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The development of seismotectonic studies on the Friuli Venezia Giulia region before and following the 1976 Friuli earthquake

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ABSTRACT The paper presents an overview of the history of oil drilling, carried out to investigate the deep tectonic structure of the Friuli Venezia Giulia region, up until a modern interpretation of the deep structural style obtained from the data of the Bernadia well. Many studies following the earthquakes of 1976 have led to the formulation of a seismotectonic model and the identification of the seismogenic structures in the study region.

Key words: 1976 earthquake, seismotectonics, Friuli, NE Italy.

1. Introduction

The knowledge of the deep underground was significantly increased by the progress in gathering data from Applied Geophysics. Consequently, data obtained from refraction seismics, and especially from reflection seismics, have been gaining considerable attention. Beyond the work conducted with this objective by geologists of oil companies, the availability of data, protected as trade secrets, has not always been so immediate. For this reason, the release of commercial seismic profiles were often expected by the scientific community of Earth Sciences with great impatience.

Knowledge of the deep geology of the Friulian chain and the underground began with the prospecting campaign conducted by the state owned oil company AGIP for oil exploration (Pieri, 1984). Following the discovery of the gas deposits at Cortemaggiore (central part of the Po Plain, northern Italy) in the late 1940s, the Italian government awarded AGIP the exclusive licence for oil and gas prospecting in the Po Plain (north-eastern Italy). With this action, all foreign and Italian private companies, such as Edison and Montecatini, also active in the search for hydrocarbons, were excluded.

In the 1960s, AGIP began an extended series of nationwide campaigns of drilling which also involved the eastern Veneto plain, following the farsighted and enterprising policy by Enrico Mattei. Among the most interesting campaigns, for a detailed knowledge of the deep subsurface of Friuli Venezia Giulia and for anchoring the seismic profiles, it is worth mentioning (AGIP, 1977) the wells drilled in the Veneto region Jesolo 1 and San Donà di Piave (both in 1956), Eraclea 1 (in 1957), Belluno 1 and Cesarolo 1 (both in 1960), Sedico 1 and Cavanella 1 (both in 1961), next to the western Friuli border, and offshore in the northern Adriatic Sea the wells Assunta 1 (in 1976) and Amanda 1 bis (in 1979), essential for the knowledge acquired with the 7,305 m depth reached.

In the Friuli Venezia Giulia region, the AGIP drillings began in 1955 with the wells Buttrio 1 and, thereafter, with Bernadia 1 (1959), Lavariano 1 (1962), Terenzano 1 (1963), these last two limited in depth and close to each other, Gemona 1 (1986) and Cargnacco 1 (1993). This latter, reaching 7163 m at the bottom of the hole, is one of the deepest wells drilled onshore in the entire national territory. In addition, of note is the SPAN 1 well (acronym of San Pietro al Natisone, created in 1976 by a private industrial consortium) and the recent wells for geothermal research Grado 1 and Grado 2, drilled, respectively, in 2008 and 2014 (reaching depths of 1106 and 1200 m) by the Autonomous Region of Friuli Venezia Giulia with European funds and intended for district heating of the Grado seaside resort. The wells produced new stratigraphic and important structural data for the regional subsoil.

Moreover, it is important to cite the deep campaigns conducted outside industrial interests mainly by the Osservatorio Geofisico Sperimentale (OGS, now Istituto Nazionale di Oceanografia e di Geofisica Sperimentale), which were chiefly related to the marine and coastal environment with a series of exploratory campaigns conducted since 1949 with refraction seismics (Finetti, 1967) and gravimetric (Morelli, 1975) investigations.

Much deeper geophysical explorations, conducted again by OGS with the Deep Seismic Soundings (DSS) refraction seismics technique, were focused on the entire Adriatic lithosphere, plotting the lower limit of the crust (Moho) and defining depth and thickness of the crustal units on the basis of changes in seismic velocity (Finetti and Morelli, 1972; Morelli and Giese, 1973; Aric *et al.*, 1976; Giese *et al.*, 1980, 1981; Italian Explosion Seismology Group and Institute of Geophysics-E.T.H. Zürich, 1981; Nicolich and Dal Piaz, 1990). For researchers who had no access to AGIP data, there was therefore a knowledge gap between the tectonic surface structures, detected on the ground by geologists[(1)], and those very deep ones interpreted by geophysicists.

2. The modern interpretation of the deep structural style

The turning point in beginning to bridge this gap was Martinis'[(2)] (1966) work, who, already in the title "Evidence of large thrust faults in the Friulian and Venetian Alps", proposed the dominant tectonic style by reinterpreting the structures interpreted at that time as recumbent fold. His work was based on data obtained from the Bernadia 1 well, in the Julian Prealps, drilled by AGIP in 1959 and reaching -2570.50 m downhole (Fig. 1). The Martinis (1966) study identified broad thrusts, also confirmed to the west (Zanferrari, 1973), involving SE-, S-, SW-verging structural units affecting the whole area (Fig. 2). Since then, this model has been extended to the entire tectonic structure of the foreland. It is important to note that Feruglio (1925) had already suggested that the pre-Alpine flexure interpreted by Dainelli (1921), which characterizes the front of the Cretaceous ellipsoids (Ciaurlec, Pala, Bernadia, Matajur, Mia, etc.), was uprooted and shifted to the south due to extended low-angle faults (Fig. 3).

(1) The geological sections attached to the Illustrative Notes of the regional sheets of the old geological map of Italy, produced between the 1920s and 1950s, extrapolated surface data up to a maximum depth of a few hundred metres below sea level.

(2) Bruno Martinis (who was to become the first Professor of Geology, initially at the University of Milan, where he was pupil of Ardito Desio and went on to succeed him in the chair, then at the University of Rome) had been working for several decades at AGIP, before turning to the academic career.

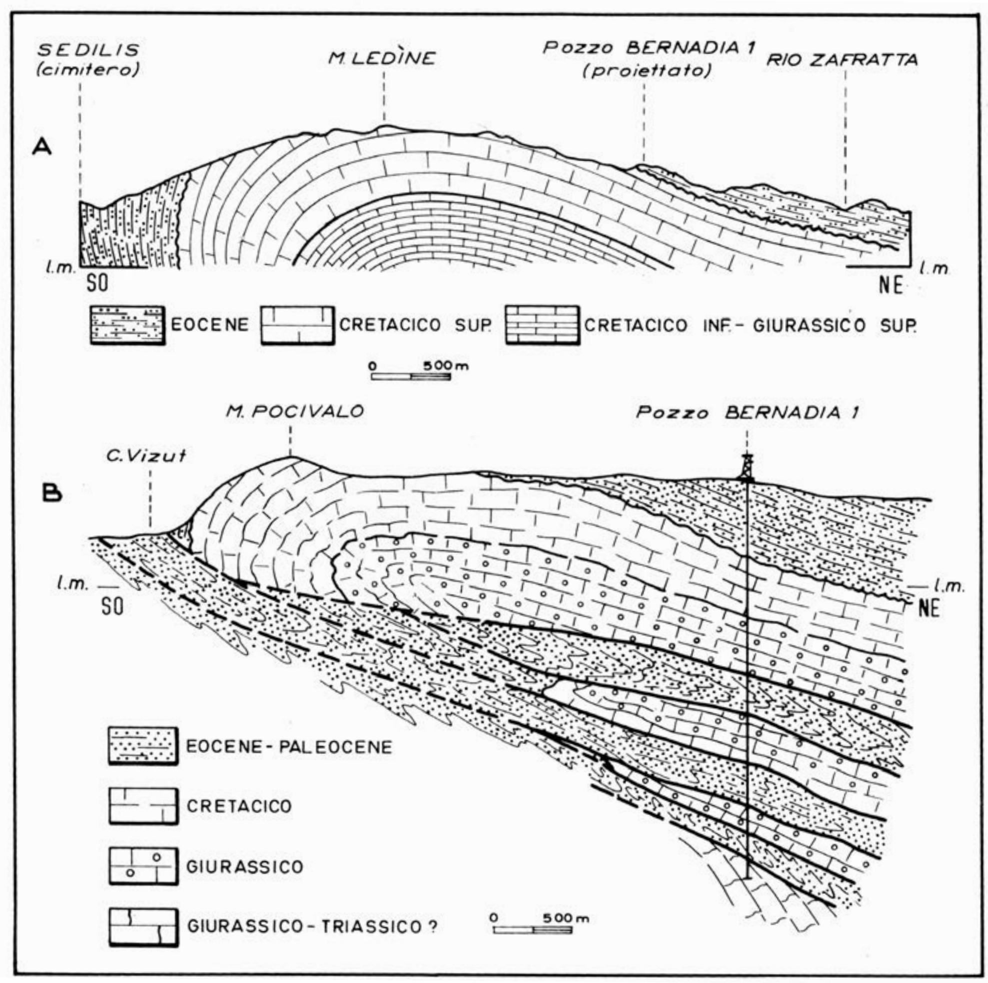

Fig. 1 - Geological cross-sections across the Bernadia Mount (Martinis, 1971): A) old interpretation as asymmetric fold structure inferred from surficial geology; B) modern interpretation as overthrusted structure based on data of the Bernadia 1 well.

In effect, the collaboration between geologists and geophysicists was not limited to within the oil companies but also extended between companies and universities and among several academic and scientific institutions, inside and outside universities. This kind of cooperation would find, from the 1990s on, its highest expression in the CROP national projects and in the TRANSALP cross-border projects.

Before the activation of such projects, the interpretation of data provided by geophysical research was focused mainly on the knowledge and improvement of the deep structural setting, without taking into account, except in rare cases, the association of tectonic structures to seismicity, namely the regional seismogenesis.

For these reasons, the earthquakes that struck Friuli in 1976 (Carulli and Slejko, 2005; Slejko, 2018) found the scientific community of the Earth Sciences quite unprepared to face such a dramatic event about which it had no direct experience. The only regional research institution seeking to keep up with the times, largely because of its official duties, was the OGS that became the main scientific reference body for a scientifically appropriate communication

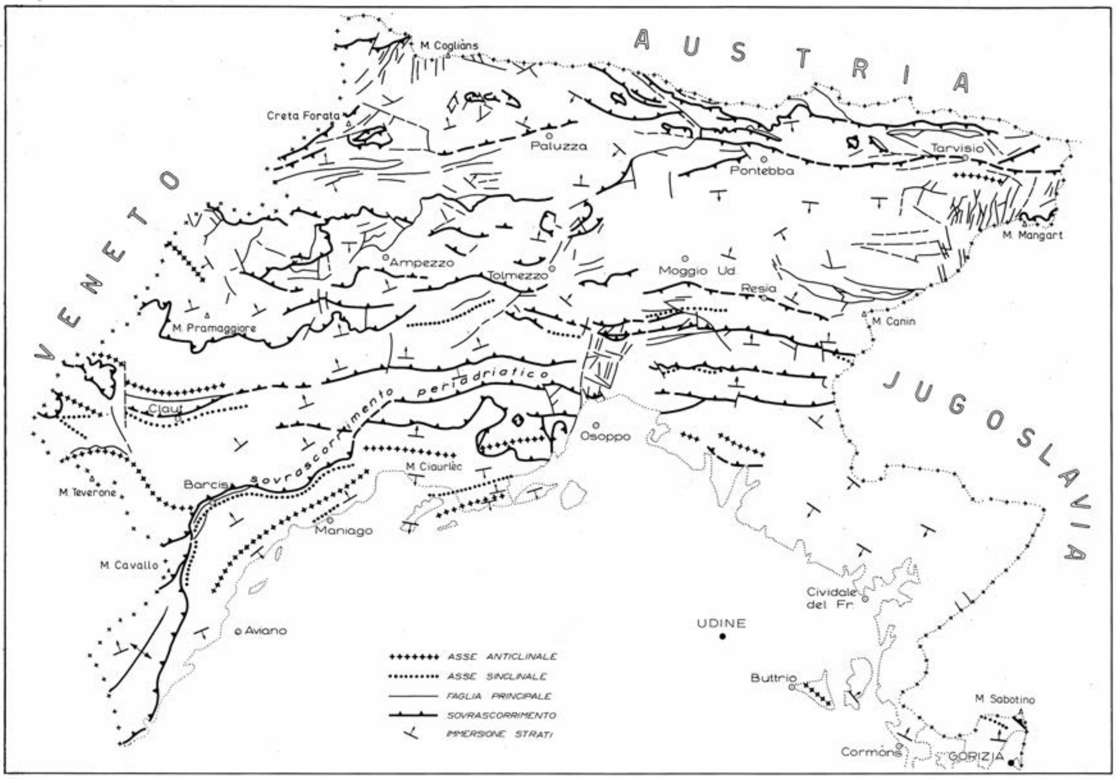

Fig. 2 - Tectonic sketch of the Friulian pre-Alps and Alps (Martinis, 1971).

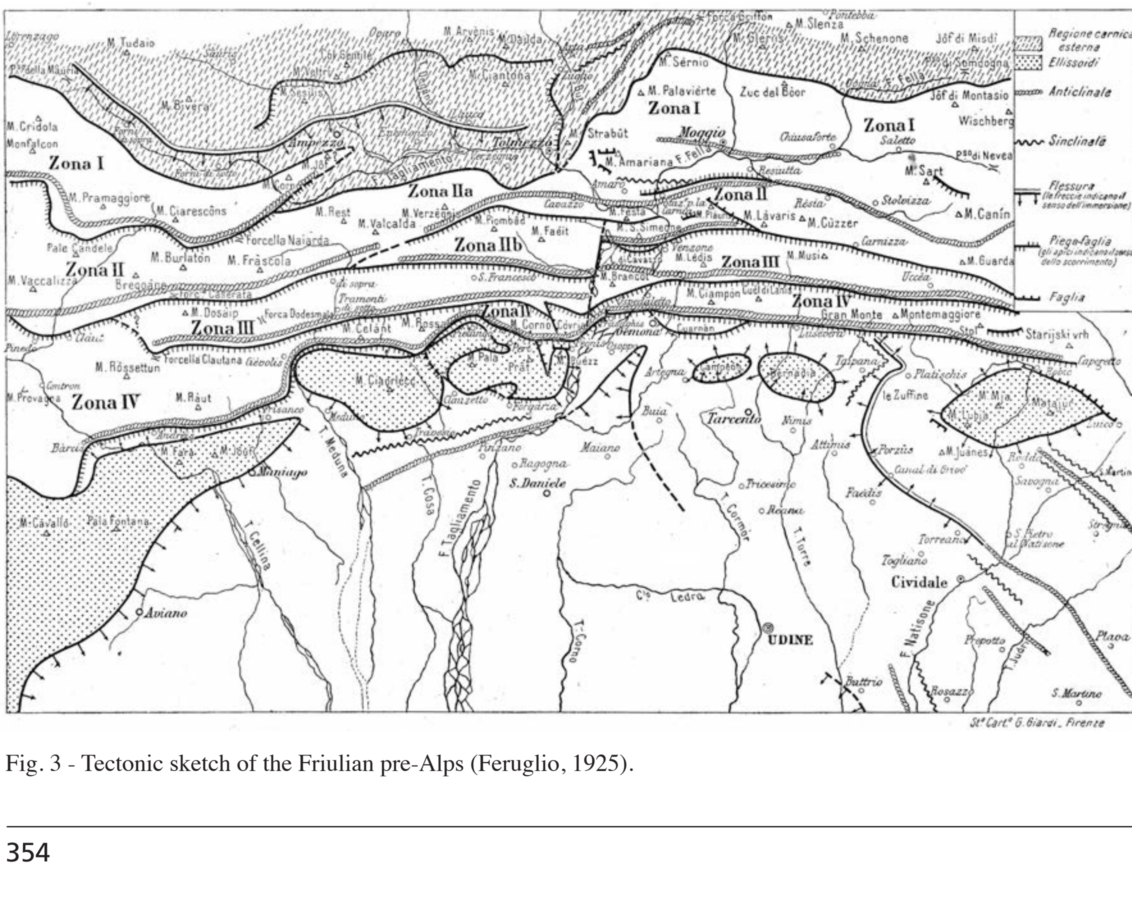

Fig. 3 - Tectonic sketch of the Friulian pre-Alps (Feruglio, 1925).

with the local population and the media[3]. Among other documents appearing in the public domain, it is worth mentioning the isoseismal map of the 6 May 1976 main shock (Fig. 4) elaborated by Giorgetti (1976).

The series of shocks started on 6 May was a rude awakening for the researchers and professional bodies and made the scientific community (geologists, geophysicists, engineers,

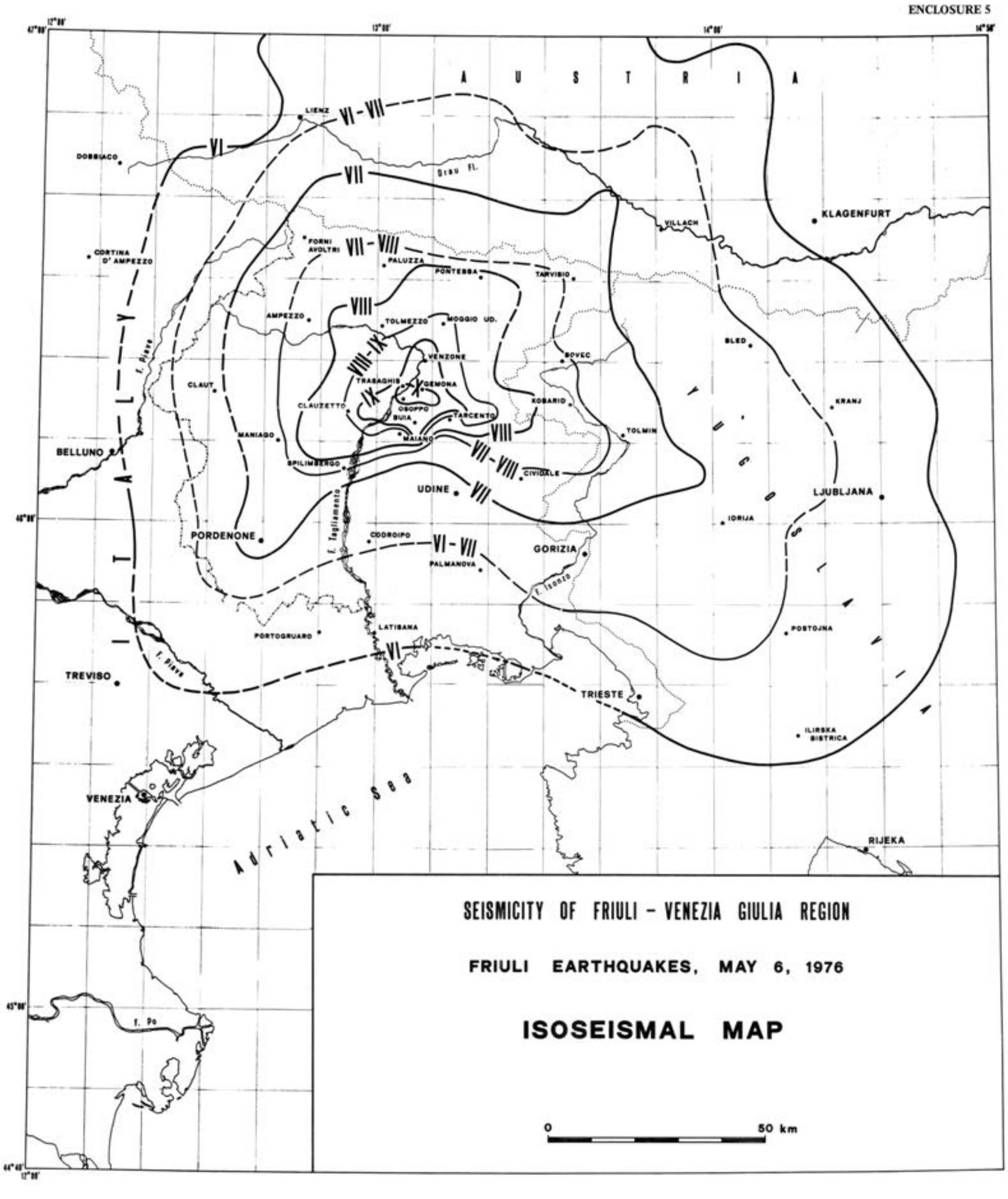

Fig. 4 - Isoseismal map of the 6 May 1976 Friuli earthquake (Giorgetti, 1976).

[3] It is worth noting that exactly one year after the 6 May earthquake three seismometers were installed by OGS as the first stations in a seismic network, financed by the Region Friuli Venezia Giulia, which currently consists of 15 short-period and 5 broadband stations mainly located in the mountains and foothills of Friuli. Over the decades, the instrumentation has achieved an increasingly advanced level of technology to allow the transmission of real-time data via radio-link, via the Internet, and by satellite to the Civil Protection and the Prefectures.

architects, etc.) aware of the problem of seismic risk in Italy, marking a milestone in research aimed at risk mitigating (see Slejko *et al*., 2018).

Indeed, after the immediate emergency interventions, even the scientific feedback was soon ready. Just seven months after the events of May and two and a half months after those of September, an international conference on the Friuli earthquake was held in Udine from 4 to 5 December 1976. The conference was organized by the International Centre for Mechanical Sciences (CISM) under the patronage of the Region Friuli Venezia Giulia and the European Association of Seismic Engineering. It was an important moment of exchange in the scientific community, of acculturation and data transfer for accurate information, through the presentation and discussion of 67 scientific papers related to topics of Seismology, Geophysics, Geology and Earthquake Engineering. With several hundred researchers attending, the conference had an international participation and resonance and marked the beginning of a fruitful interdisciplinary work. The conference proceedings were published in a 1626-page issue of the "Bollettino di Geofisica Teorica ed Applicata" (BGTA), an international scientific journal published by OGS, which was made available to the scientific community in a very short time. The geological map of the entire Friuli Venezia Giulia region (Amato *et al*., 1976), albeit on a very small scale and in black and white (Fig. 5), appeared for the first time in that volume; the map was designed

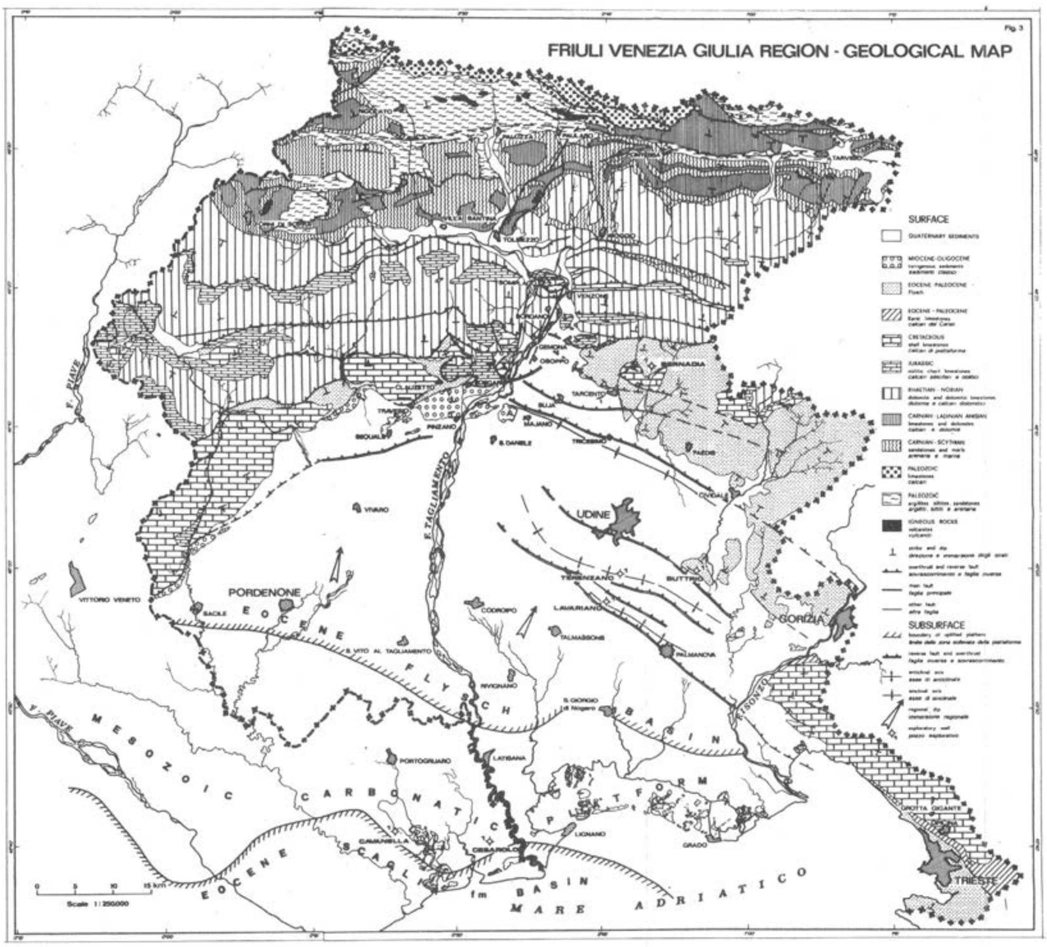

Fig. 5 - Geological map of the Friuli Venezia Giulia region (Amato *et al*., 1976).

on the basis of the data provided by two companies, namely AGIP and SNIA Viscosa. The same authors also published the regional seismotectonic map, overlapping the isolines of the maximum expected intensity (Mercalli - Cancani - Sieberg scale) for a return period of 1000 years on the sketch of the main tectonic features (Fig. 6). Finetti *et al.* (1976) showed the epicentral distribution (Fig. 7) recorded by a local seismometric network operating in central Friuli during the seismic sequence and a geological section (Fig. 8), where the hypocentres were screened showing their NW-ward migration and their correlation with the deep sliding plane known as Buja - Tricesimo fault. In the same volume, the seismotectonic map of Friuli region, western Slovenia and Istria (Arsovski *et al.*, 1976) was also published (Fig. 9).

AGIP contributed to the geological knowledge of the deep underground of the area hit by the 1976 earthquake. It applied its expertise gained from over 1,000 km of seismic reflection profiles, recorded in the region from 1972 to 1974 with a multi-channel digital acquisition (Fig. 10), from gravimetric maps with the Bouguer anomalies, obtained from about 6,000

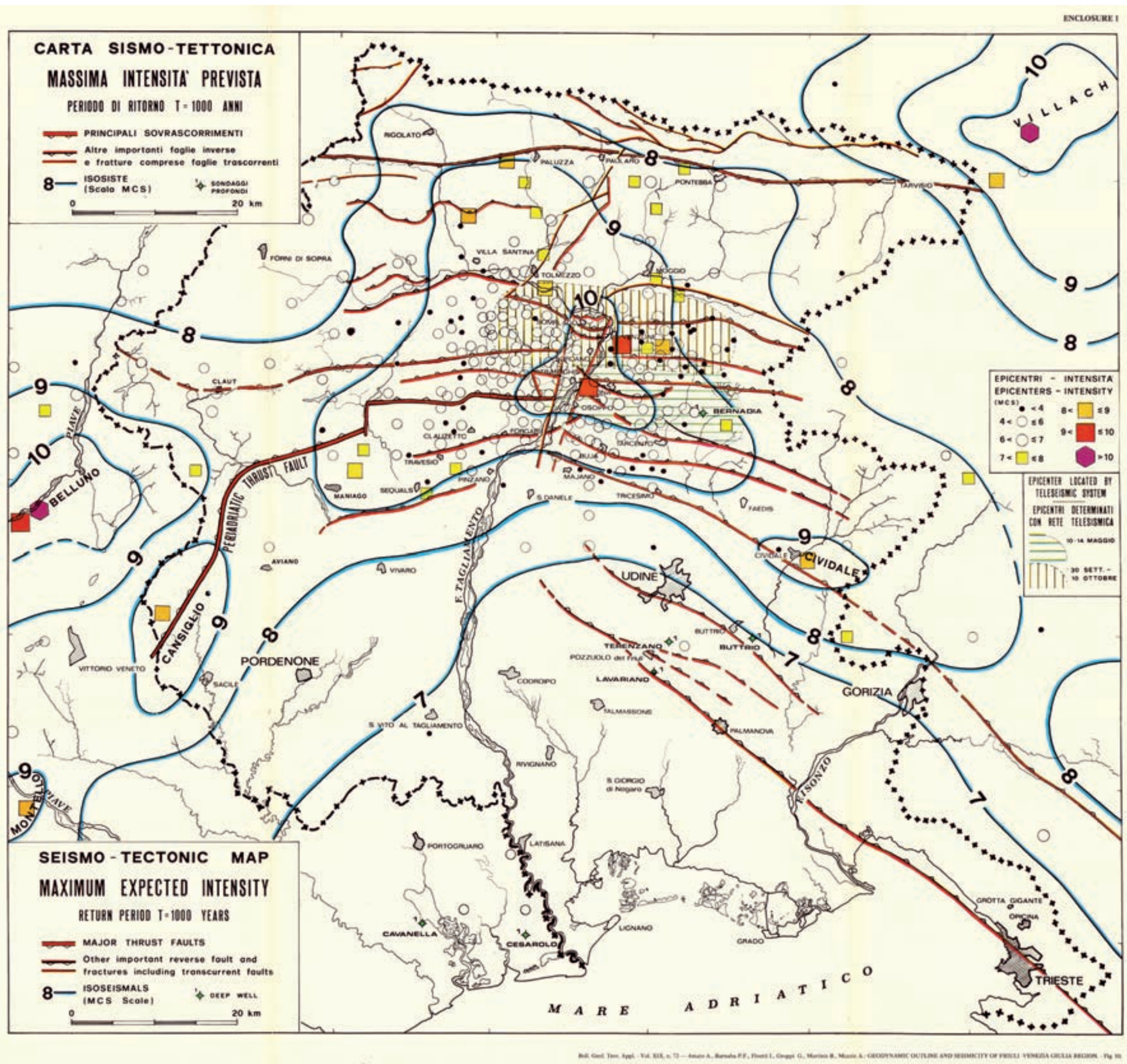

Fig. 6 - Seismotectonic map with main tectonic features, seismicity, and isolines of the maximum expected intensity for a return period of 1,000 years (Amato *et al.*, 1976).

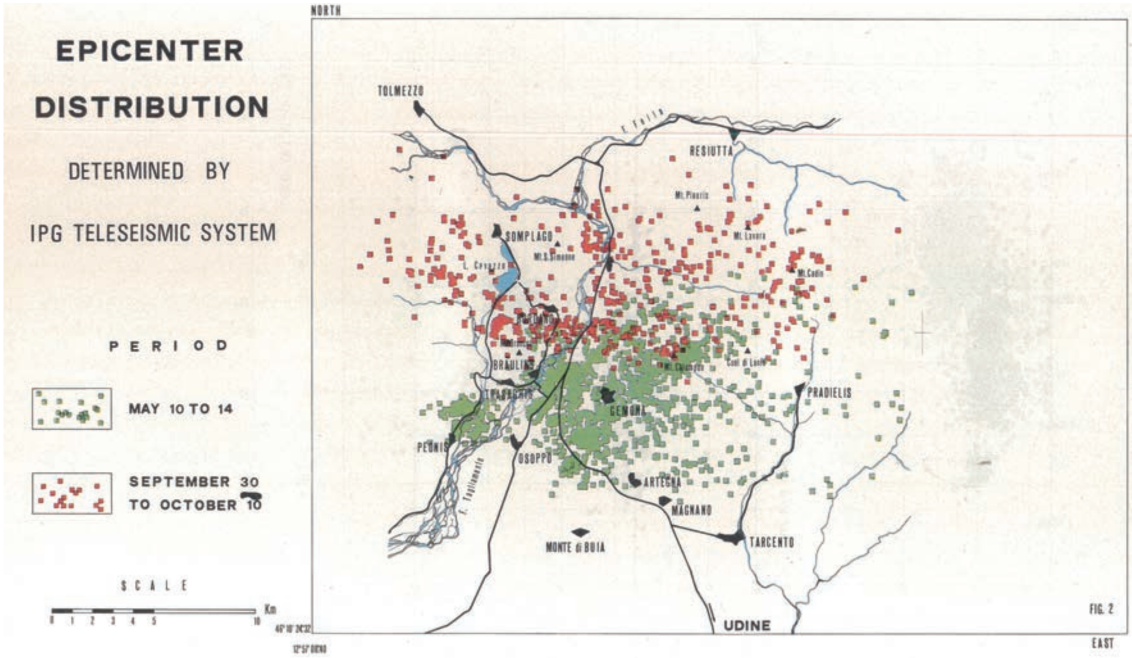

Fig. 7 - Epicentre distribution of 10 to 14 May (green) and 30 September to 10 October (red) 1976 determined by a local teleseismic network (Finetti *et al.*, 1976).

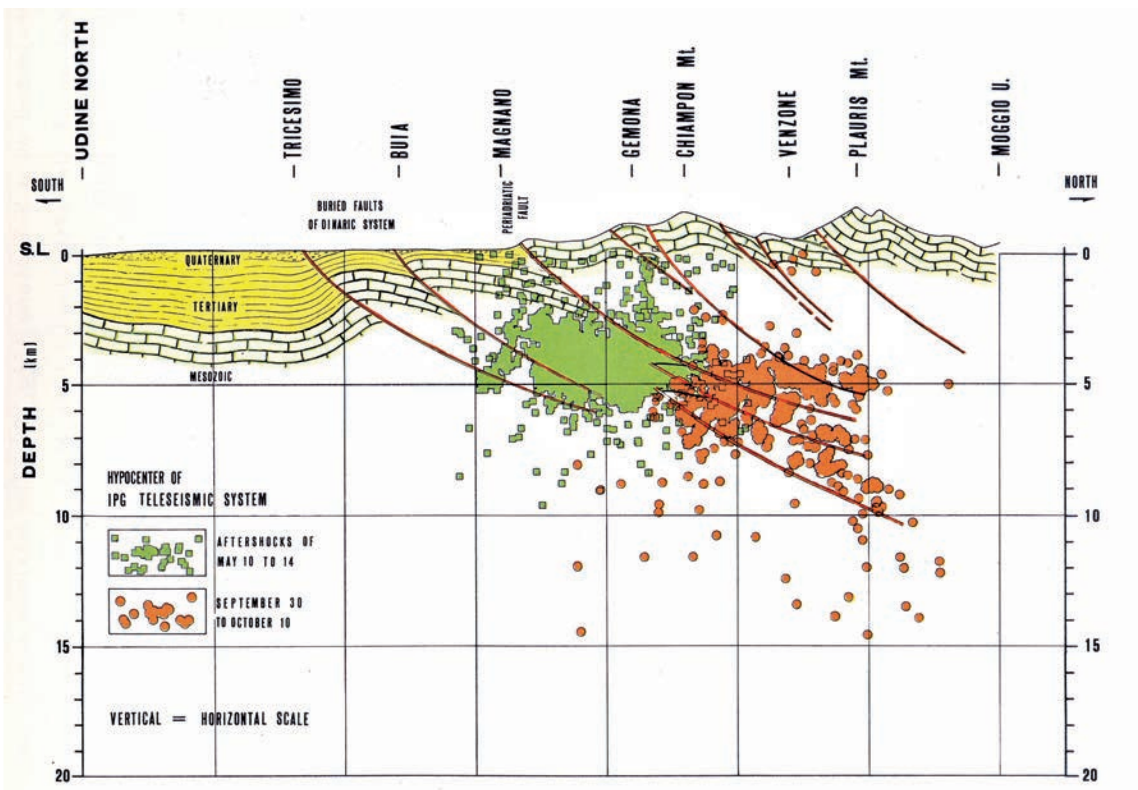

Fig. 8 - Geological section crossing the area hit by the 1976 earthquakes, highlighting the hypocentres of 10 to 14 May (green) and 30 September to 10 October (red) 1976 (Amato *et al.*, 1976).

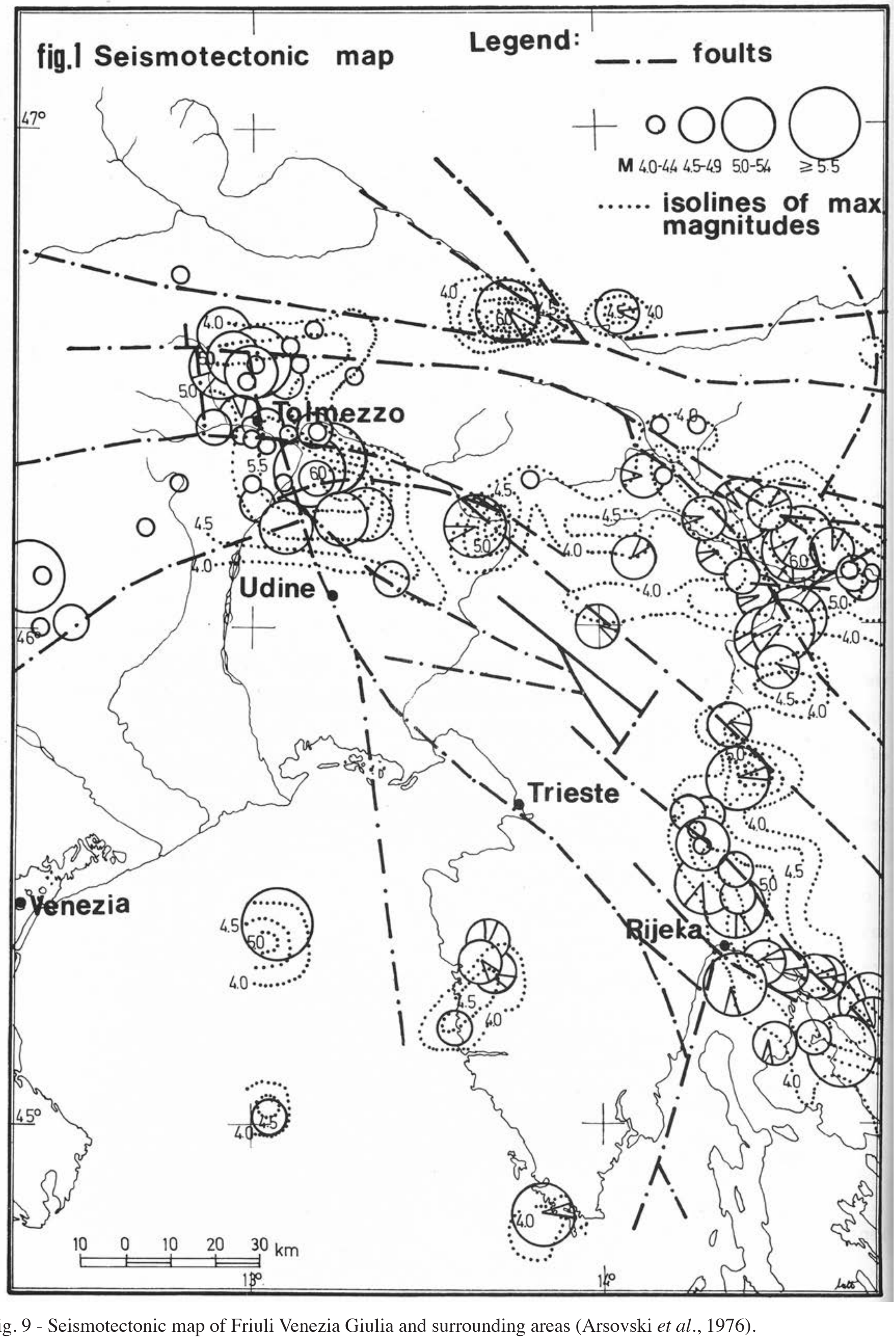

Fig. 9 - Seismotectonic map of Friuli Venezia Giulia and surrounding areas (Arsovski *et al*., 1976).

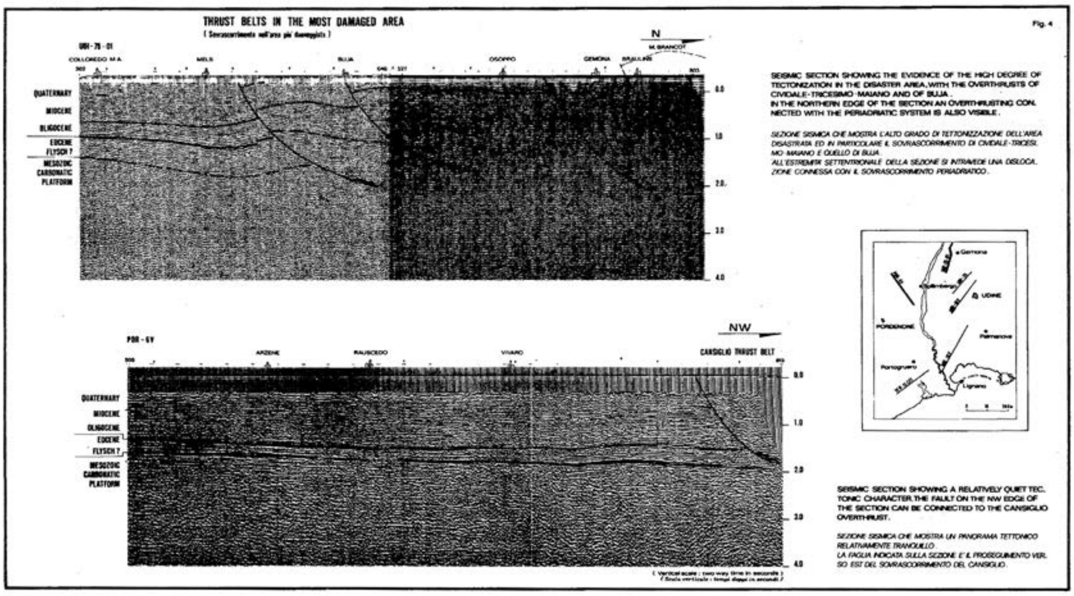

Fig. 10 - The AGIP seismic profile with the geological interpretation of the thrust belts in the most damaged area (Amato *et al*., 1976).

stations, as well as from drilling reports and electrical logs of the aforementioned boreholes. AGIP also produced, upon request of the Italian Council for Research (CNR), 64 km of digital multichannel seismic lines in the disaster area. All this information allowed the structural setting of the reconstruction of the subsoil to a depth of about 5 km in the southern part of the Friuli Plain and 3 km in the northern one.

An interpretation of the seismic sequence of Friuli, inserted in the geodynamic context of the Adriatic microplate, was also given by Colautti *et al*. (1976) and Finetti *et al*. (1979), who confirmed the Alpine nature of the earthquakes with a low angle fault plane dipping to the north and the reverse mechanism.

3. Studies following the 1976 earthquakes

The researches conducted as part of the "Progetto Finalizzato Geodinamica" (PFG), financed by the CNR, also began with the earthquakes of 1976. PFG was launched in 1976, and the Friuli earthquake was to prove a testing ground for its coordination and start of operations. PFG was divided into six sub-projects (SPs), four of which were related to the issues of earthquakes: seismic networks, seismic risk and earthquake engineering, structural model, and neotectonics. The latter issue was particularly challenging for the geological community and decisive, in cooperation with seismologists, for updating the knowledge on seismotectonics and seismogenesis.

For the studies referring to Friuli Venezia Giulia, various operating units were created requiring the geological interventions of several universities (Bologna, Ferrara, Milan, Modena, Padua, Parma, Pavia, Torino, etc.), in addition to the University of Trieste(4), and of other

(4) The University of Udine was established in 1978 thanks to the initiatives taken by the Italian government after the 1976 earthquakes; two years later, the local Institute of Earth Sciences was created, though researchers here were already making contributions right from the time of the immediate emergency.

Regional Authorities (Emilia Romagna, Liguria, Lombardy, Piedmont, Veneto, etc.).

The PFG represented a turning point in Italian research since it was a new method to deal with scientific problems. Firstly, it introduced the fundamental principle of interdisciplinary pooling skills of geologists, geophysicists, engineers, architects, historians, economists, sociologists, etc. (categories, up to that time, often confined to their respective specialist spheres) with the consequent professional and cultural mutual enrichment. From a management perspective of the research, a general coordination was established, ending disconnected initiatives. Better compliance with schedules and timing was achieved through previously unusual cadences (half-yearly progress reports, annual conferences). This gave greater stimulus to in-depth and continuous research, as well as to scientific comparison. Eventually, a very important element was represented by the goal of the researches, highlighted by the term 'project', i.e., studies with a direct impact on society and not merely academic research.

Within the SP Neotectonics, the Plio-Quaternary evolution of Friuli Venezia Giulia was studied (Carulli *et al.*, 1980) and the map of the neotectonic evolution in north-eastern Italy was produced (Zanferrari *et al.*, 1982). It contained, through the critical analysis of linear and areal structural elements, the assessment of the tectonic behaviour of the area during 4 periods of its evolution, from upper Pliocene to Present, with the elaboration of the related tectonic maps.

The works carried out in the framework of the SP Structural Model of the PFG saw, instead, the tectonic review and updating (Castellarin, 1981) of all 12 geological sheets referring to Friuli Venezia Giulia, considering that the elaboration of some of them dated back to the 1920s.

As part of the initiatives promoted by the PFG, it is worth remembering the decisive participation of AGIP, with the interpretation, through the integration of geological and geophysical (gravimetric and magnetic) data, of the seismic profiles performed throughout the Po Valley in the fundamental works of Pieri and Groppi (1981), Cassano *et al.* (1986) (Fig. 11), and by Cati *et al.* (1988), in north-eastern Italy, aimed at reconstructing the buried margin of the thrust and fold belt of the eastern Southern Alps (Fig. 12).

The line of research "Seismotectonic Map of the Alps", operating within the cited SP, saw the commitment of all the researchers involved in the study of the Alpine chain and led (Carulli *et al.*, 1981) to a first comparison of data on the crustal model (Italian Explosion Seismology Group and Institute of Geophysics-E.T.H. Zürich, 1981), and those coming from seismology, structural geology, and neotectonics, with the purpose of defining the seismogenic zones of Friuli, as a basic condition for a correct and accurate assessment of the regional seismic risk. In fact, in some later works (Carulli *et al.*, 1982; Slejko *et al.*, 1987, 1989), further structural data and the OGS hypocentral locations were reported on three strategically located geological sections placed at the centre of a variable strip ranging between 6 and 10 km in width (Fig. 13).

The CROP (CROsta Profonda) project (see www.crop.cnr.it, where further details can be found), set up in 1982-1985 with an overall feasibility study, had a first phase of implementation (1985-1988) as a CNR Strategic Project. Since the 1990s, it developed through CNR agreements among CNR, ENI-AGIP and ENEL, which enabled the acquisition, processing and interpretation of some 10,000 km of reflection seismic profiles on land and, for the most part, marine. Through these agreements it was possible to establish an interaction on basic scientific research between public and private industry and the community.

The CROP project was a multidisciplinary research program aimed at achieving the following objectives through the study of geophysical data: understanding the basic geodynamic

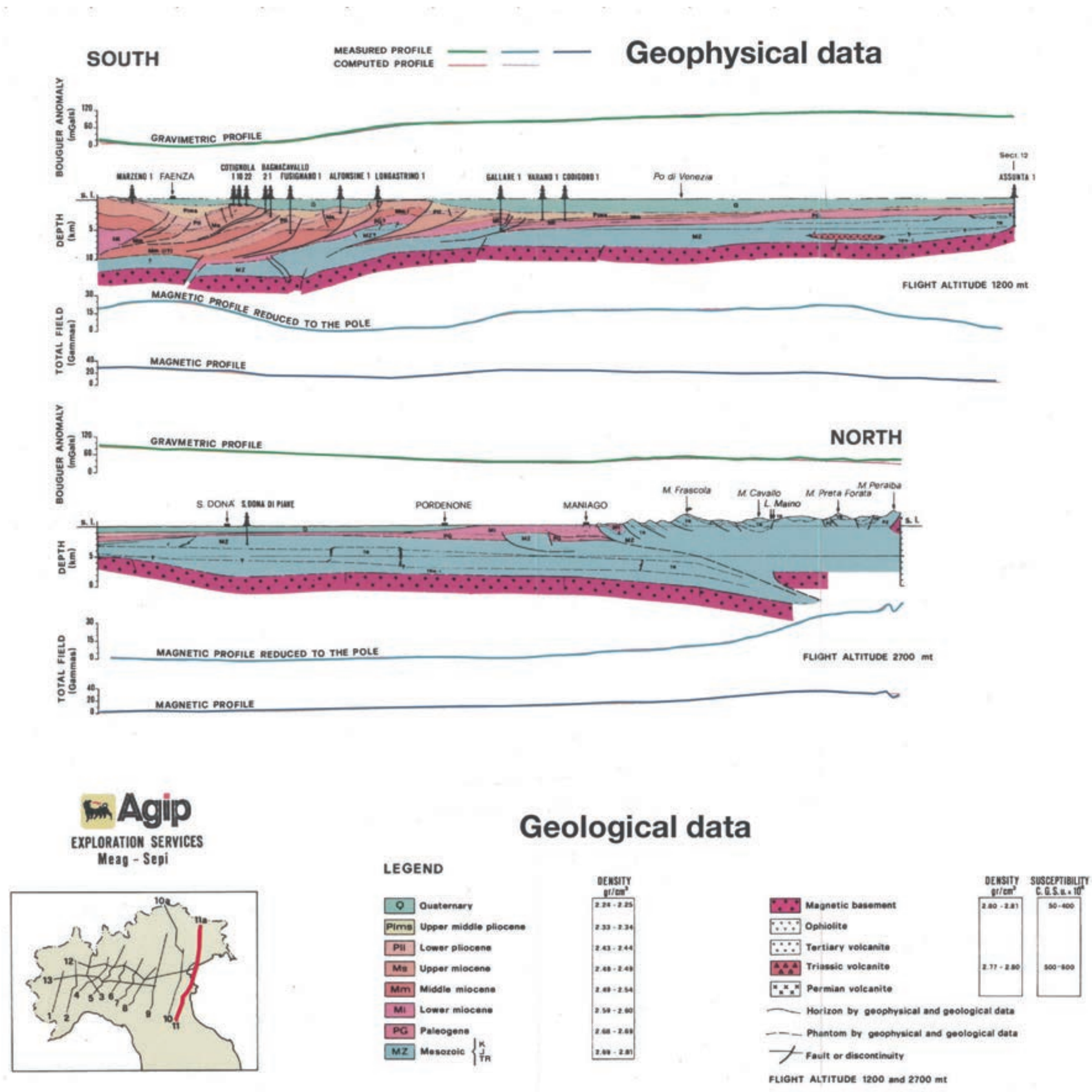

Fig. 11 - Geophysical and geological integrated interpretation in the easternmost part of the Po Plain (modified from Cassano *et al*., 1986).

processes that have produced the current configuration of the Italian territory, the definition and prevention of geological risk, the search for energy resources (hydrocarbons and geothermal energy), the identification of stable areas to establish industrial areas, and the disposal of waste in the safest conditions. The information gained from the project led to the revamping of basic geological models, thanks to the new knowledge on the deep geometry of the Earth's crust, and the work of revision and integration of all existing geophysical and geological data. At the same time, this research activity promoted the Italian technological development in the field of deep seismic reflection exploration and of the processing and interpretation techniques of NVR seismic data. With the CROP project, Italy was inserted in the group of countries engaged in the scientific study of the deep crust together with the England (project BIRPS), France (project ECORS), Germany (project DEKORP), Switzerland (project NFP20) and United States (project COCORP).

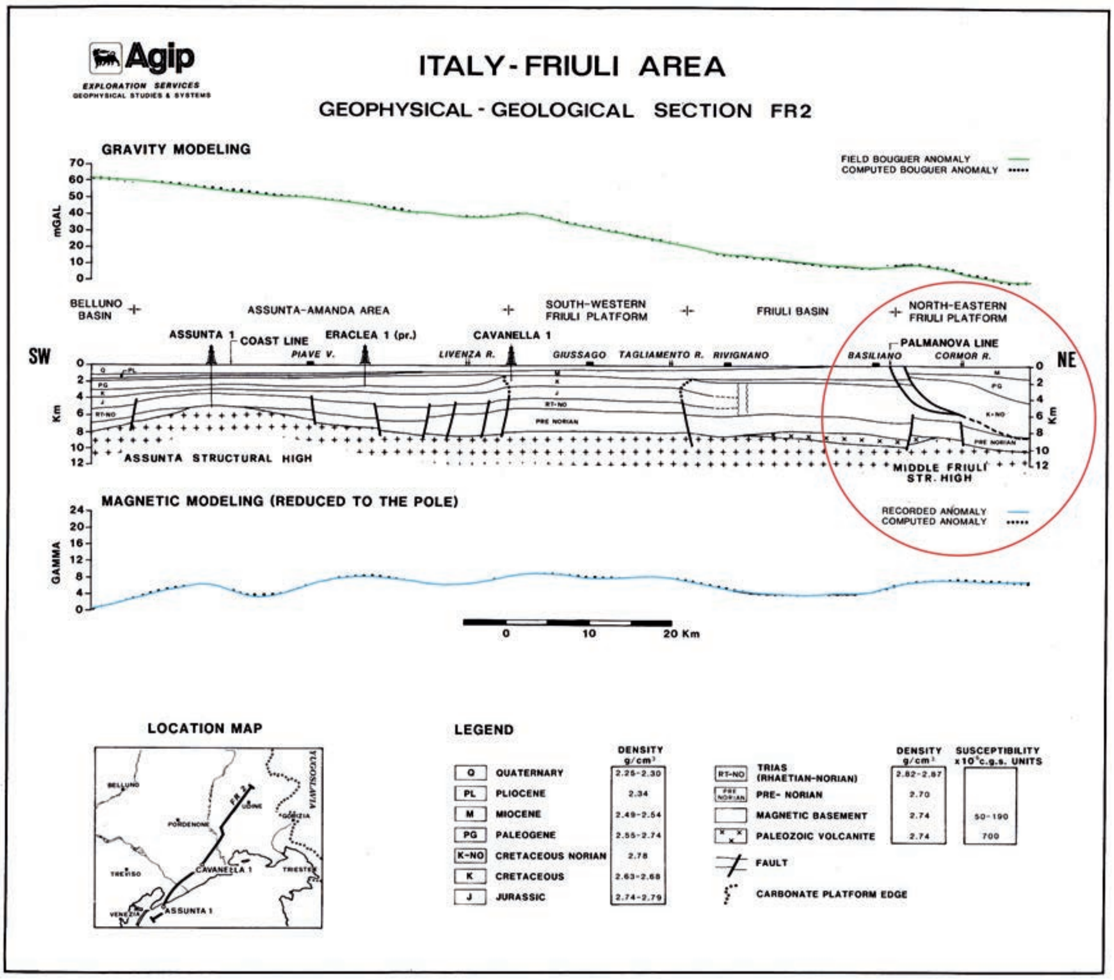

Fig. 12 - Geophysical and geological section in the eastern Alps. The circle shows the buried margin of the thrust belt in the Friulian pre-Alps (modified from Cati *et al*., 1988).

Three CROP profiles, with international cooperation, were made on the Alpine mountain chain, crossing the western Alps (ALPS CROP-1, south-eastern continuation of the French ECORS profile), the central Alps (transects CROP 1-2-3-4), jointly with the Swiss NFP 20 EAST profile, and the eastern Alps (TRANSALP), in cooperation with Austria and Germany (Finetti, 2005). The latter ran in an almost N-S direction from Monaco to Venice, hence crossing all the structural units of the chain, from the Bavarian molasses to the Po foredeep. The mountain sector of Friuli was, therefore, not directly involved but some important information was obtained, also because it stimulated different interpretations on how to extend the crustal data eastwards (Castellarin et al., 2003, Lammer and TRANSALP Working Group, 2003).

The offshore profile CROP M-18, however, carried out with a NE-SW direction in the northern Adriatic Sea (Fig. 14), traversed, in its north-eastern portion, the Gulf of Trieste. The sedimentary cover, calibrated on the Amanda 1 well, showed a weak progressive increase in thickness towards SW and a resulting thickening of the crust under the Friuli and the Istria platforms.

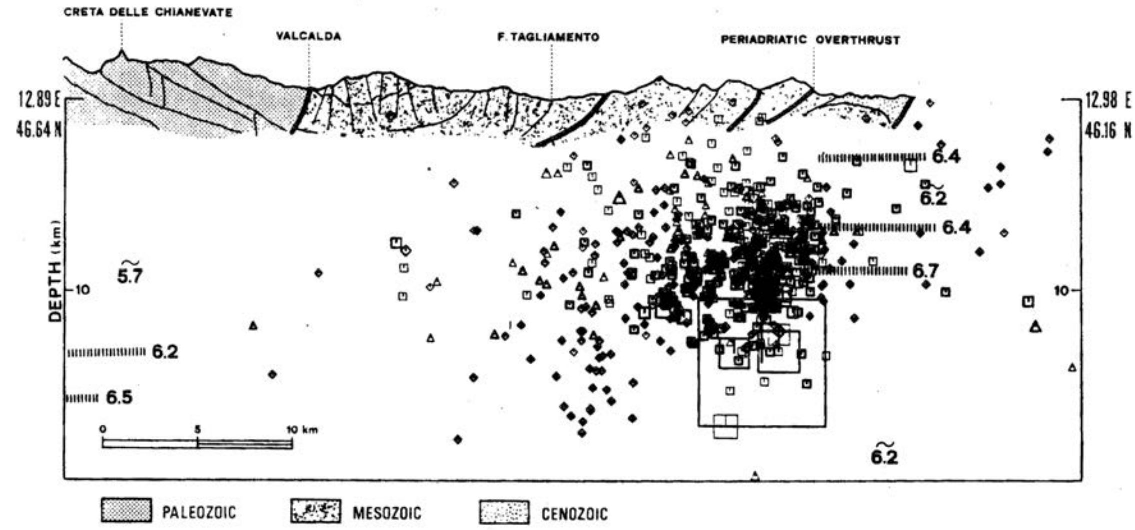

Fig. 13 - Geological geophysical cross-section, 10-km wide, across the Paleocarnic Chain and the western Friulian pre-Alps (Slejko *et al.*, 1989). Different symbols refer to foci recorded by the OGS seismometric network of Friuli Venezia Giulia in different periods: squares from 1977 to 1978; triangles from 1979 to 1981; rhomboids from 1982 to 1986. The velocities refer to horizons revealed from refraction seismics.

In the design phase of the CROP 1 profile, for the Carnia sector, a deep geological section was proposed (Carulli and Ponton, 1992) parallel to the planned route for the extreme north-eastern transect of the same profile: this north-eastern transect was, unfortunately, never realized. The cited section, extending for approximately 70 km in the N-S direction, hence perpendicular to the structural axes of the mountain chain, extended from the Gail Valley to the northern Friuli plain and had been made on the basis of both published and unpublished geological and geophysical (DSS, magnetic, and gravimetric) data. The hypocentres of the earthquakes recorded between 6 May 1977 and 31 December 1989 by the Seismometric Network of Friuli Venezia Giulia, managed by OGS, were reported on a 10-km wide band, having the section itself as axis (Fig. 15).

The proposed section shows the extent of the involvement of the basement in the Alpine shortenings. It is always dislocated from the main faults forming the different structural units. The main faults show high-angle and out-of-sequence structures at the rear of a regional nature.

Considerable analytic progress in deep structural knowledge, especially of the mountain sector, was provided by Merlini *et al.* (2002) along a geological profile between the Fella - Sava line and the Adriatic foreland, extrapolated to depths of 8-10 km below sea level.

4. The new cartography

The late 1990s were characterized by a remarkable cartographic production in Italy, thanks especially to the project "CARtografia Geologica" (CARG), promoted by the Geological Survey of Italy [SGI, then APAT, and today converged in the Istituto Superiore per la Protezione e la Ricerca Ambientale (ISPRA)], in line with the mapping programs adopted in other European

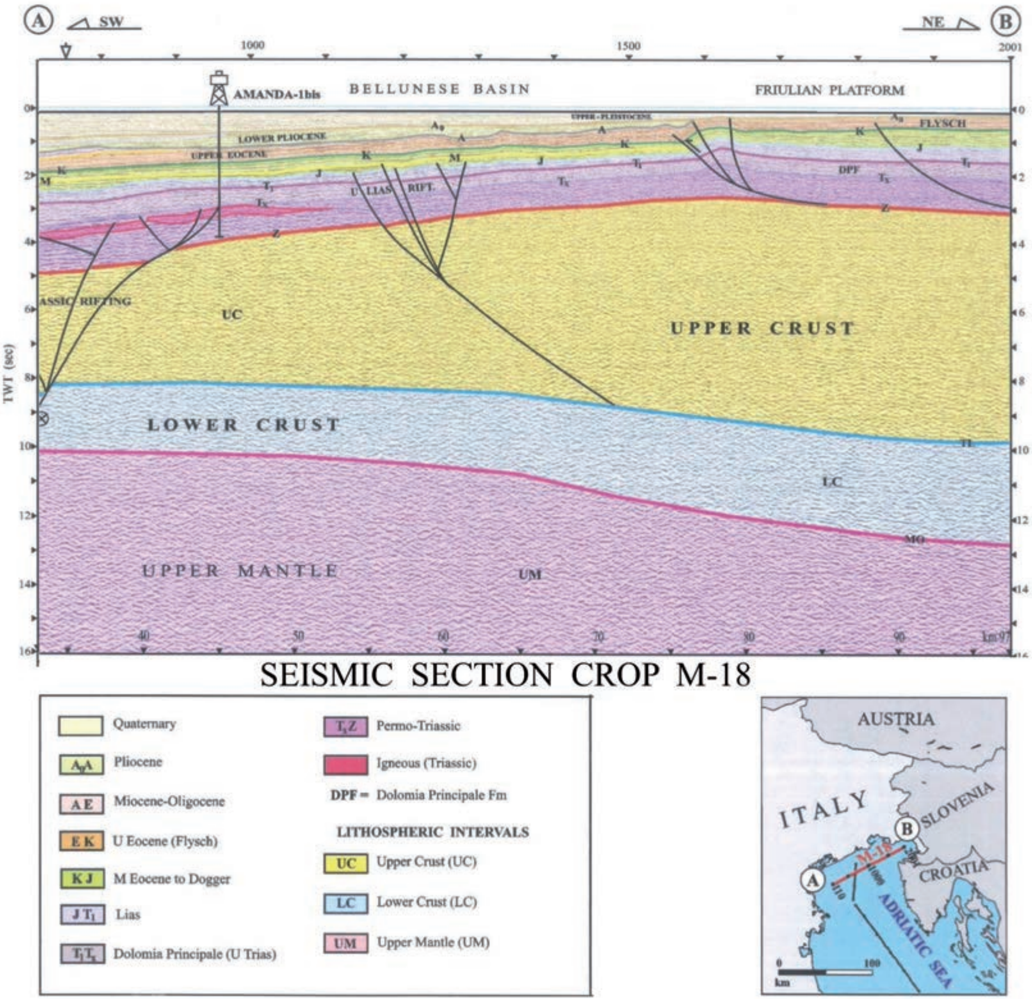

Fig. 14 - Seismic section CROP M-18 across the northern Adriatic Sea (modified from Finetti, 2005).

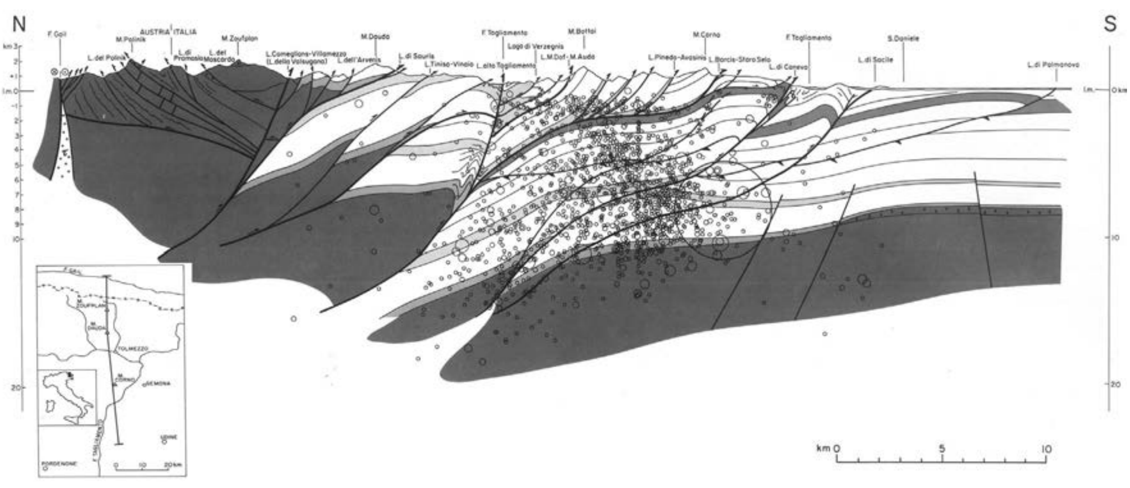

Fig. 15 - Seismo-geological section across the Carnian and Friulian Alps. The circles show the hypocentres of the earthquakes recorded between 6 May 1977 and 31 December 1989 by the OGS seismometric network of Friuli Venezia Giulia (Carulli and Ponton, 1992).

Union countries. It aimed at updating the knowledge of the geological and geophysical characteristics of the Italian territory and at the realization of geological and geothematic sheets at a 1:50,000 scale, most appropriate to summarize the need for a regional synthesis and more detailed than the preceding sheets at the 1:100,000 scale.

The Friuli Venezia Giulia Region, also considering the age of the existing geological sheets (e.g., the old "Udine" sheet, at the 1:100,000 scale, dated back to 1925), funded, through its Geological Survey, the construction of the sheets "065 Maniago" (Zanferrari *et al*., 2008a), "066 Udine" (Zanferrari *et al*., 2008b), "086 San Vito al Tagliamento" (Zanferrari *et al*., 2008c), "049 Gemona del Friuli" (Zanferrari *et al*., 2013, still in print but published on the web by ISPRA), and "031 Ampezzo" (Venturini, 2009; Venturini *et al*., 2009), all accompanied by the related explanatory notes. The cognitive tools, such as the surface and subsurface geological data, essential for proper land planning and management and, more particularly, for the prevention and mitigation of the geological and seismic risks, have been made available in such a way.

The "Map of the subsoil of the Friuli plain" (Nicolich *et al*., 2004) was also published following the agreement between the Friuli Venezia Giulia Region and the University of Trieste. The map reports the thickness of the Quaternary deposits of the plain, together with the depth of the top of the carbonates, five deep geological sections, and the lithostratigraphic sections of the wells drilled in the region in the search for hydrocarbons. This document is of great importance because it provides the scientific community with the processing and interpretation of industrial data for the deep subsurface.

Most of these data are summarized in the "Geological Map of Friuli Venezia Giulia at the scale 1:150,000" (Carulli, 2006), published by the Geological Service of the Friuli Venezia Giulia Region. This map includes the accompanying notes, some geological sections, and other summary maps, useful to understand the regional reality and the natural history.

5. Seismotectonic research

In the late 1980s, the results of innovative research led to the "Seismotectonic Model of north-eastern Italy" (Slejko *et al*., 1987, 1989), published by CNR and the National Group for the Defence against Earthquakes (GNDT). The skills of structural geologists, applied geologists, geomorphologists, geophysicists and seismologists, related to OGS and the universities of Ferrara, Milan, Modena, Padua, Torino, Trieste and Udine, contributed to this project, demonstrating the interdisciplinary approach and collaboration promoted by the PFG philosophy. The study analyses and compares all the geological and geophysical data available on the wide area characterized by high seismicity, extending from Lake Garda to the Slovenian border and from the Adriatic Sea to the Austrian border.

From a geological point of view, a structural model and a neotectonic model were developed first. In the former, the areas with a different behaviour were identified: they correspond to sectors having different pre-Quaternary geological evolution. In the second, the tectonic evolution in the Pleistocene-Holocene interval was highlighted. From the geophysical point of view, the geophysical, geodetic, gravimetric, magnetic, and especially seismological data, were analysed. The latter, based on the spatial distribution of both historical and instrumental earthquakes, identified the high seismicity area in the foothills.

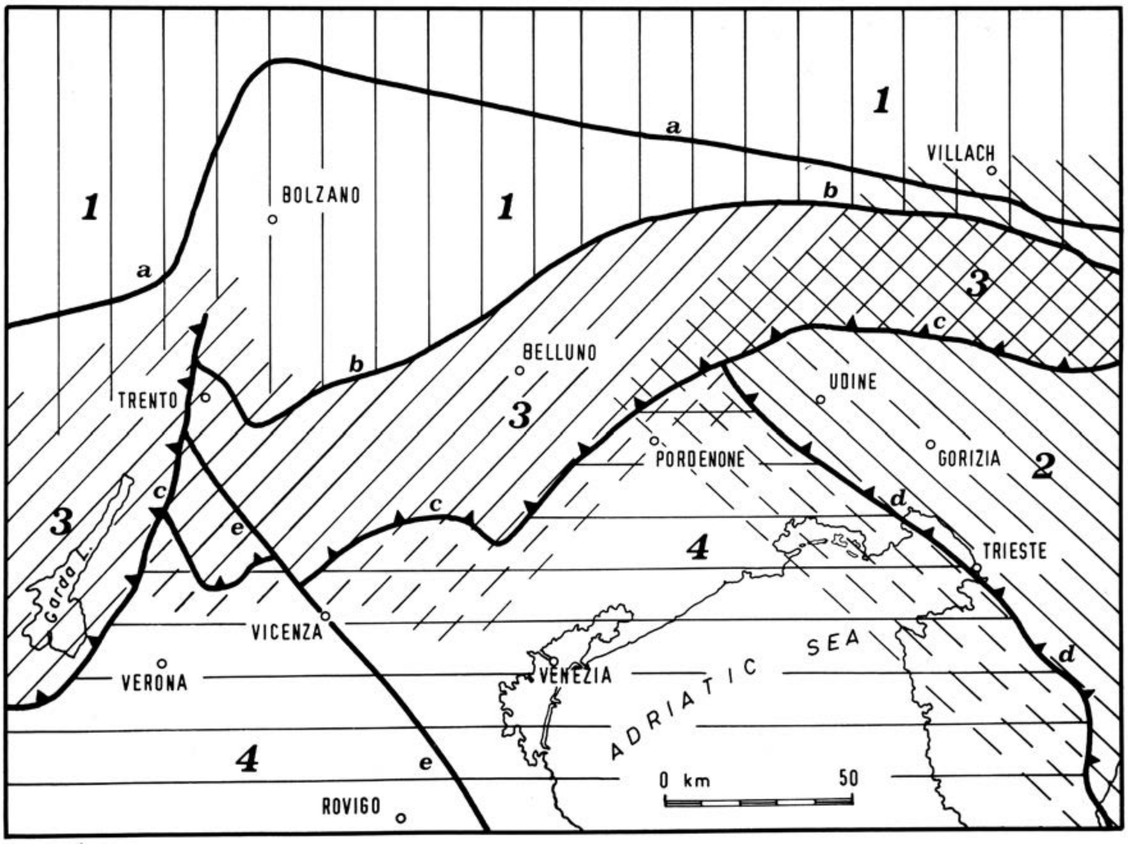

Fig. 16 - Kinematic and structural units in north-eastern Italy (Slejko *et al.*, 1989). Legenda: 1 - Alps s.s. and northern sector of the Southern Alps; 2 - External Dinarides; 3 - southern sector of the Southern Alps; 4 - Southern Alps and Apennines foreland. Tectonic limits: a - Insubric Lineament; b - Valsugana line (at west) and Fella-Sava line (at east); c - Southern Alps front; d - External Dinaric front; e - Schio-Vicenza line.

Four distinct kinematic-structural megaunits were proposed in such a way (Fig. 16); based on seismological considerations; these were then divided into ten homogeneous zones from the seismogenic point of view (Fig. 17).

The seismotectonic studies continued also in order to define a more precise location of the source of the 6 May 1976 main shock and of those of September the same year. Immediately after the event, the first location of the main shock was roughly defined by the seismologists of OGS Trieste station (TRI), belonging to the World Wide Standardized Seismographic Network and closest to the epicentre, in the Mount San Simeone area and released to the information media[5].

For this purpose, specific seismotectonic studies continued and have been refined in parallel with the improvements in interpreting the regional deep tectonic structures, while the active faults and related seismic sources were also defined (Aoudia *et al.*, 2000; Galadini *et al.*, 2001, 2005; Poli *et al.*, 2002, 2008; Carulli and Slejko, 2005; Burrato *et al.*, 2008; Cheloni *et al.*, 2012; Moratto *et al.*, 2012; Bressan *et al.*, 2016).

[5] In the collective imagination of legends and folklore in Friuli, Mount San Simeone was for years, and still is for many of the elderly, the home of the "orcolàt", the enormous evil ogre who sometimes comes out of his den, trampling on the mountains heavily and causing earthquakes.

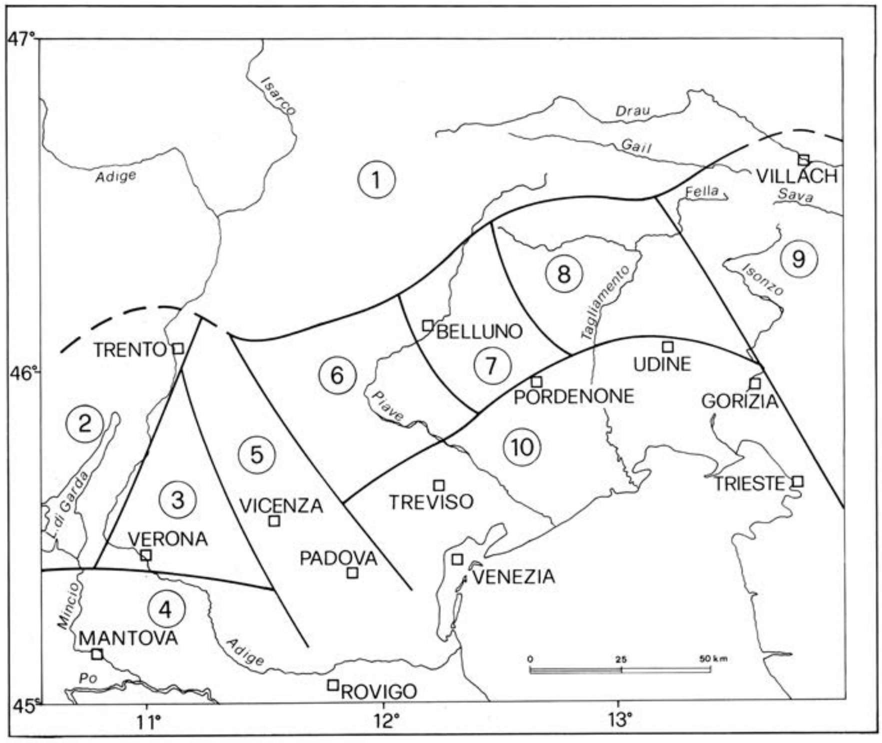

Fig. 17 - Seismotectonic model of north-eastern Italy (Slejko *et al.*, 1989).

The framework of active Pliocene-Quaternary faults in the entire eastern Southern Alps, from Thiene to Friuli, were defined in the seminal work of Galadini *et al.* (2005), on the basis of new geomorphological and structural data. The authors identified ten seismogenic sources as potentially responsible for earthquakes with $M \geq 6$ in the complex system of thrust faults of the Southern Alpine front. Six of these sources (Arba-Ragogna, Cansiglio, Gemona-Kobarid, Medea, Polcenigo-Maniago, Susans-Tricesimo and Trasaghis) belong to fault segments of the Friuli region. The epicentres of the main events, highlighting those of 6 May and 15 September, according to the locations of Slejko *et al.* (1999), Peruzza *et al.* (2002), and Poli *et al.* (2002), are projected on a N-S oriented geological section from the Gail Valley to the Cargnacco, Lavariano and Terenzano wells (Fig. 18).

The geometry of tectonic structures, as well as the interrelationships between them and the different evolutionary stages they have undergone over time, are illustrated in the volume of Ponton (2010), through 8 longitudinal and transversal geological sections with respect to the Alpine chain. On some of these central eastern sections (Fig. 19), Bressan *et al.* (2016) projected the hypocentres of the earthquakes located by OGS. They stressed the spatial organization of the seismicity in Friuli and western Slovenia and its relationship with the complex structure resulting from the overlapping of several tectonic phases that caused the maximum interference between the Alpine and Dinaric domains.

Finally, making a brief retrospective summary, it can be considered that the structural model of the seismic area affected by the 1976 and following earthquakes has remained largely unchanged, although greatly enriched by a better definition of the tectonic structures and, especially, their seismogenesis. Moreover, only in the 1980s was the importance of the

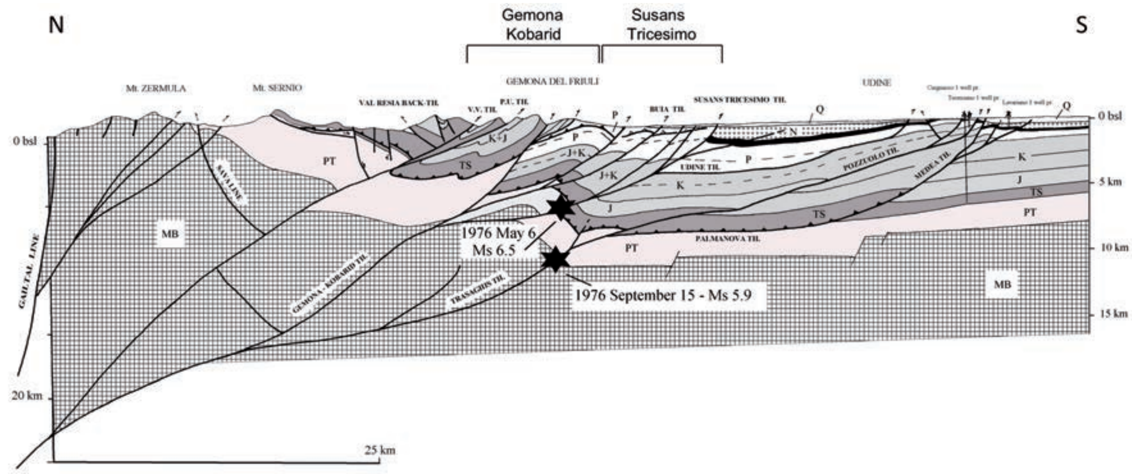

Fig. 18 - Reflection seismic section with the 1976 main shocks (modified from Galadini *et al*., 2005). The two segments show the DISS seismic sources intersected by the section.

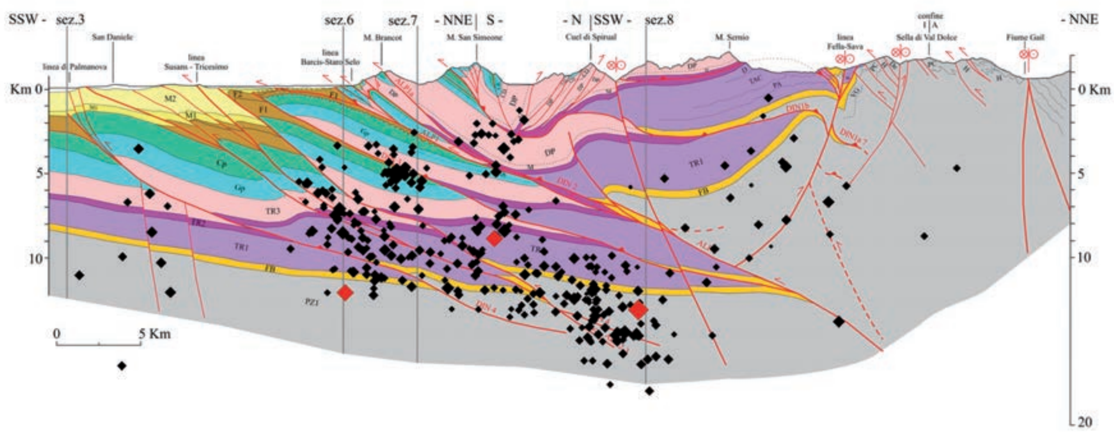

Fig. 19 - Geological section with seismicity (modified from Bressan *et al*., 2016).

discipline "Structural Geology" recognized. It became a key discipline in the Italian universities, becoming an independent scientific field (GEO/03) in the macrosector of Geosciences in 1990, and, in quick succession, a focal point of very active research groups.

5. Conclusions

In conclusion, it is worth highlighting that the scientific work triggered by the 1976 earthquake, from that date until today, adds up to more than 300 papers [see a summary in Slejko (2018)]. These demonstrate that this event was, and still is, a topic whose importance has never been matched in the Italian seismic history.

Further studies, under improvement and refinement, are still in progress by researchers of Earth Sciences who are interested in understanding the seismic risk in Friuli Venezia

Giulia (Poli and Zanferrari, 2018; Rebez *et al.*, 2018). They are conscientiously involved in these issues that have a profound impact on the entire society, being aimed at an ever-greater definition of seismic hazard and risk as priority instruments for the defence against earthquakes.

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