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The TRANSALP seismic profile and the CROP 1A sub-project
Il profilo sismico TRANSALP e il sottoprogetto CROP 1A

Transalp Working Group

CASTELLARIN A. ([1]), CANTELLI L. ([1]), BERTELLI L.([2]), BORRINI D.([3]), FANTONI R. ([3]), SELLA M. ([3]), NICOLICH R. ([4]), MAZZOTTI A. ([5]), SELLI L. ([1]), BERNABINI M. ([6]), LAMMERER B. ([7]), LUESCHEN E. ([7]), GEBRANDE H. ([7]), MILLHAN K. ([8]), GRASSL H. ([8]), NEUBAUER F. ([9]), ONCKEN O. ([10]), STILLER M. ([10])

Abstract - The CROP 1A Profile corresponds to the southern section (in Italy) of the Central European Profile (CEP), which the following geophysical-geological institutions have acquired as part of their seismic exploration studies of the lithosphere: DEKORP (Germany), OEKORP (Austria), and CROP (Italy). The joint program, which consists mainly of seismic reflection acquisition along the profile from the Bavarian foreland (München) down to the Adriatic Venetian Plain (Treviso), was brought under the umbrella of the TRANSALP Project in 1998; the seismic acquisition part of this Project has now been completed, as most of the data processing. The seismic profile was acquired during 1998, by the contractor THOR in the Bavarian segment, and by the contractor GEOITALIA in the southernmost Venetian sector (between Conegliano and Peron, a village north of Belluno). The Profile was completed in 1999 by THOR. In order to integrate the seismic data of the Transalp Profile, shown in figure 6 and in Plates 68-71, which are the main topic of this paper, we include a brief description of the more significant superficial geological and structural conditions in the zones crossed by the Profile. The various structural belts and their major tectonic features are described from south to north, from the "Venetian Molasse" of Montello and the Belluno mountains in the Italian Dolomites and, N of the Insubric Line, to the eastern sector of the Northern Alps, including the Tauern window, and the Northern Calcareous Alps and, in the foreland, the Bavarian Molasse structural settings.

Key Words: Eastern Alps, reflection seismic, structural style, deep crust.

Riassunto - Il Profilo CROP 1A corrisponde al segmento meridionale, localizzato in Italia del Profilo Centrale Europeo (Central European Profile) (CEP) programmato dalle seguenti Istituzioni geologico-geofisiche per l'esplorazione sismica della litosfera: il DEKORP (Germania); l'OEKORP (Austria) e il CROP (Italia). Il programma congiunto, sostanzialmente basato sull' acquisizione sismica profonda nelle Alpi Orientali tra l'alta Pianura Veneta (Treviso) e l'Avampaese Bavarese (Monaco), nel 1998 e' stato unificato nel Progetto TRANSALP che e' attualmente completo sia per quanto riguarda l'acquisizione sismica che per la parte sostanziale dell'elaborazione dei dati. Il Profilo sismico venne acquisito nel 1998, in Baviera dalla Compagnia THOR e, nel settore veneto più meridionale (tra Conegliano e Peron, poco a N di Belluno), dalla Compagnia GEOITALIA. Il Profilo e' stato completato alla fine del 1999 dalla Compagnia THOR. Al fine di completare la presentazione dei dati sismici del Profilo TRANSALP (illustrati alle Tavole 68-71 e fig. 6) che rappresentano il principale obbiettivo di questo lavoro, vengono qui riportate sinteticamente le condizioni geologiche e strutturali più salienti di superficie presenti nelle zone lungo il tracciato del Profilo sismico. Le differenti fasce strutturali vengono esaminate da S a N: dalla "Molassa Veneta"del Montello e dai Gruppi montuosi del Bellunese nelle Dolomiti Italiane si passa , oltre la linea Insubrica, alla sintesi degli elementi della catena Nordalpina che comprende la Finestra tettonica degli Alti Tauri, le Alpi Calcaree Settentrionali e la Molassa Bavarese nell'Avampaese Europeo.

Parole Chiave: Alpi orientali, sismica a riflessione, assetto strutturale, crosta profonda.

([1]) Dipartimento di Scienze della Terra e Geologico Ambientali, Universita' di Bologna, Via Zamboni 67, I-40127 Bologna, Italia.
([2]) Novak AGIP A/S, Travbaneveien 3, P.O. Box 101, Forus, N - 4064 Stavanger, Norway.
([3]) ENI-AGIP, Via Emilia 1, I-20097 S. Donato Milanese, Milano, Italia.
([4]) Dipartimento di Ingegneria Civile Sez. Georisorse e Ambiente, Università di Trieste, Via Valerio 10, I-34127 Trieste, Italia.
([5]) Dipartimento di Scienze della Terra – Sezione Geofisica, Università degli Studi di Milano, Via Cicognara 7, I-20129 Milano, Italia.
([6]) Dipartimento Idraulica, Trasporti e Strade, Area Geofisica, Università "La Sapienza", Via Eudossiana 18, I- 00184 Roma, Italia.
([7]) Department of Earth and Environmental Sciences,LM Universität München,Theresienstrasse 41, D-80333 München, Germany.
([8]) Geophysical Institute, Montanuniversität Leoben, Franz-Josef Strasse 18, A-8700 Leoben, Austria.
([9]) Institut für Geologie und Paläontologie, Universität Salzburg, Hellbrunnerstr. 34, A-5020 Salzburg, Austria.
([10]) GeoForschungsZentrum, Telegrafenberg AB-3, D-14473 Potsdam, Germany.

1. - FOREWORD

The Italian CROP 1-1A Project (CROsta Profonda stands for Deep Crust), financed by CNR, ENEL and AGIP S.p.A., was launched in 1991, as documented by the reports of Workshops held in Bologna (22.04.1991) and Pietrasanta, Lucca, (04.06.1993) in order to draw up a scientific program (CAPOZZI & CASTELLARIN, 1992, 1994). The activity had to be suspended in the period 1996-1997 due to a severe shortage of funds. Thanks for the most part to the financial input from AGIP, and to the scientific collaboration between the Italian CNR and their Austrian and German colleagues conducting similar projects in the Eastern Alps, reflection seismic acquisition was able to resume on the CROP 1 Profile in 1998, although only for its northernmost Alpine sector (1A). The CROP1-1A Profile corresponds to the southern section (in Italy) of the Central European Profile (CEP), scheduled for lithospheric seismic exploration by the following geophysical-geological institutions: DEKORP (Germany), OEKORP (Austria) and CROP (Italy). Their joint program, based mostly on seismic reflection acquisition along the profile from the Bavarian foreland (München) to the Adriatic Venetian Plain (Treviso), was brought under the TRANSALP Project in 1998; the seismic acquisition part of this Project has now been completed, along with most of the data processing. The joint work modified substantially the original CROP 1 program, due to its change from a national to a European scientific research project, conducted by Austrian, German and Italian geoscientists.

The seismic profile was acquired during 1998, by the contractor THOR in Bavaria, and by the contractor GEOITALIA in the southernmost Venetian sector (from Conegliano to Peron, a village north of Belluno). The Profile was completed in 1999 by the contractor THOR.

The project has a number of targets. The seismic studies of the crustal and lithospheric setting of the Eastern Alps ended in the late seventies with the interesting results of the DSS refraction seismic traverses obtained by the Italian and Helvetic Explosion Group. These results consist of some basic reconstructions of crustal overlapping beneath the Dolomites, where the "European" Moho was identified under the Adriatic lithosphere, incorporating nearly 50 km of crust. A reinterpretation of these data subsequently proposed that the Adriatic lithosphere was thrust over the subducting European plate and under the Northern Alpine chain, along the Insubric Line (or "peri-Adriatic Lineament" according to other Authors) which was interpreted as a high-angle reverse fault (FANTONI *et alii*, 1993). The revised DSS for the entire Southern Alps are compatible with these interpretations but evidenced several irregularities in the distribution of the crustal masses and of the Adriatic Moho interface (SCARASCIA & CASSINIS, 1997). In accordance with ARGAND's (1924) structural and geometric interpretation of the Alps, huge wedges of the Adriatic lithosphere have been really recognized as large-scale indenters over the European subducting lithosphere and beneath the Northern Alpine units, along the Insubric Line of the Central and Western Alps (the Swiss NFP20 profile and the French-Italian ECORS-CROP profile) (ROURE *et alii*, 1990a, 1996; PFIFFNER *et alii*, 1997). The structural setting of the Eastern Alps, however, is different from that of the Central and Western Alps, especially in the south where the external Montello-Friuli compressional belt has no equivalent in the west. This frontal unit was severely deformed and shortened during the Adria- Po Plain compressional events (Messinian - Pliocene) (CASTELLARIN *et alii*, 1998b; CASTELLARIN & CANTELLI, 2000) which mostly affected the Apennine frontal zones.

2. - SEISMIC DATA ACQUISITION AND PROCESSING

The data acquisition campaign for the 340-km line between Munich and Venice (fig. 1) was divided into three phases: the northern 120 km were collected in autumn 1998, the southern 50 km in winter 1998/1999, and the central 170 km in autumn 1999. Combined vibrator-explosive sources were selected after the success of the NFP20-Swiss Profile in the Central Alps , where this mixed-source strategy proved to be effective both as regards deep lithospheric penetration and good crustal resolution.

The basic parameters include an average of 130-fold Vibroseis measurements, combined with 2-fold recordings of explosive sources, with a shot-point spacing of about 5 km (charges of 90 kg in 30-m boreholes, at least three per shot point). Four heavy vibrators (total peak force of up to 872 kN) were used in split-spread configuration of 360 receiver channels with a geophone spacing of 50 m (spread length of 18 km). Source spacing of 100 m resulted in a common-midpoint coverage of approximately 90 fold. A sweep signal of 28 s length and a frequency range of 10-48 Hz, eight-fold vertically stacked, were used to provide a 20 s record length after Vibroseis correlation.

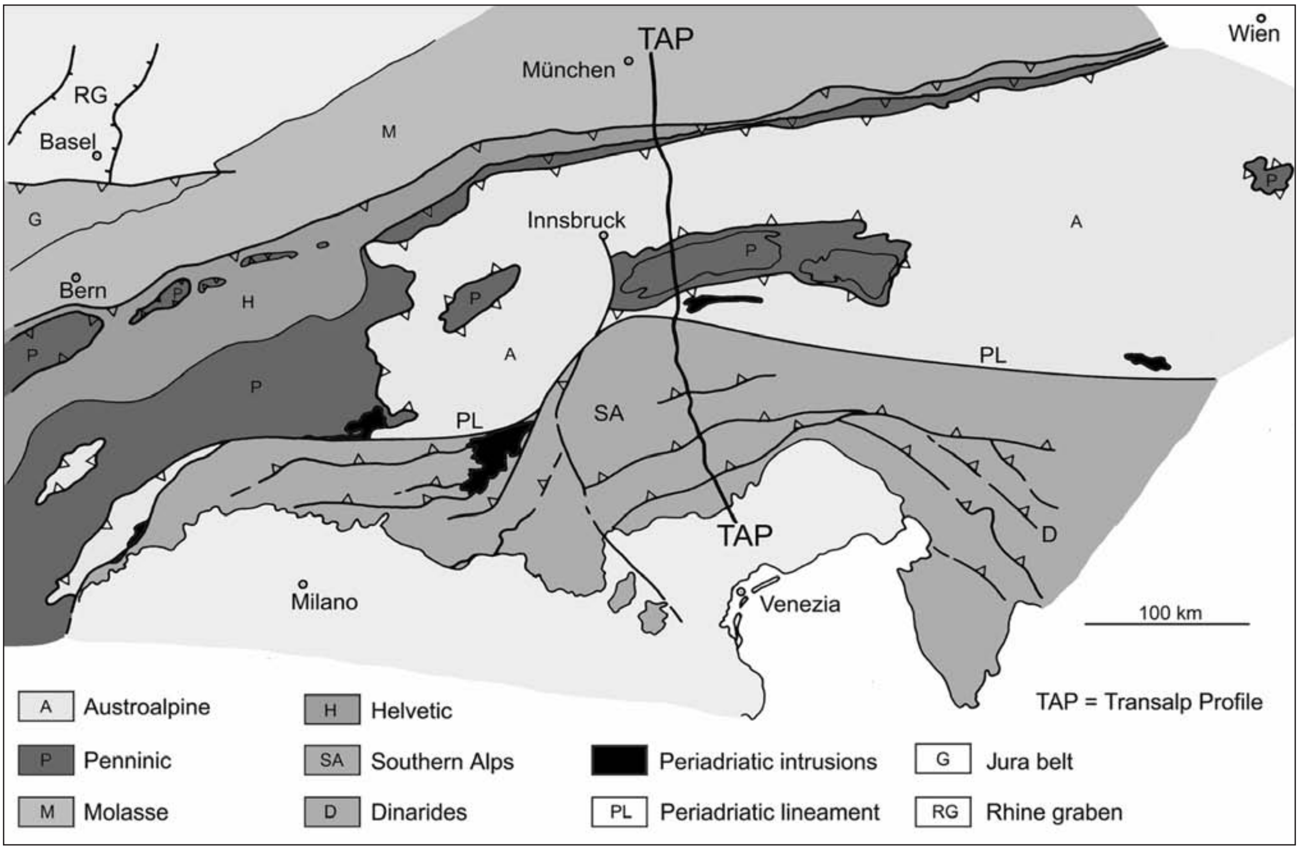

Fig. 1 – Simplified structure of the Alps (modified from CNR, 1990-1992, Sheet N.5) and location of the TRANSALP seismic profile (TAP).
– *Struttura delle Alpi (semplificata da CNR, 1990-1992, Foglio N.5) e localizzazione del profilo TRANSALP (TAP).*

While recording the main vibrator-explosive profile, some cross-lines were also recorded, listening to explosive shots and the vibrations along the main line, to ensure three-dimensional control at selected locations (7 cross-lines of about 20 km each). A widespread three-component stationary network passively recorded all seismic sources in wide-angle configuration for velocity control. Another network recorded local and global earthquakes continuously over more than nine months for lithospheric tomography and earthquake studies.

The northern 290 km of the transect were acquired by THOR with an ARAM24-system, using a second ARAM24-system during undershooting of the main Alpine crest. While rolling along the main N-S-line, the two systems also recorded the cross-lines Q3, Q4, and Q6 in stationary 400-channel configuration. The cross-line Q1 was recorded by the contractor DMT in 1998, Q2 (twice in 1998 and 1999) and Q6 by the contractor JOANNEUM Research in 1999, both using 200-channel SUMMIT-2 systems, and Q4 and Q6 by OGS and THOR.

On the southern part of the main north-south line (from Conegliano to Perom), GEOITALIA used four vibrators and a SERCEL 368 system to record a 360 active channel spread for the main line. The nominal group spacing was 50 m. While rolling along the main profile, the SERCEL 368 system was used to record the 220 channel fixed-spread cross-line (Q7). The cross-lines recorded all Vibrator and explosive shot/vibro points of the main line within certain offset ranges, as well as repeated off-end shots on the cross-lines.

The teams working in the field for the contractor companies and universities coordinated the various sub-projects, solved the problems posed by having to work over extremely difficult terrain under winter conditions, and the bureaucratic difficulties of crossing three national borders, as well as handling more than 1100 recording channels distributed over the main line, on cross-lines and, temporarily, on both sides of the main Alpine crest. The subcontractor GEOTEC, which also obtained the necessary permits for the Italian parts of the Project , drilled into the hard crystalline rocks in Austria and Italy, in 1999. Most of the main recording line had to be deployed in densely populated and noise-contaminated valleys, such as the "Ziller" valley in Austria and the 'Aurina' valley in Italy, in extremely adverse conditions. Difficulties with permits meant that many of the nominally 5-km spaced 90-kg shot-points had to be shifted by several kilometres and divided into several shots with smaller charges. Nevertheless, the whole line was continuous except for a 2-km gap crossing the 'Inn' valley in Austria and a 6-km gap at the main Alpine crest between Austria and Italy, which were subsequently completed by undershooting.

The data acquired along the main profile have been processed with a time-processing flow that was designed in such a way as to improve at the best S/N ratio on Vibroseis records. The processing basically followed the common-midpoint (CMP) stacking scheme and post-stack depth and time migration normally used in oil and gas exploration. Processing was performed at the AGIP data processing centre in Milano and at the universities of München and Leoben, using different hardware and software platforms (DISCO/FOCUS at München, PROMAX at Leoben and München, WESTERN- OMEGA at ENI-AGIP Milano) and different approaches.

It was however universally agreed that the major objectives in the data processing were to create one consistent data set from the three different campaigns, transforming all the coordinates into one uniform system (UTM-WGS84), and to propose an appropriate solution for the static corrections computation problem. AGIP and the München/Leoben universities developed a number of different solutions.

During pre-processing (geometry implementation, spherical divergence correction, amplitude scaling, editing, muting, deconvolution, band-pass-filtering, etc.), München/Leoben discovered that static corrections (to a datum level of 500 m a. s. l.) were of crucial importance. A combination of elevation statics, velocity statics based on a tomographic inversion of the first arrivals, and subsequent residual statics, proved to be very effective in achieving stacking enhancement. Stacking velocity analysis was done continuously along the entire line using constant-velocity stacking analysis. As a standard, conventional stacking and post-stack time- and depth migration (based on the Kirchhoff technique), with subsequent coherence enhancement for plotting purposes, were applied consistently along the whole line. Alternative methods, such as Dip-Move-Out (DMO) and pre-stack Depth Migration, were also applied on selected parts of the line, i.e. the northern 120 km and the central 50 km close to the Insubric Line. However, the conventional techniques proved to be the most robust. The velocity model required for depth migration was obtained by analysis of the stacking velocities in the layered structure of the Molasse areas and by tomographic inversion of the first arrivals in the Alpine areas (including the first arrival recordings on the passive networks). For the deeper parts a macro-velocity model from older deep seismic refraction measurements (MILLER *et alii*, 1977; ITALIAN EXPLOSIVE SEISMIC GROUP *et alii*, 1981) was used.

AGIP's analysts took particular care in the re-computation of static through the first break picking of all VP records and in the construction of a single-layer surface-velocity model derived from the analysis of the first refractor velocities. A hybrid EGRM algorithm was utilised for computation of delay-times. Velocities were estimated using a reciprocal analysis approach. The computed surface-velocity model fits reasonably well with the interval velocities of the outcropping geological formations along the main profile. For this reason sea level was used as datum plane and a variable replacement velocity was applied in order to smoothout the refractor velocity, for re-computation of the primary static corrections. This approach permitted us to solve the long-wave component of the statics correction and to improve the results significantly applying these new refraction statics to the data. The pre-stack flow included, after geometry assignment and QC, the editing of the bad traces, the first break picking for re-computation of statics corrections, T.V. filter, F-K filter, gap deconvolution before stack, pre-stack TV array simulation, pre-stack random noise attenuation, three iterations of residual statics, preliminary velocity analysis, final velocity analysis and 9000% stack and post-stack coherency enhancement routines. The final stack was time-migrated using the Omega-X algorithm, utilising a velocity field obtained from the stacking velocity field after appropriate smoothing and scaling.

The explosive seismic data were handled separately and were processed at the München University. The aim was mainly to image the lower crust, including the crust-mantle boundary ('Moho' discontinuity). From the low-fold data, only the good quality seismic traces were selected to form a single-fold section, which was then depth-migrated. An image of the Moho was also provided by receiver functions obtained from P- to-S-wave conversions of teleseismic events.

The cross-line data were processed in a conventional way, using CMP techniques, in order to provide alternative N-S and E-W sections. The data of lines Q3 and Q4 provided particularly valuable information on seismic anisotropy (approx. 10 % magnitude), which is consistent with the predominant E-W preferred orientation of the texture of the metamorphic rocks of the Tauern Window. The data of the cross-lines are also input to three-dimensional pre-stack migration techniques.

The data of the stationary, three-component network, the one which recorded all Vibrator and explosive sources of the main line, were collected to provide wide-angle common-station gathers. Then the arrivals were picked and input to refraction and reflection tomographic inversion schemes. Arrivals were detectable up to about 80 km offset and provided information models to about 15 km depth (doctorate thesis of F. Bleibinhaus, University of München). The data of the long-term (9 months in 1998/99, 2 months in 1999) recording network were handled at the GFZ Potsdam and at the ETH Zurich for lithospheric velocity modelling using teleseismic events. Local earthquakes were selected from this network and analysed at the University of München. Epicenter maps show that most of them are concentrated in the Inn Valley in Austria and South of the Agordo-Valsugana thrust zone, thus confirming previous focal maps. Most of the Inn Valley earthquakes were analysed for their focal mechanism and showed quite a mixed character, from normal-fault to thrust and strike-slip types.

3. - GEOLOGICAL FRAMEWORK

The geological interpretation of the Transalp seismic reflection profile is an important scientific opportunity to assemble major geological informations on all of the Eastern Alps from the Bavarian Foreland in the north to the Venetian Plain of the Montello foothill zone in the south (fig. 1).

3.1. - The Southern Alps

The Eastern Southern Alps correspond to the structural belt located south of the eastern side of the Insubric Line (Pustertal and Gailtal Lines) (figs. 2, 3). This belt is affected by intense back-thrusting, which forms the orogenic structure of the Alps verging southwards (Africa-verging belt) and faces the tectonic polarity of the Northern Alpine chain verging northwards (Europa-verging orogenic chain), located north of the Insubric Line. The Southern Alps are still in structural continuity with the northern border of the Adria microplate, which is considered a domain of the Alpine belts belonging to the African Promontory (D'Argenio *et alii*, 1980; Channell *et alii*, 1979; Vai, 1994). The African Promontory was incorporated in the NE border of Africa during the Late Precambrian, mostly as a consequence of the Pan-African or Cadomian orogenic events that occurred from 750 to 550 Ma BP, deformations that also affected rock systems of older age (Khain, 1977). These basement rocks underwent the subsequent tectonic evolution. The "porphyroid thermal event", also known as the "Caledonian" event, that took place in the Ordovician is not yet clearly understood and may correspond to an early extensional episode of the continental rifting that pre-dates the Hercynian orogenic events (Vai, 1991). The Hercynian or Variscan orogenic evolution is easily identified and well documented both in the non-metamorphic Palaeozoic (Carnic Alps) and in the metamorphic basement rocks of the Southern Alps (Selli, 1963; Vai & Cocozza, 1986; Zanferrari & Poli, 1992). These basement rocks include huge magmatic intrusions, sometimes pre-dating and mostly post-dating the Hercynian orogenic events, such as the acidic intrusion of Ordovician age (446 ± 18 Ma) (Assunta well: AGIP, 1977; Pieri & Groppi, 1981) and the widespread granodioritic intrusions (Brixen, Cima d'Asta, etc.), which are mostly located along the Insubric Line, pene-contemporaneous to the early Permian ignimbritic plateau of the Bolzano-Trento Provinces (CNR, 1990-1992, Sheet N.1).

An early continental rifting evolution is documented by the extensional tectonics and major magmatic activities that occurred during the Lower Permian and Middle Triassic (Dal Piaz, 1993; Selli, 1998; Castellarin *et alii*, 1998a), whereas the later Norian-Liassic rifting evolution is well documented by the strong extensional tectonics controlling the carbonate platform-basin systems throughout the Southern Alps (Bernoulli, 1964; Bosellini, 1973; Bertotti *et alii*, 1993). The drifting evolution, related to the spreading centre of the Tethys, is consistent with the progressive drowning of the southern continental margin, as documented by the transgressive mega-sequence of successions from the Mid Jurassic (about 157 Ma) to the late Early Cretaceous (about 115 Ma) (Winterer & Bosellini, 1981), which are the distant equivalent of the Ligurian sequence capping the Tethyan oceanic basement (Steinman, 1927).

At the end of the Early Cretaceous a fundamental change occurred in the kinematics of the plates, which modified their motion, and began a process of continental convergence (see, e.g., Cow-

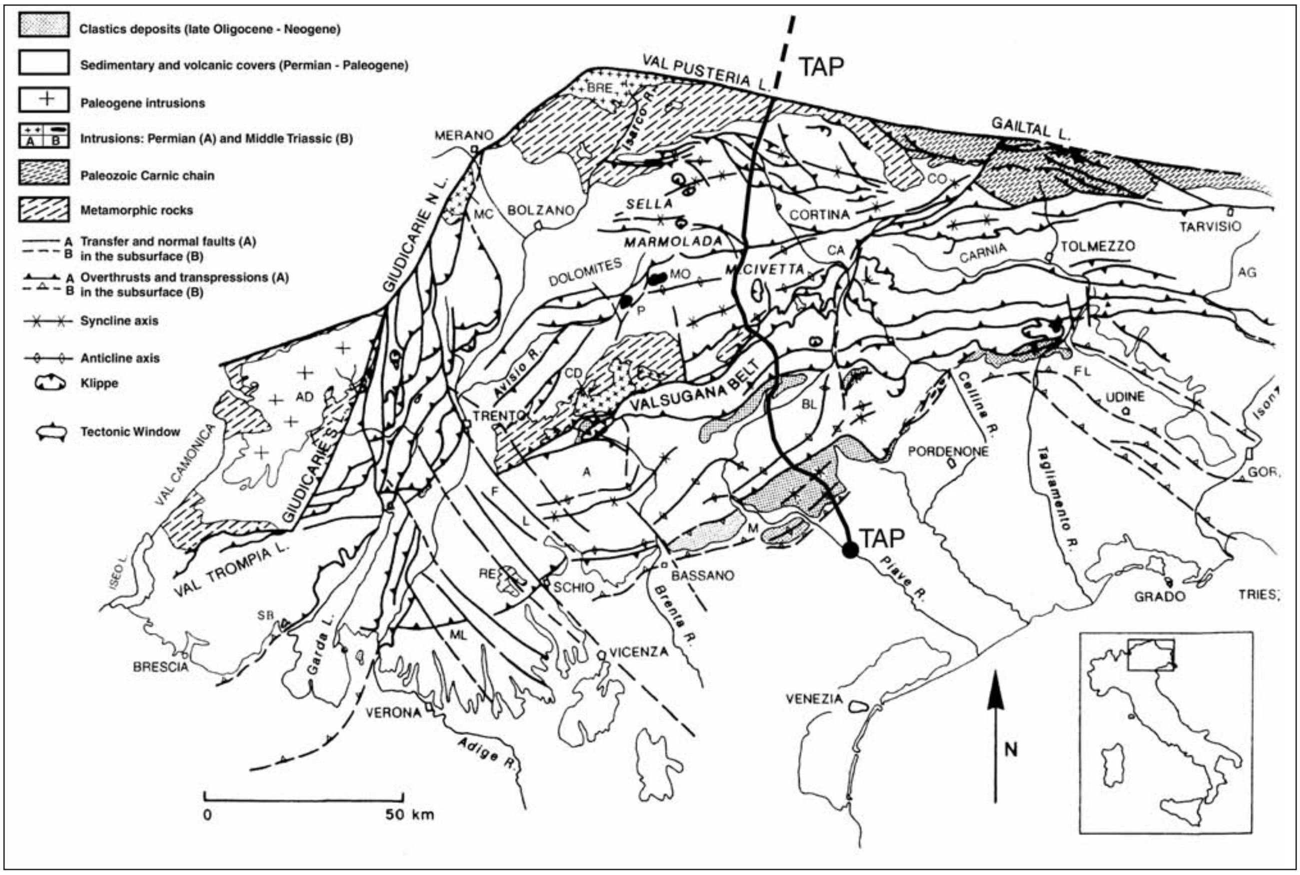

Fig. 2 – Synthetic structural map of the Eastern Southern Alps (from CASTELLARIN *et alii*, 1998b, simplified from CNR, 1990-1992, Sheet N. 1 and 2). Abbreviations: AG, Alpi Giulie; FL, Friuli; CA, Cadore; CO, Comelico; MO, Monzoni; P, Predazzo; BL, Belluno; M, Montello; RE, Recoaro; ML, Monti Lessini; F, Folgaria; L, Lavarone; A, Asiago zone; SB, S. Bartolomeo hill (Salò, Lake Garda); MC, Monte Croce; BRE, Bressanone, Ivigna; CD, Cima d'Asta; AD, Adamello; Orobie, Grigna and Presolana (Bergano Province, Lombardia) see PA (Pre Adamello Belt) in figure 3. TAP, Transalp profile (Italian sector).

– Carta tettonica sintetica delle Alpi Meridionali (da CASTELLARIN et alii., 1998b, semplificato da CNR, 1990-1992, Fogli N. 1 e 2). Lettere e sigle come nel testo inglese.

ARD & DIETRICH., 1989; ROURE *et alii*, 1990a; DAL PIAZ, 1995). The gradual convergence of the Alps included the Upper Cretaceous pre-collisional (eo-Alpine), the Eocene collisional (meso-Alpine) and the Paleogene-Neogene post-collisional (neo-Alpine) compressional events (TRÜMPY, 1973). The pre-collisional-collisional events have left no structural evidence in the Venetian Southern Alps. They are indicated only by the drastic change in marine sedimentation in the Upper Cretaceous, with strong siliciclastic input in the basinal areas close to the uplifted orogenic chain, such as the thick successions of Flysch deposits in the Judicaria zone (Insubric Flysch), in the Dolomites (Ra Stua and Antruille), Carnian (Val di Resia), and Julian Alps (Slovenia) (CASTELLARIN, 1977).

The Lower Eocene siliciclastic Flysch from the Friuli to the Belluno zones is mostly a distant marker of the meso-Alpine compressional event affecting the external Dinaric orogenic domain rather than the Eastern Alps (CNR, 1990-1992, Sheets No.1, 2). Nevertheless, intense Eocene tectonic deformations related to these compressional events affected the Carnic Alps and the eastern sector of the Dolomites (DOGLIONI & BOSELLINI, 1988; CARULLI *et alii*, 1982), which were generally rearranged by the subsequent Chattian-Burdigalian, nearly coaxial, compressions (figs. 3, 4) (see later).

The continental collision and the oceanic subduction end were followed by a rapid increase in temperature during the Paleogene under the orogenic eo- to meso-Alpine chain and extensional uplifting. Magmatic processes led to the emplacement of large acidic intrusive bodies (mainly granodiorities and tonalites) along the Insubric border of the Alps (Bergell, Adamello, Riesenferner-intrusive masses and minor bodies of other localities) (DAL PIAZ, 1986; LAUBSCHER, 1986; CNR, 1990-1992). In the sector affected by maximum stretching in the back-foreland lithosphere, towards the south, widespread alkaline basalt lava flows were erupted, to-

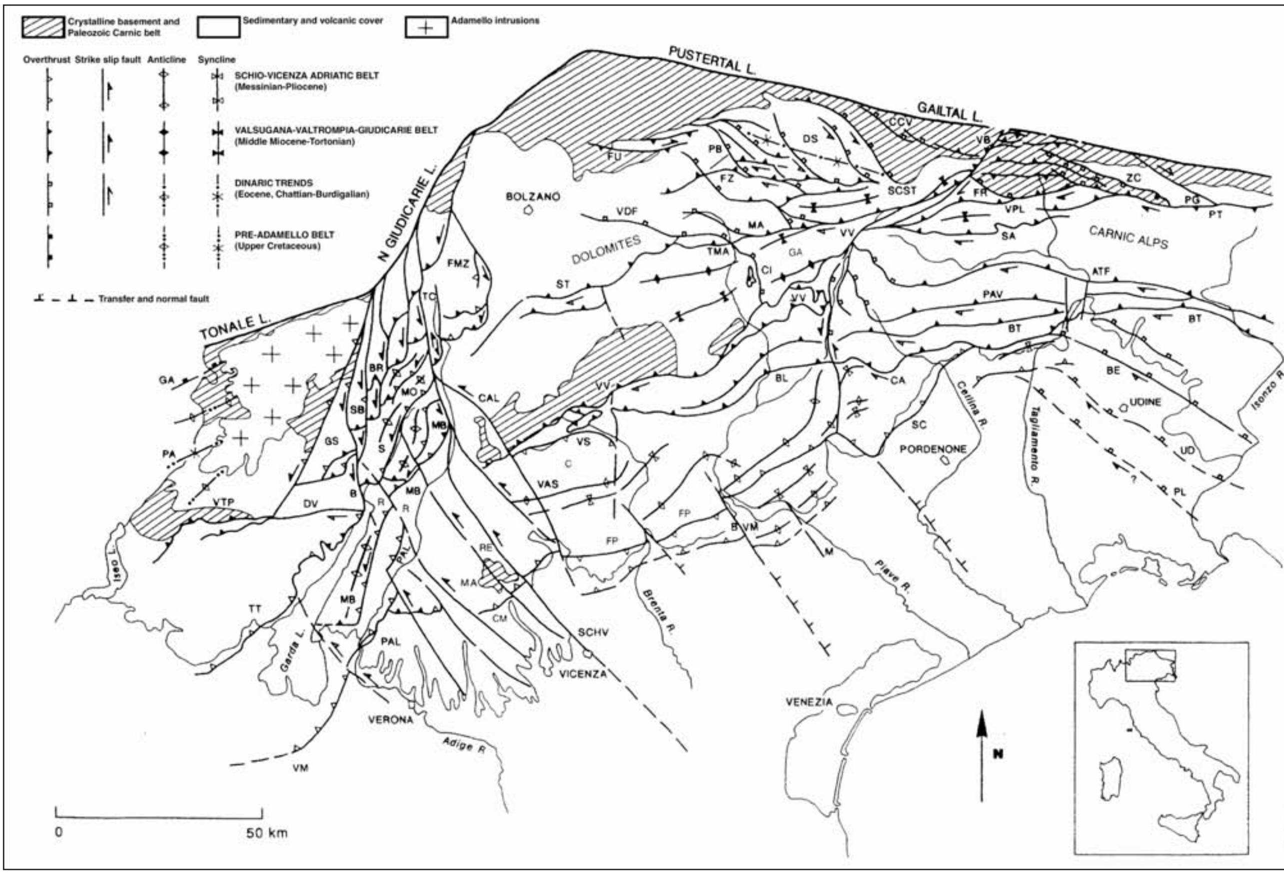

Fig. 3 – Structural interpretation of the Eastern Southern Alps (modified from CASTELLARIN *et alii*, 1998b). Abbreviations: L, tectonic line, lineament overthrusting, transfer faults. S: local structural system. B: structural belt. Palmanova L. (PL); Udine L. (UD); Bernadia L. (BE); Sacile L. (SC); Bassano-Valdobbiadene-Montello L. (BVM); Caneva L. (CA); Pinedo-Avasinis L. (PAV); Barcis-Taro Selo L. (BT); Alto Tagliamento L.-Fella L. (ATF); Sauris L. (SA); Val Pesarina-Lozzo L. (VPL); Pontebba-Tarvisio L. (PT); Poludnig L. (PG); M. Zermula-M. Cavallo L. (ZC); Forni Avoltri-Ravascletto L. (FR); Croce di Comelico-Val Visdende L. (CCV); S. Candido-S. Stefano di Cadore L. (SCST); Val Bordaglia L. (VB); Dolomiti di Sesto S. (DS); Funes L. (FU); Falzarego L. (FZ); M. Parei-Col Becchei-Fanes S. (PB); Stava-Collaccio L. (ST); Marmolada-Antelao L. (MA); "Giunzione Cadorina" (GA); Valsugana S. (VV); Val di Sella L. (VS); Colombarone klippe (C); Belluno L. (BL); Civetta L. (CI); Duron-Fedaia L. (VDF); Foiana-Mezzocorona S. (FMZ); Trento-Cles L. (TC); Calisio L. (CAL); Val d'Astico L. (VAS); Schio-Vicenza L. (SCHV); Castel Malera klippe (MA); Rovereto-Riva-Arco transfer zone (R); Recoaro zone (RE); Cima Marana L. (CM); "Flessura Pedemontana" (FP); M. Pastelllo-Ala L. (PAL); Volta Mantovana L. (VM); Doss del Vento L. (DV); Tremosine-Tignale-Costa L. (TT); Giudicarie S. L. (GS); Val Trompia L. (VTP); Brenta Group S. (BR); Ballino L. (B); M. Baldo-M. Stivo-M. Bondone L. (MB); Sarca-Paganella L. (S); Molveno L. (MO); Pre Adamello B. (PA); Gallinera L. (GA).

– Interpretazione strutturale delle Alpi meridionali orientali (modificata da CASTELLARIN *et alii, 1998b). Denominazione delle strutture, lettere e sigle come nel testo inglese.*

gether with co-magmatic subvolcanic bodies (Lessini Mts and the Euganei Hills) (BARBIERI & ZAMPIERI, 1992; ZAMPIERI, 1995).

3.1.1. - *The Permian – Triassic Magmatic Events*

The post-Hercynian, late Palaeozoic and Mesozoic magmatic and tectonic evolution of the eastern part of the Southern Alps had a strong effect on the later, mainly Tertiary structural inversion. Important examples of this are the extensive Lower Permian magmatic occurrences and the less widespread events of the Mid Triassic, which have largely been superimposed in the Dolomites. These events combined to create a more rigid post-magmatic upper crust in these areas and to reinforce this sector, which was less intensely affected by further upper crustal tectonic deformations (CASTELLARIN & VAI, 1986). Intense structural deformations, on the contrary, occurred in the contiguous sectors towards the east (Cadore, Carnia) where the magmatic bodies are much more restricted, or absent. Furthermore, this more rigid block is, apparently, the part of the Southern Alpine belt that has undergone the most intense tectonic displacement in the Austroalpine structure along the northern Giudicarie fault zone (PROSSER 1998, 2000) (figs. 1, 2).

The Lower Permian magmatism is represented by the volcanic porphyry plateau of Bolzano province (Bozener Porphyrplatte Auct.), which covers an area of more than 2,000 km^2, and by several magma in-

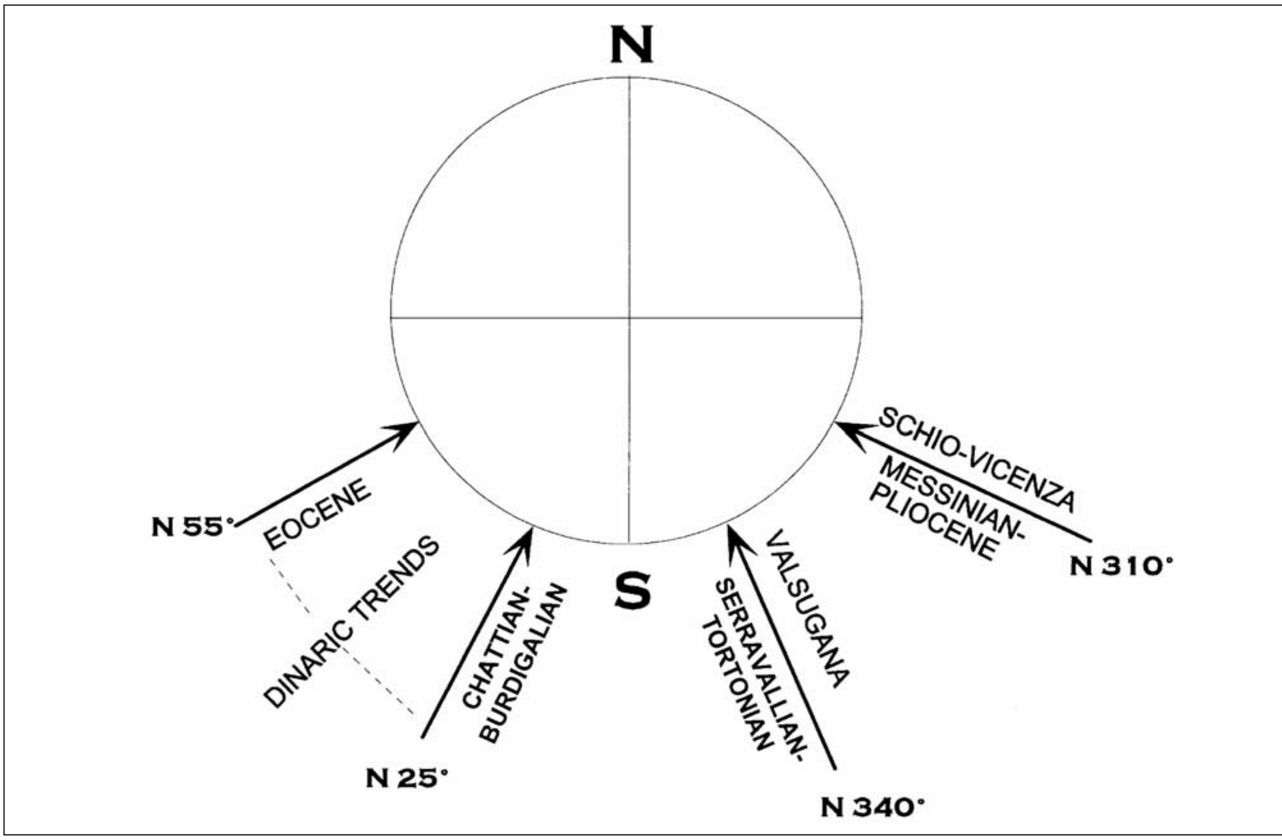

Fig. 4 - Present azimuthal direction of the main paleo-stress (compressional) axes of the eastern Southern Alps polyphase structural system (from Castellarin *et alii*, 1998b).

- Direzione azimutale attale degli assi di massima compressione relativi ai sistemi strutturali polifasici delle Alpi meridionali orientali (da Castellarin *et alii, 1998b).*

trusions (Cima d'Asta, Bressanone-Chiusa, Ivigna and Mt. Croce) (fig. 2, CD, BRE, MC). These magmatic products display typical calc-alkaline evolutive trends with geochemical and isotopic features that are consistent with the interaction of different magmas generated both in the upper mantle and the lowermost crust (Barth *et alii*, 1993). The volcanic sequence is generally formed by the lower andesite-dacite lava flows and lava domes, followed by rhyolitic ignimbrites and pyroclastic flow deposits (D'Amico, 1979). Recent stratigraphic and structural analyses documented that the volcanic activity was controlled by extensional tectonics (Selli *et alii*, 1996), which produced drastic increases in the thickness of the volcanic covers from a few hundred metres to more than 2 km, within short distances. Calderic collapses enhanced the tectonic depressions, which migrated in time as the volcanic activity gradually expanded and enlarged eastwards (Selli, 1998).

The Mid Triassic magmatic products in the Eastern Alps are represented by rhyolites/andesites (Recoaro, Tarvisio) and shoshonitic basalts in the Dolomites where there are also rare shallow intrusive equivalents (Monzoni Mts) with differentiated products (Predazzo) (fig. 2, MO, P). All of these magmatic rocks define calc-alkaline suites that are widespread in several sectors of the Southern Alps (see, e.g., Castellarin *et alii*, 1988). New stratigraphic and structural data (Castellarin *et alii*, 1998a) indicate that the tectonic control over these magmatic activities can be found in extensional crustal conditions, as documented by the syn- and post -magmatic normal faults observed in the Dolomites. The evidence of compressional tectonics (folding, local overthrusts and strike-slip tectonics) that was previously thought to be linked to the Middle Triassic tectonic-magmatic events (Castellarin & Vai, 1982; Castellarin *et alii*, 1988, see also Doglioni, 1984), is now considered to be strong diapiric anticlines of the Upper Permian evaporites that gave rise to large, unstable submarine reliefs, producing huge sliding masses, chaotic assemblages ("agglomerati") and gravity deformations; these diapiric activities were triggered by the Mid Triassic magmatic event coupled with the extensional tectonics (Castellarin *et alii*, 1998a). A number of real compressional structures (wrongly considered Mid Triassic in previous works) can be related to the neo-Alpine compressional evolution.

3.1.2. - *The Structural Systems of the Eastern Southern Alps*

3.1.2.1 – The pre-Adamello Structural Belt

The pre-Adamello structural belt is characterized by south-verging, ENE-WSW trending thrusts with large crystalline basement implications; the superposition of the large fold ramps produced severe deformations and shortening in the Orobic, Presolana and Grigna zones (LAUBSCHER, 1985). This structural system extends eastwards into the Val Camonica as far as the western sector of the Adamello batholith, which clearly post-dates the tectonic deformation of the system (BRACK, 1986). This belt has to be considered eo-Alpine in age (Late Cretaceous) (DOGLIONI & BOSELLINI, 1988; BERSEZIO & FORNACIARI, 1988) and has not been recognized east of the Southern Giudicarie fault (fig. 3, PA, GA).

3.1.2.2. - The Dinaric Structural Trends

The Dinaric structural trends include two structural systems of similar orientation but of different age.

Eocene structural system - The Eocene structural system largely developed in the easternmost sector of the eastern Southern Alps with prominent SW verging, NW-SE trending thrusts, located on the NW continuation of the external Dinaric orogenic chain (figs. 2, 3). These structures are typical of the Alpi Giulie and Friuli. They also severely affected the Carnic Alps and the Cadore, where the Dinaric deformations were drastically rearranged by the subsequent Alpine compressions (mostly by the Valsugana event). The implication of the Palaeozoic and the crystalline basement (Carnia, Comelico) in the internal frontal ramps indicates that these deformations must have expanded towards the SW to involve the Mesozoic and Tertiary covers of the Dolomites, as proposed previously (DOGLIONI & BOSELLINI, 1988; DOGLIONI, 1987). The Eocene age (early Mid Eocene) of the conglomerates that are discordantly superimposed on the latest folded Triassic carbonates in the Tolmezzo zone (Carnia) (CARULLI *et alii*, 1982), together with other stratigraphic and structural data, indicate that this structural system can be related to the meso-Alpine compressional event (Eocene).

Chattian-Burdigalian system - NW-SE (WNW-ESE) verging thrusts are well documented by the syntectonic clastic wedges buried in the Udine plain (PIERI & GROPPI, 1981). Similar stratigraphic constraints in several localities in the east (Friuli, Montello, Belluno) (MASSARI, 1990) and in the Lake Garda zone (LUCIANI, 1989) well document the age of these associations. The best correlations are established with the structural system located in Lombardy that has affected the syntectonic wedges of the Gonfolite clastic sequence (ROURE *et alii*, 1990b); this structural system has also been clearly identified in the pre-Alpine zone between Brescia and Bergamo (PICOTTI *et alii*, 1997). These deformations may be related to the neo-Alpine post-collisional deformations of the compressional Insubric or Helvetic event. During these compressions in the Dolomites, the preceding Eocene thrusts were strongly re-activated and a new frontal system was expanded towards the SW as far as the central Dolomites (fig. 3). According to CAPUTO (1996), the two Dinaric associations in the eastern Dolomites can be distinguished by the differences in their axial trend. The earlier system (Eocene) is probably connected to NE-SW compressions, whereas NNE-SSE compressions are proposed for the later system.

3.1.2.3. - The Valsugana Structural System

The Valsugana structural system has developed widely throughout the southern Alpine domain and displays a morpho-structural prominence in the eastern part of the belt (figs. 2, 3, VV). The structural system is characterized by SSE (S) verging and ENE-WSW (E-W) trending thrusts that are particularly intense in the Valsugana zone where the crystalline basement rocks are largely involved in the frontal ramp, overthrusting a still preserved syntectonic deformed post-Langhian clastic wedge, mostly made up of sequences of Serravallian and Tortonian age (CASTELLARIN *et alii*, 1992; SELLI, 1998). The intense activity of this compressional event is documented both by stratigraphic-structural data and by fission track studies, which indicate an uplifting in the hanging wall of the Valsugana overthrust of approximately 4 km between 12 and 8 Ma B.P. (DUNKL *et alii*, 1996). Detailed macro- and meso-structural analysis indicates that the paleo-stress field is homogeneously NNW-SSE (N-S) oriented throughout the belt, with an average value of N 340° (fig. 4) (CASTELLARIN *et alii*, 1992; CANTELLI & CASTELLARIN, 1994; PROSSER & Selli, 1992; PICOTTI *et alii*, 1995, 1997; SELLI, 1998). In the sector of the Giudicarie (including Lake Garda and the

Adige River to the east) (figs. 2, 3), the system is dominated by several very long NNE-SSW (NE-SW) sinistral lateral ramps that join short and generally narrow ENE-WSW (E-W) trending fold ramps (PICOTTI *et alii*, 1995). The Giudicarie belt of deformations (of the Valsugana structural system) is connected to the Valsugana overthrust in the east by the NNW-SSE (N-S) trending Trento-Cles and Calisio-Val d'Astico transfer fault (fig. 3, TC, CAL, VAS) (SELLI, 1998). The Giudicarie system underwent further deformations as a result of late WNW (NW) compressions that have been interpreted differently (compare CASTELLARIN *et alii*, 1998b with CASTELLARIN *et alii*, 1992).

The Valsugana structural system spread widely eastwards with strong overthrusts of the Belluno Dolomites (fig. 3, VV), with their intense Carnic continuations (fig. 3, SA, ATF). In the northern zone of the Piave River, the Dinaric NW-SE trending thrusts are cut by the younger ENE-WSW trending Valsugana main tectonic elements to form a typical structural crossing zone, previously indicated as the Cadore junction ("Giunzione Cadorina") (LARGAIOLLI & SEMENZA, 1966, fig. 2, GA). Good images of the Valsugana structural system are visible in the Vibroseismic section (Plates 68, 70), north of Belluno and at Agordo (the Belluno and Valsugana low-middle angle overthrusts within the upper crustal zone up to 10-15 km in depth).

3.1.2.4. - The Bassano-Montello-Friuli Structural Belt

The Bassano-Montello (M)-Friuli (FL) structural belt (fig. 2) is located east of the Schio-Vicenza (SCHV) and Val d'Astico (VAS) transfer faults (fig. 3) and includes a wide belt from the Belluno (BL) depression ("Vallone Bellunese") (fig. 2) in the north to the border of the Venetian Plain (the "foothill flexure" by BARBIERI, 1987, FP of fig. 3) in the south. The belt is dominated by prominent NE-SW trending, SE verging folds and thrust associations that deform and partly override the thick syntectonic clastic successions of the foothill (fig. 2). This syntectonic wedge is made up of prevailing clastic deposits with conglomerates of Late Tortonian and mostly Messinian age of more than 2 km in thickness (Montello-Friuli), which are locally capped by deformed Pliocene clays (at Cornuda, Montello M, fig. 2; MASSARI *et alii*, 1986). The paleo-stress directions obtained from the meso-structural analysis (CANTELLI & CASTELLARIN, 1994) are oriented NW-SE with the prevailing value between N 300° and N 330° (CASTELLARIN & CANTELLI, 2000). The ages of the accretions and deformations of this structural belt can be easily identified from the syntectonic clastic sequences and ascribed mainly to the Messinian-Pliocene up to the Pleistocene. In the seismic section the low-to middle-angle north dipping overthrust of the Flessura Pedemontana-Passo di S. Boldo ramp anticline on the Montello clastic wedge is clearly visible down to a depth of 10-12 km (Plates 68, 70). Despite its different structural origin and opposite polarity this Alpine structural belt is an accretion-time equivalent of the frontal Apennines, buried beneath the Po Plain and Adriatic Sea. These structures can be related to the late post-collisional neo-Alpine evolution of the Adriatic-Po Plain compressional events. In the east (Friuli and Carnia), there were strong re-activations of the previous structures, mostly in the frontal zones (VENTURINI, 1990; see also ZANFERRARI *et alii*, 1982). The eastern Dolomites were affected by a conjugate system of strike -slip faults during this deformational interval (CAPUTO, 1996).The large overthrusts of the Valsugana are also involved in the re-activation of the Adriatic compressions, as documented by the Val di Sella back-thrust (fig. 3, VS). This structure disconnected the in-sequence propagation of the thin-skinned frontal zone of the Valsugana system (M. Colombarone klippe, fig. 3 C; BARBIERI & ZAMPIERI, 1992), at present uplifted about 2 km in the hanging wall of the Val di Sella back-thrust (SELLI, 1998) (fig. 3, VAS). The effects of the Adriatic compressions were also transferred to the contiguous western sector, south-west and west of the Schio-Vicenza and Val d'Astico transfer faults (CASTELLARIN & CANTELLI, 2000).

The northward inflection of the Adriatic lithosphere connected to the foredeep sedimentary evolution of the Venetian area (Montello-Friuli), with a Neogene clastic wedge up to 4-5 km in thickness (MASSARI *et alii*, 1986), can also contribute to our understanding of the mechanical behaviour of the Adria microplate at the southern edge of the seismic Profile, where the seismic acquisition ends.

3.1.2.5. - Late Southern Alpine Structural Events and Regional Kinematics

In the Carnia and Friuli zones, the tectonic activity that produced the present seismicity has been attributed to N-S compressions, as recognized from its focal mechanisms (aftershocks of the 1976 Friuli earthquake: SLEJKO *et alii*, 1987; see also ANDERSON & JACKSON, 1987 and CARULLI *et alii*, 1990). However, in the zone between the Cellina and Tagliamento Rivers (fig. 3), across the hills and at the border of the Plain, prominent E-W folds (enclosing the thick Messinian conglomerates) have developed extensively and also affect the subsurface of the Plain of the Tagliamento river (AMATO *et alii*, 1976). In this area the N-S compressions are also documented by unpublished local meso-structural studies. This structural setting could have originated from particular mechanical conditions in the area, such as anomalous crustal block movements. Moreover, alternations of N-S and NW-SE trending compressions cannot be excluded during the Late Pliocene-Pleistocene in this area; the N-S compressions mostly affected the Friulian foothill zone of the Tagliamento river (VENTURINI, personal communication). So far they have not been observed in the Carnic Alps (VENTURINI, 1990) nor in the eastern Dolomites (CAPUTO, 1996). The extensional tectonics are well represented in the eastern Southern Alps, generally by minor structural systems of normal faults that post-date the compressional events and originated during the uplifting of the orogenic chain. Several main normal-to-listric faults correspond to Mesozoic structures, mostly of the previous Norian-Liassic continental rifting, which were not (or only partly) inverted during the compressional evolution.

As to the regional framework of the neo-Alpine compressional tectonics, the detailed studies carried out on the magnetic evolution of the Central Atlantic indicate that the post-collisional convergence between the African and European plates, referred to the eastern Southern Alps longitudes, is of the order of 150-200 km in the last 26 Ma (MAZZOLI & HELMAN, 1994): the movement of the African plate northwards (referred to Iblei, Sicily) occurred in the following kinematic conditions: displacement to the NE between 26 and 16. 22 Ma (Chattian-Burdigalian); towards the NNW between 16.22 and 7.9 Ma (Burdigalian-Tortonian) and towards the WNW from 7.9 Ma onwards. These kinematic conditions and their chronological development are coherent with the compressional evolution of the three superimposed thrust systems recognized in the polyphase structure of the Eastern Southern Alps (figs. 3, 4).

3.2. - THE INSUBRIC LINE AND THE NORTH ALPINE OROGENE

3.2.1. - *The Insubric Line (IL)*

The Insubric Line (IL) in the Pustertal and Gailtal zones is a very strong tectonic separation between the south verging thrust belt of the Southern Alps, unaffected by Alpine metamorphism (Africa-verging orogenic chain) and the metamorphic nappe building of the Alps characterised by strong tectonic polarity towards the north (Europa-verging orogenic chain) (DAL PIAZ, 1934, 1942; LAUBSCHER, 1974, 1986; ROEDER & BÖGEL, 1978; LAMMERER & WEGER, 1998).

The IL is a very sharp structural divide of the two facing sectors of the Alps. Their lack of a N-S continuity is also enhanced by the significant E-W dextral strike-slip displacement affecting the IL (LAUBSCHER, 1974, 1986; SCHMID *et alii*, 1989) and other sub-parallel strike-slip minor faults. Although the sub-vertical setting prevails on the surface, both N and S high-middle angle dips can be assumed at depth (see below).

The following structural units are present across the Transalp profile trace, north of the Insubric Line (CNR, 1990-1992, Sheet N.1) (figs. 1, 5).

3.2.2. - *The Tauern Window (TW)*

Framed by Austro-Alpine crystalline nappe units, the Tauern window is exposed in the central Eastern Alps between the Brenner and Katschberg passes to the west and east, and by the Salzach and Aurina valleys to the north and south (figs. 1, 5). Two major complexes form the window: the deepest exposed parts belong to the European basement, which is topped by a thin sheet of cover rocks. These are overthrust by nappes of oceanic lithosphere and metasediments, which are strikingly similar to the North Penninic Bündnerschiefer in the Engadine window.

The basal part of the Tauern window shows Germanic and Helvetic affinities in the sedimentary record similar to the external massifs of the Western Alps. On the other hand, it is ductilely deformed and covered by oceanic nappes, like the Penninic zones of Switzerland. The Helvetic paleo geographic affinities on the one hand, together with the Penninic style of deformation on the other, have frequently caused confusion with regard to the position of the Tauern window within the Alpine edifice (North Penninic, Briançonnais or Helvetic), which seems absurd considering its unique situation.

Precambrian to Lower Paleozoic paragneisses, graphitic schists and metabasites (mainly amphibolites) are the oldest rocks of the Tauern window. Ultramafics, such as antigorite-serpentinites, are less frequent and marbles are found only occasionally. The whole complex is considered as a volcano-sedimentary rock suite of oceanic, cordilleran or island arc provenance (FRISCH & NEUBAUER, 1989). In part, it resembles a metamorphosed olistostrome or a coloured melange. The serpentinites, at least in part,

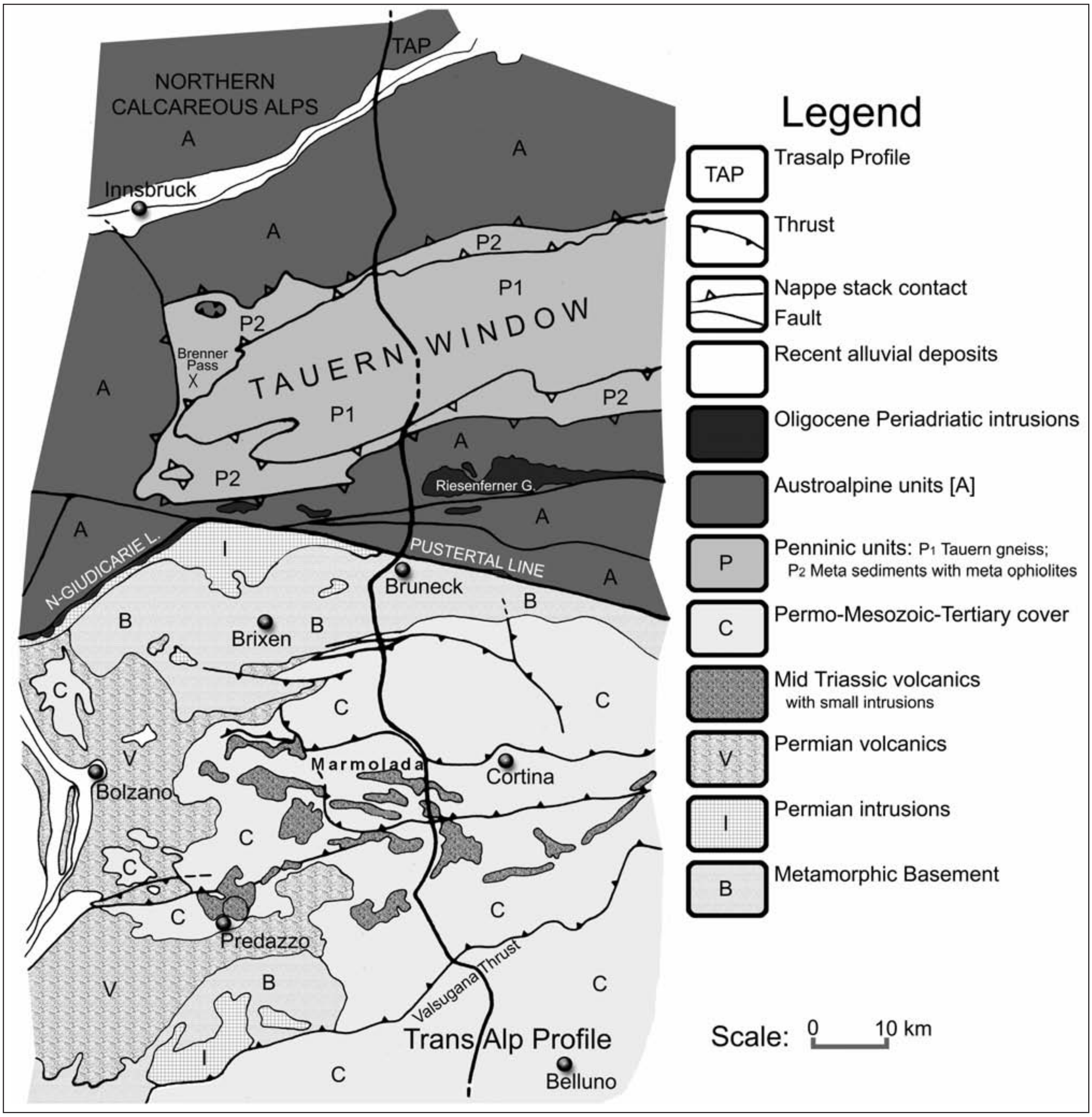

Fig. 5 - Structural scheme of the Italian Dolomites and of the Tauern window zone (simplified from CNR, 1990-1992, Sheet N.1).
- Schema strutturale delle Dolomiti e della zona della finestra tettonica degli Alti Tauri (semplificato da CNR,1990, Foglio N.1).

derive from ophicalcitic rocks, marked by considerable amounts of calc-silicate and carbonate minerals.

These "old roof rocks" were intruded by Hercynian plutonites between 309 and 295 Ma. The entire spectrum, from ultramafic cumulates to leucogranites, occurs, with a predominance of granodiorites and tonalites (MORTEANI & RAASE, 1974; CESARE *et alii*, 2002). They form sills (''Zentralgneisslamellen") of decametric thickness or laccolithic bodies of up to 2 or 3 kilometres in thickness (previously thought to be batholiths). A contemporaneous E-W stretching affected all rock types, leading to a strong structural anisotropy.

Post-Hercynian sedimentation starts with metaconglomerates or breccias and graphitic schists that contain Upper Carboniferous to Lower Permian plant fossils (FRANZ *et alii*, 1991). Locally, metaquartzporphyries and meta-arkoses ("Porphyrmaterialschiefer") serve as good marker beds for the Permian. Younger siliciclastic sediments are finer grained and more mature in the upper parts, and grade into white hematite-bearing quartzites (former red sandstones "Buntsandstein"). Middle Triassic (Anisian) crinoid-bearing grey dolomites and bedded white and yellow limestones and cargnieuls are overlain by chloritoid schists ("Quartenschiefer"), arkoses and quartzites (Keuper facies). The Jurassic strata are supposed to start with black kyanite-bearing schists and black marls (Liassic) and continue with some meters of reddish sandy limestones (Dogger).

Rocks older than the Malm are only spatially present and fossil records are scarce. The Upper Jurassic Hochstegen marble, however, is well dated by ammonites and radiolarians. It is present all over the Tauern window but with changing thickness from 20 m up to 300 m, with large uncertainties due to strong internal deformation. In its sedimentary and faunal characters it is similar to the Helvetic Quinten limestone of Switzerland and the South German Malm limestones (KISSLING, 1992).

Sediments of confirmed Cretaceous age are unknown in the basal part of the Tauern window. Arkosic gneisses (Kaserer series) on top of the Hochstegen marble were considered to be of Cretaceous age due to "sedimentary contacts" (FRISCH, 1975). This interpretation was later accepted by many other workers. In the meantime, some serious doubts were raised: the zircons from quartz porphyries at the base of the Kaserer series gave a U/Pb - age of 284 +2/-3 Ma (SÖLLNER *et alii*, 1991), and Middle Triassic carbonates are embedded within the middle part of the Kaserer as thin beds and as thick boudinaged bodies. The Kaserer series has therefore been confirmed to be Permian-Triassic in age and belongs to the basal part of the Penninic nappe system.

The Alpine tectonic history starts with an eo-Alpine shearing and thrusting. North verging fault propagation folds developed in the sedimentary cover. Slices of the crystalline core were also partly dislocated. This tectonic shearing accompanied the transport of the Penninic nappes over the Tauern. Thrust planes within the ophiolitic nappes are frequently decorated with isolated Triassic dolomite or serpentinite bodies.

In a second stage the entire mass of the Tauern was compressed, leading to internal thrusts and a high amplitude and long wavelength folding that includes the granitoid sills and laccoliths. Two main antiforms (Tux and Zillertal core), separated by a gneiss and schist synform (Greiner synform), developed and dominated the present structure. Earlier folds were refolded and, mainly along the northern rim of the Tauern, upsidedown structures formed, as the synformal anticline of the Hoellenstein. As this tectonic phase was accompanied by a penetrative east-west stretching, a transpressive regime was proposed (LAMMERER, 1988; LAMMERER & WEGER, 1998).

The steep southern limb of the Tauern window is cut by dikes of the Periadriatic plutons which, virtually, had not been rotated to a larger amount; FÜGENSCHUH *et alii* (1997) suggested, therefore, that the main folding occurred prior to 30 Ma.

The uplift of the Tauern is crucial to our understanding of the East Alpine history. Internal deformation cannot explain its present high position, with the result that a sub-Tauern ramp was proposed, in which the Tauern were uplifted by reverse faulting. Exhumation started at the end of the Oligocene and continued to the beginning of the Miocene (around 20 Ma), with rapid uplift rates of 4 mm/a, which decreased to 1 mm/a until 10 Ma. It was followed by a very slow uplift of 0.2 mm/a until today (FÜGENSCHUH *et alii*, 1997). On the other hand, recent fine geodetic levelling measurements produced much higher recent rates (>1 mm), which cannot be a consequence of glacio-isostatic effects only.

3.2.3. - *The Northern Calcareous Alps*

The Northern Calcareous Alps comprise a stack of Austro-Alpine nappes that covers most of the north-eastern Alps (figs. 1, 5). They have been detached from their original Hercynian low-grade metamorphic basement and, in their northern part , rest rootless on top of Rheno-Danubian Flysch or detached Helvetic units.

To the southeast, the substratum is the Northern Greywacke Zone, a series of Cambro – Ordovician to Devonian fine clastic sediments with minor carbonates and mainly Ordovician bimodal volcanics (e.g. Blasseneck porphyry) and intrusives (gabbros), including rare ultramafics (serpentinite at the Marchbachjoch). To the southwest, the basement is formed by quartzphyllites and phyllonites (Innsbruck, Telfs, Landeck) similar to the Brixen quartzphyllite.

Comparable to the history of the Dolomites, the sedimentary record of the Northern Calcareous Alps starts with Permian-Scythian siliciclastics (Verrucano, Alpine Buntsandstein, Werfen beds) and evaporites, in part with larger amounts of rock salt (Berchtesgaden, Hallein and many others). Since the Anisian the platform has been drowned and a reef-basin topography developed mainly in the Ladinian (Wetterstein limestone reefs and Partnach marls in the basin).

Due to a Carnian drop in sea-level, siliciclastics with subordinate coal seams and evaporites were again deposited. Cellular dolomites and limestones at the surface are represented by kilometer-thick dolomite-anhydrite series in the Vorderriss 1 borehole (BACHMANN & MÜLLER, 1981). The Norian Hauptdolomit, identical to the Dolomia Principale of the Southern Alps, covers the older topography uniformly. Isolated basins are filled with oil shales and slump units (BRANDNER & POLESCHINSKI, 1986). The basin-platform topography is accentuated in the Lower and Middle Jurassic (MANDL, 2000), when some basins sank under the CCD and slumping and turbidites are frequent along the basin margins.

The compressive movements first started in the Upper Jurassic (GAWLICK *et alii*, 1999) and had their first climax during the Lower Cretaceous: the Cenomanian and Gosau group sediments cover already folded Triassic rocks, which are locally eroded down to the Ladinian Wetterstein limestone. The tectonic setting of the Gosau group is under debate: ongoing compression, strike slip, oblique subduction and tectonic erosion of the crystalline basement followed by strong subsidence under the CCD (see discussion in WAGREICH, 1995).

The sector covered by the TRANSALP profile is dominated by the Lechtal nappe. The higher Inntal nappe ends some kilometres to the west, the lower Allgäu nappe is very thin, imbricated and barely visible in the seismic section. Two prominent anticlines are thrust over synclinal areas: the Thiersee thrust further to the south and the Wamberg anticline, which compresses the "Bavarian synclinorium" into narrow folds around Lake Spitzing. The Thiersee thrust is younger than the Lower Cretaceous, as Neocomian marls are involved in the movements.

To the north, the Northern Calcareous Alps end in a complex orogenic front with small-scale nappes and slices (Schuppenzone) against the Rhenodanubian Flysch and a small dissected band of Helvetic outcrops, which are steeply thrust onto folded Molasse.

3.2.4. - *The Bavarian Molasse Basin*

The Molasse sedimentary basin accompanies the northern Alpine front from Geneva to Vienna over a distance of 800 km. The basin resembles a broad triangle in map view, with an apex at Regensburg, where the Molasse, of about 130 km in extent, reaches its greatest width in a north-south direction. The north-eastern border, against the Bohemian Massif, is marked by a southeast trending, steeply dipping Mesozoic fault (active during the Upper Jurassic and Cretaceous) with a minimal throw of ~2 kilometres. Covered by Molasse sediments, a further step in the basement (south-western block 1 km down) parallels this fault near Landshut. The north-western limit of the Molasse, along the emergent Jurassic strata of the Swabonian – Franconian Jura Mountains, is marked by a cliff line of the Miocene Molasse sea, cut into Upper Jurassic reef or platform limestones. A belt of folded and imbricated Molasse sediments accompanies the Alpine front (folded Molasse). To the south, the Molasse trough is overthrust by Helvetic nappes (its own substratum units), Flysch nappes (Rheno-Danubian Flysch) and Austro-Alpine nappes (Northern Calcareous Alps).

The Molasse basin is underlain by Hercynian granites and gneisses which have been recognized in several boreholes. Locally, Permian-Carboniferous and Triassic siliciclastics (drilling of Giftthal 1) with coal seams and evaporites occur in graben, half-graben or pull-apart structures (e.g. Schaffhausen trough). With the exception of local horst positions, the entire region was drowned in the Middle Jurassic, and shallow marine shelf sediments of a mixed carbonate–siliciclastic character were deposited, with a total thickness of up to 1 km, ending with Lower Eocene sandy marls.

An erosional surface with lateritic paleosoils marks the break to the molasse-type sedimentation, which started in the Upper Eocene with flysch-like turbiditic sequences in the very southern areas (North Helvetic Flysch), and marine globigerina marls, algal limestones and fish shales in other areas. Marly and shaly sediments with sandy and turbiditic interlayers followed. Conditions remained marine throughout the Lower Oligocene (Lower Marine Molasse). Triggered by a world - wide drop in sea level, terrestrial influences proceeded from west to east, and brackish-to-freshwater sediments covered the western sector of the basin (Lower Freshwater Molasse). Siliciclastics of mainly Alpine provenance were deposited, in part also from the Bohemian Massif ("glass-sands").

The coal seams, within the delta-type sequences, had been exploited for centuries until 1971. The eastern part of the basin, however, remained marine during this time span. Widespread erosion affected the whole area during the Lower Miocene. Marine conditions came back in the Middle Miocene (Upper Marine Molasse) for only a short time span, which left mainly marly and sandy deposits. These were soon replaced by freshwater deposits (Upper Freshwater Molasse).

The mixed marine, brackish or fluvial sedimentary filling of the Molasse basin is a consequence of worldwide sea level changes and contemporaneous basin subsidence throughout the Tertiary.

Due to extensive hydrocarbon exploration, the geometry and sedimentary history of the Molasse basin is well known. The sedimentary apron thickens from a few meters in the north up to more than 5 km along the Alpine margin, reaching 8 km under the nappe front of the Northern Calcareous Alps. The geometry clearly approaches that of a flexural basin (ROEDER & BACHMANN, 1996).

The folded Molasse at the southern rim of the basin includes from one to four synclines, separated by thrusts. Anticlines are generally missing or cut. An elevated pore fluid pressure, which reaches super-lithostatic values locally, is typical for this zone. It decreases with distance from the Alpine nappe front but is still present in the southern part of the unfolded molasse (MÜLLER & NIEBERDING, 1996).

Oil traps in the foreland Molasse are mostly bound to the footwall block of north dipping antithetic faults with throws of some tens or hundreds of meters. About 60 small oil and gas fields have been discovered so far.

4. - THE SEISMIC SECTIONS

The Vibroseis stack (time) and depth-migrated sections (Plates 68, 69, 70, and 71) exhibit the best resolving power for the upper and middle crust, although lower reflections can also be seen in several sectors. The lower crust is better resolved by the explosive seismic data (fig. 6). The 'receiver functions', in particular, image the crust-mantle boundary by conversions at the velocity gradient zone. Slight discrepancies with respect to the explosive seismic reflections from the lower crust are due to the lower lateral and vertical resolving power because of the long wavelengths (20-30 km) of the receiver functions.

In the north the Vibroseis section displays about 80 km of the Bavarian Molasse, showing the base of the Tertiary and Quaternary sedimentary infill as the most prominent reflections. This is the area where oil and gas exploration took place in the sixties and seventies. Clearly visible antithetic normal faults were the targets for oil exploration. The Alpine front is characterised by an abrupt down-step of the Tertiary base and a change of the sub-horizontal Molasse reflections to southward dipping reflections of Northern Calcareous nappes. The top of the crystalline basement, known from drilling to be located beneath thin layers of Jurassic and Cretaceous sediments, can be traced towards the south, underneath the Northern Calcareous Alps and possible Cretaceous to Tertiary sediments to 9-10 km depth as far as the northern rim of the crystalline Tauern Window in the centre of the section.

There are two vertical displacements of 4-5 kilometres beneath the Alpine front and beneath the Inn valley. These might represent Mesozoic listric normal faults and tilted blocks within a downbending crust. At the southern flank of the Inn valley a prominent southward dipping reflection pattern is visible, which indicates that the Northen Calcareous Alps are overthrust along the Inn valley by its former basement, the Greywacke Zone. Both form the northern orogenic wedge over a width of 60 kilometres, showing north-verging structures throughout the section. The basal angle of dip reaches 9°, which is relatively steep, accompanied by a sub-parallel pattern of the reflective lower crust. This belt formed during previous eo- to meso-Alpine convergence, but was drastically rearranged during the post-collisional early-middle Miocene compressions responsible for the Tauern uplift (LAMMERER & WEGER, 1998). South of the Tauern window there is a prominent giant bi-verging pattern of sub-parallel reflections, which extends from the surface to the crustal root at about 55 km depth. From the seismic section one gets the impression that the most dramatic events of the continental collision are concentrated in this narrow part south of the Tauern window. Further to the south the crust is characterised by isolated reflective spots in the midcrust at about 20 km depth. Additionally, the relatively shallow layers of the Dolomite Mountains are accompanied by a reflective pattern in the first few kilometres of depth. Northward dipping reflections can be attributed to a system of backthrust faults. Upper-crustal stratified seismic reflections reaching about 10-15 km depth characterise the southernmost sector of about 50 km length.

From the north to the central part of the section the base of the reflective lower crust can also be followed, with a slight dip from 30 km in the north to 55 km depth beneath the Tauern window. This seismically pronounced lower crust has been remarkably thinned from north of the Molasse basin where previous DEKORP seismic reflection data (MEISSNER & BORTFELD, 1990) detected this type of reflective lower crust between 15 km and 30 km depth beneath a relatively transparent upper crystalline crust. In the TRANSALP section the top and bottom of the European crust, including midcrustal reflective patterns, are almost parallel and display a continuously increasing bending towards the Tauern window. A pattern of reversed and stronger dip is visible on the Adriatic-African side of the section, which provides an asymmetric image with respect to the Alpine axis. The

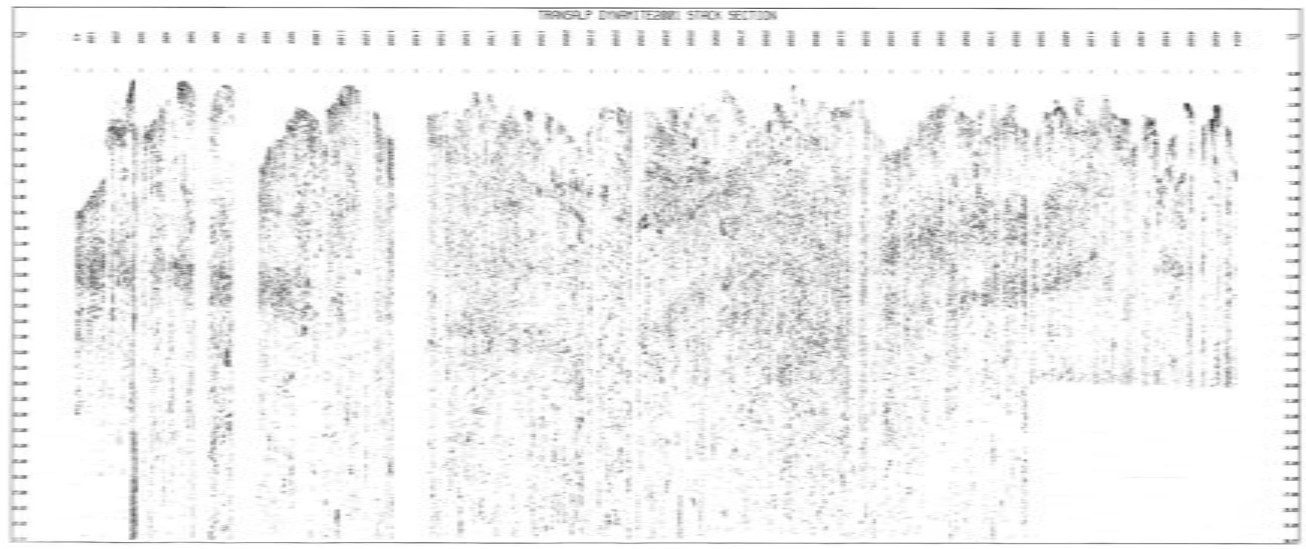

Fig. 6 - Dynamite seismic section of the TRANSALP Profile.
- *Sezione sismica a dinamite del Profilo TRANSALP.*

southern side of the section is characterised by a strongly thickened lower crust, evidently subdivided into two patterns, one on top of the other, with a maximum thickness of about 20 km, which is considerably larger than the lower crust thickness on the European side. In the Alpine root zone, located beneath the IL, the lower crust is seismically transparent. Granulitisation and eclogitisation of crustal rocks might have lowered the impedance contrast between mantle and lower crustal rocks, and tight folds may scatter the seismic energy. This is a common feature in most orogenic belts. Above this zone, the highly prominent bi-vergent reflection pattern mentioned above occurs. This might be due to a hydro-fractured crust following dewatering of subducted continental crust during progressive metamorphism and melting processes beneath. Fluids and/or partial melts could locally enhance the reflective character of deformation traces.

5. - THE AXIAL ZONE OF THE PROFILE: CONCLUSIVE REMARKS

The structural relationships of the two sectors of the Alps facing across the Insubric Line correspond to the more complex problem of the entire TRANSALP profile (figs. 1, 5). North of the Insubric Line, the European units of the Central Gneiss Zone, with their tectonic cover of oceanic meta-sediments and ophiolites, were affected by strong ductile deformations, dominated by narrow vertical folds where the gneiss are predominant. (Lammerer & Weger, 1998). These units underwent very intense shortening and uplifting, rising and/or exhuming for 30-35 km during the last 40 Ma (mostly in the early-mid Miocene, between 20 and 15 Ma), as documented by the 10 kbar decompressional P-T path recognized for the same interval (Von Blankenbourg *et alii*, 1989; Christensen *et alii* 1994). According to the previous deep seismic reconstruction (Giese *et alii*, 1982; Blundel *et alii*, 1992; Freeman & Mueller , 1992), the European Moho discontinuity descends regularly to the south, to the zone below the Tauern window. Consequently the strong deformation and rise of the Tauern window can be considered intra-crustal and restricted to the orogenic wedge. Similar crustal structures are only partly confirmed by the images of the Transalp seismic profile due to wide transparent zones in the very deep axial sector of the profile, underneath the Tauern crest (Plates 68-71, fig. 6).

The deformational history of the Alps and the structural setting of the zone located south of the Insubric Line, i.e. the Italian Dolomites sector of the eastern Southern Alps, is completely different. This sector underwent mostly south verging thrusts and brittle deformation (see previous paragraph) and only moderate uplifting, as documented by the low-grade metamorphic association (mostly phyllites) of the Hercynian basement and its Permian-Triassic non-metamorphic cover, located close to the Insubric Line (Plan de Corones, Bruneck). Similar conditions are well documented by fission track investigations throughout the eastern Southern Alps, where the hanging walls of the most prominent tectonic structures (S. Giudicarie transpression and Valsugana overthrust) attained uplifts of up to 4-5 km, mostly between 10 and 6 Ma B.P. (MARTIN *et alii*, 1998; DUNKL *et alii*, 1996). Moreover, these vertical movements occurred in concomitance with the strongest neo-Alpine compressional events (see previous paragraph). The uplift values in the Neogene are, however, much smaller than those observed in the Tauern window. Excluding the uplift rate, stratigraphic sequences similar to those of the Italian Dolomites occur in the Upper Austro-Alpine units of the Northern Calcareous Alps and in the "Drau Zug" belt (Lienz), where the Permian-Tertiary covers are unaffected by any metamorphic signature and show strong similarities in their sedimentary, mainly Triassic-Jurassic, facies associations.

The dip at depth of the Insubric Line is a key to defining the lithospheric setting of the Alps in their axial zone. In the Central and Western Alps, the Insubric Line has been interpreted to dip north and north-west , as proposed by ARGAND (1924) (see for instance, LAUBSCHER, 1974; SCHMID *et alii*, 1989; DAL PIAZ, 1995). Modern tectonic reconstructions based on deep seismic reflection data in the Central and Western Alps (ROURE *et alii*, 1990a; 1996; PFIFFNER *et alii*, 1997) have confirmed these hypotheses on the deep structural settings. In the Eastern Alps, the Insubric Line can been assumed to dip both north and south at depth.

Immersions of the Insubric Line towards the north at depth, in the sector crossed by the Transalp Profile, are consistent with the tectonic structures present at the surface. In fact, in the few places in which the contacts are visible along the Puster Valley, high-angle northward dips of the Insubric Line can be observed. These settings are always accompanied by an overturning of the metamorphic Austro-Alpine sequence due to back-folding of the structures close to the contact with the Insubric Line (see DAL PIAZ, 1934, tavv. X-XIII; and the "Geological Map of Italy", sheets Bressanone (1969) and Merano (1970). The TRANSALP reflection data are consistent with this interpretation. In fact, a transparent zone underneath the southern side of the Tauern window produces a sharp break in the reflective seismic facies, which could correspond to a continuation of the north dip of the Insubric Line at depth for about 20 km.

The southward vergence at depth of the Insubric Line was proposed by a number of authors over the past few decades (for the Western Alps see POLINO *et alii*, 1990, and ROURE *et alii*, 1996). Nevertheless, the seismic data across this lineament at depth show high to middle angle south dipping prominent reflectors, joining the Insubric Line at the surface. A similar setting of the Insubric Line at depth could indicate a different overall crustal interpretation for this sector of the Alps. The southward dipping Insubric Line could be seen as the upper surface of a large Penninic indentation of the Tauern window structure that protuted the crust of the Adriatic Plate. This hypothesis, forwarded in a different general model (subduction underneath the European continental margin) by OXBURGH (1972) is an interesting and innovative interpretation of the Eastern Alps alternative to the reconstructions above outlined.

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