *Tectonic erosion at the Adria margin and accretionary processes for the Cretaceous orogeny of the Alps*. In: ROURE F., HEITZMANN P. & POLINO R. (Eds.): "Deep Structure of the Alps". Mém. Soc. Géol. Fr., Paris, **156**; Mém. Soc. Géol. Suisse; Zürich, **1**; Vol. spec. Soc. Geol. It., Roma, **1**: 345-367.
- REY D., QUARTA T., MOUGE P., MILETTO M., LANZA R., GALDEANO A., CARROZZO M.T., BAYER R. & ARMANDO E. (1990) - *Gravity and aeromagnetic maps of the Western Alps: contribution to the knowledge of the deep structures along the ECORS-CROP seismic profile*. In: ROURE F., HEITZMANN P. & POLINO R. (Eds.): "Deep Structure of the Alps". Mém. Soc. Géol. Fr., Paris, **156**; Mém. Soc. Géol. Suisse; Zürich, **1**; Vol. spec. Soc. Geol. It., Roma, **1**: 107-121.
- ROURE F., POLINO R. & NICOLICH R. (1989) - *Poinçonnement, rétrobarriages et chevauchements post-basculément dans les Alpes occidentales: évolution intracontinentale d'une chaîne de collision*. C. R. Acad. Sci. Paris, **309**: 283-290.
- ROURE F., POLINO R. AND NICOLICH R. (1990) - *Late Paleogene deformations beneath the Po Plain: constraints on post-collisional alpine evolution*. In: ROURE F., HEITZMANN P. & POLINO R. (Eds.): "Deep Structure of the Alps". Mém. Soc. Géol. Fr., Paris, **156**; Mém. Soc. Géol. Suisse; Zürich, **1**; Vol. spec. Soc. Geol. It., Roma, **1**: 309-322.
- ROURE F., BERGERAT F., DAMOTTE B., MUGNIER J.L., & POLINO R. (Eds.). (1996) - *The ECORS-CROP Alpine Seismic Traverse*. Bull. Soc. Géol. Fr., **170**: 1-113.
- THOUVENOT F., SENECHAL G., HIRN A. & NICOLICH R. (1990) - *ECORS-CROP wide-angle reflection seismics: constraints on deep interfaces beneath the Alps*. In: ROURE F., HEITZMANN P. & POLINO R., (Eds.): "Deep Structures of the Alps". Mém. Soc. Géol. Fr., Paris, **156**; Mém. Soc. Géol. Suisse; Zürich, **1**; Vol. spec. Soc. Geol. It., Roma, **1**: 97-106