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G.N.D.T. - U.R.1.4. SISMOTETTONICA DELLE ALPI

SEISMOTECTONIC MODEL OF NORTHEASTERN ITALY: AN APPROACH

Lavoro presentato all'International Symposium on
"ENGINEERING GEOLOGY PROBLEMS IN SEISMIC AREAS"
Bari, 13-19 Aprile 1986

Estratto da
GEOLOGIA APPLICATA E IDROGEOLOGIA
BARI, 1986 - VOLUME XXI - PARTE II

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SEISMOTECTONIC MODEL OF NORTHEASTERN ITALY: AN APPROACH

INTRODUCTION AU MODELE SEISMOTECTONIQUE DE L'ITALIE DU NORD-EST

SUMMARY

All the geological and geophysical data available for northeastern Italy, area of high seismicity, have been updated and reciprocally compared to identify seismotectonically homogeneous zones. Neotectonic and seismic activities are relevant especially at the interaction between the Southalpine Chain and the External Dinaric one. The obtained result consists in the definition of four megaunits, which are the first sketch of the regional seismotectonic model, basis for hazard zoning.

RESUME

Toutes les données géologiques et géophysiques disponibles pour l'Italie du Nord-Est, région à sismicité élevée, ont été mises à jour et comparées dans le but de repérer des zones homogènes au point de vue sismotectoni-

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que. L'activité néotectonique et sismique est importante surtout dans les zones d'interaction entre les Alpes méridionales et les Dinarides. Le résultat obtenu consiste dans la détermination de quatre mégaunités constituant la premiére ébauche du modéle sismotectonique régional, représentant la base pour une zonation de « hazard ».

1. PURPOSE OF THE RESEARCH

For the assessment of the regional seismic hazard it is necessary to define the seismogenetic zones that determine the seismicity. These zones can be precisely defined in geometry and seismic character only having available a seismotetonic model, which explains the geodynamic evolution and justifies the seismicity of the region. From regional seismic hazard maps, more detailed studies (microzoning) can be performed. The seismotectonic modelling has been recognized as one of the prominent research themes by the « Gruppo Nazionale per la Difesa dai Terremoti » (G.N.D.T.) of the « Consiglio Nazionale delle Ricerche » (C.N.R.) in the frame of which the present work has been carried on.

The studied area is comprised between the Garda lake and Yugoslavia and between the Po delta and Austria and it is characterized by high seismicity especially in the prealpine belt.

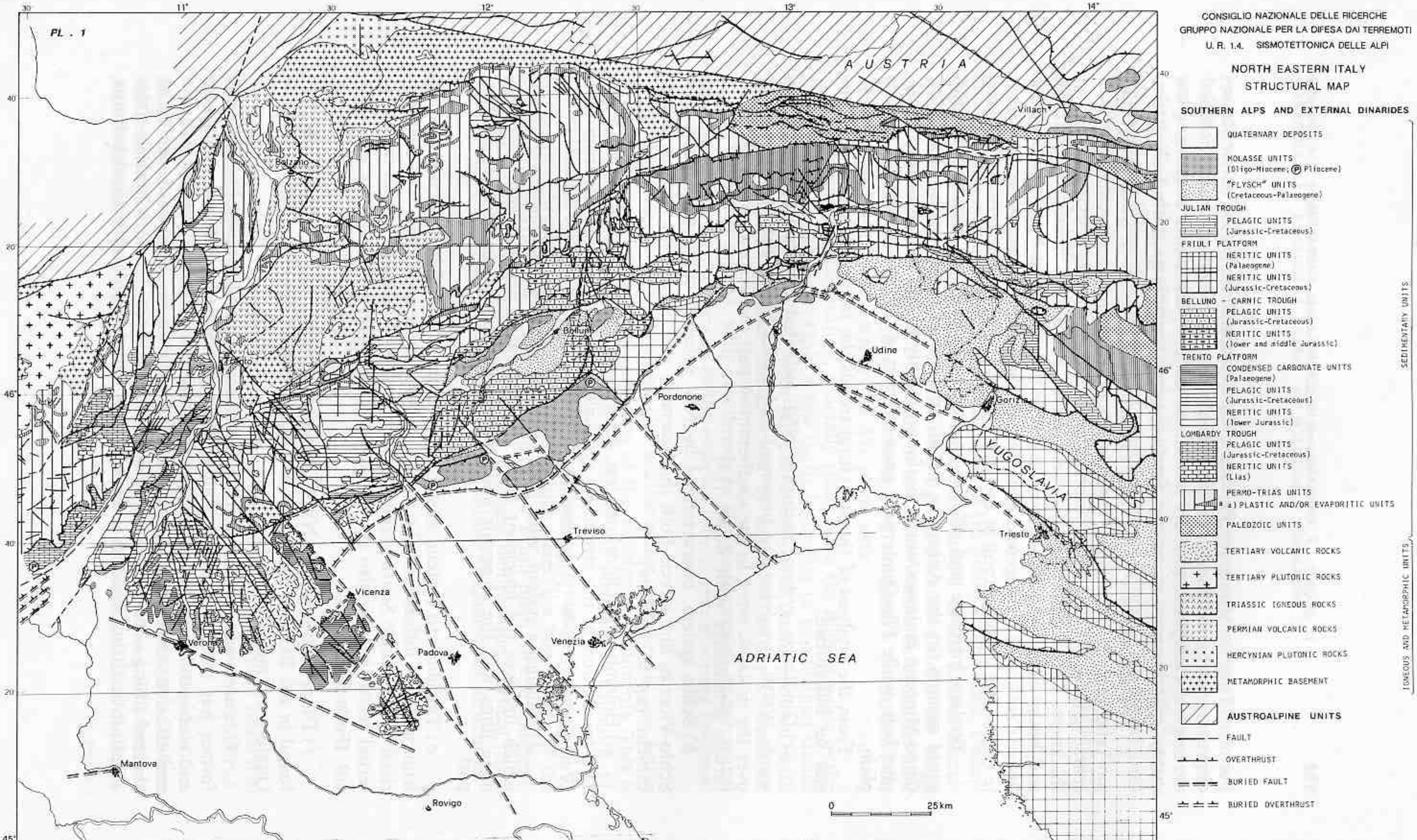
Updated geological [7, 9, 14] and geophysical data [2, 10] have been collected, and through a general comparison, an approach to the seismotectonic model has been proposed. As basic documents the final results from the C.N.R.'s « Progetto Finalizzato Geodinamica » have been used, integrated with further information, while most of the seismological data have been ad hoc produced.

2. GEOLOGY

In the studied area, which encompasses the central and eastern sector of the Southern Alps, as well as a small part of the External Dinarides, the following elements are to be observed (Pl. 1).

a) The crystalline basement mainly consists of phyllites and gneisses metamorphosized in Hercynian or pre-Hercynian times, intruded by upper Ordovician or Permian granitoids. It is widely interested by South-verging overthrusts with WSW-ENE strike and North-verging overthrusts with E-W strike which involve the cover as well.

b) The Paleozoic non-methamorphic sequences are made up of terrigenous, carbonatic and volcanic rocks, whose age ranges from Caradoc to middle



PL . 1
CONSIGLIO NAZIONALE DELLE RICERCHE
GRUPPO NAZIONALE PER LA DIFESA DAI TERREMOTI
U. R. 1.4. SISMOTETTONICA DELLE ALPI
NORTH EASTERN ITALY
STRUCTURAL MAP
SOUTHERN ALPS AND EXTERNAL DINARIDES
QUATERNARY DEPOSITS
MOLASSE UNITS (Oligo-Miocene; (P) Pliocene)
"FLYSCH" UNITS (Cretaceous-Palaeogene)
JULIAN TROUGH
PELAGIC UNITS (Jurassic-Cretaceous)
FRIULI PLATFORM
NERITIC UNITS (Palaeogene)
NERITIC UNITS (Jurassic-Cretaceous)
BELLUNO - CARNIC TROUGH
PELAGIC UNITS (Jurassic-Cretaceous)
NERITIC UNITS (lower and middle Jurassic)
TRENTO PLATFORM
CONDENSED CARBONATE UNITS (Palaeogene)
PELAGIC UNITS (Jurassic-Cretaceous)
NERITIC UNITS (lower Jurassic)
LOMBARDY TROUGH
PELAGIC UNITS (Jurassic-Cretaceous)
NERITIC UNITS (Lias)
PERMO-TRIAS UNITS
a) PLASTIC AND/OR EVAPORITIC UNITS
PALEOZOIC UNITS
SEDIMENTARY UNITS
TERTIARY VOLCANIC ROCKS
TERTIARY PLUTONIC ROCKS
TRIASSIC IGNEOUS ROCKS
PERMIAN VOLCANIC ROCKS
HERCYNIAN PLUTONIC ROCKS
METAMORPHIC BASEMENT
IGNEOUS AND METAMORPHIC UNITS
AUSTROALPINE UNITS
FAULT
OVERTHRUST
BURIED FAULT
BURIED OVERTHRUST
AUSTRIA
YUGOSLAVIA
ADRIATIC SEA
Villach
Bolzano
Trento
Belluno
Udine
Pordenone
Gorizia
Trieste
Treviso
Vicenza
Verona
Padova
Venezia
Mantova
Rovigo
0
25 km
11°
12°
13°
14°
45°
46°

Plate 1.

Permian. They constitute the Paleocarnian Chain and are buried below the sedimentary cover southwards. Alpine tectonics have reactivated and modified an original Hercynian severely tectonized pattern. The above sequences are thinly split because of mostly South-verging overthrusts with E-W strike.

c) The sedimentary cover ranges in age from Permian to Quaternary. Permo-Triassic units (alternating carbonatic and terrigenous sediments, as well as sparse igneous bodies) are widespread and characterized by varying facies and thickness. Those units ageing upper Triassic-Cretaceous consist of platform and basin carbonatic sediments. They are then followed by flysch units of lower Cretaceous-Paleogene age in the central eastern sector, while Paleogenic carbonatic units outcrop in the western part and in the External Dinarides.

Tertiary intrusive and effusive masses outcrop in the Lessini-Berici-Euganei mounts, in the Adamello massif, and subordinately in the Dolomites. Oligo-Miocene molasses are to be found mainly in the central-eastern prealpine belt, while Plio-Quaternary ones outcrop in the Veneto - Friuli and Po plain.

From the analysis of the structural trends the following tectonic systems can be indentified.

a) Giudicarie system, featuring NNE oriented overthrusts dipping towards WNW, involving the basement and which brings the Mesozoic units over the molassic ones. In the southernmost part the vertical dip of the overthrusts diminishes with depth [14].

b) Schio system, characterized by NW oriented subvertical faults. The Schio-Vicenza line affects both the basement and cover with variable displacement (up to 2000 m).

c) Dolomites sinclinorium, less deformed than the neighbouring areas. The orientation of the structures gradually changes towards NE from ENE (Valsugana) to E-W (Tagliamento).

d) Valsugana system, with ENE oriented and NNW dipping overthrusts, which involves the basement along the Valsugana and Bassano-Valdobbiadene lines, and the Neogenic and Quaternary molasses in its most external part.

e) Tagliamento system, eastern extension of the above mentioned one, from which it differs in strike and in its being more shortened. It is characterized by low angle South-verging overthrusts, E-W oriented, which in the external sector involve also the molassic units. Subvertical faults are also present (Fella-Sava line).

f) Dinaric system, with NW-SE oriented overthrusts NE dipping. They are found in the External Dinarides and in the Friuli plain where they affect the Quaternary molassic units.

This area was involved in both the Hercynian and Alpine orogenies. The former has interested the crystalline basement and the Paleocarnian Chain and was accompanied by intrusive and effusive phenomena. Further intrusive and effusive manifestations, particularly evident in the Dolomites, denote an aborted rifting occurred during middle-Triassic times. Then, in Jurassic times a definitive rifting created a series of N-S oriented paleostructural features, from East to West: Lombardia basin, Trento platform, Belluno-Carnia basin, Friuli platform, Tolmin basin and the High Karst. The rifting process supposedly caused a crustal thinning and activated listric faults. Since the Cretaceous, the approaching of the African plate to the European one would lead to the Alpine collision and subsequent crustal shortening which continued until recent times.

Tectonic activities during middle Pleistocene-Holocene times has been recognized [3, 16] in the following tectonic system (Pl. 2).

a) Giudicarie system, marked by overthrusts and reverse faults in the southern sector. There is evidence of a general uplifting.

b) Schio system, particularly active East of the Schio-Vicenza line. Underground data show the movements to be mostly vertical. In the Lessini-Berici-Euganei block there is a complex rise with a general southward dip: the hinge zone with respect to the plain appears to be in the Verona deformation belt. Further South there is a zone characterized by subsidence phenomena increasing eastward and towards the Po plain axis.

c) Dolomites synclinorium, generally rising, with the highest value in the Cortina area: 1 mm/year. Only a few faults belonging to two distinct trends are considered active, either with NE-SW direction or, more recently, with NW-SE direction; the latter characterized by dextral strike-slip movements.

d) Valsugana system, with overthrusts in the southernmost sector which are responsible for the genesis of the external reliefs, area of strong deformation.

e) Tagliamento system, where the southernmost overthrusts are active and may be seen in large deformations of the Pleistocene sediments. This is also the zone of maximum crustal shortening of the Southalpine Chain [6, 8].

f) Dinaric system, which in the area considered is mainly represented by buried overthrusts the most external of which mark the boundaries of the subsidence area located in the middle and low Friuli plain. In the southernmost mountain sector, which shows the strongest deformation, vertical faults with Dinaric direction dislocate the longitudinal Tagliamento structures.

3. CRUSTAL STRUCTURE

The Alps have been studied by means of several deep seismic refraction soundings (DSS) carried out, since more than 30 years, mainly within international cooperation programs [11, 12].

Yet, the results obtained do not allow an easy contouring of the Moho isobates, especially in the area we are dealing with. The true connections between the geometry of the structures at the base of the crust in the Po-Adriatic foreland and those which are found in the Alps and towards North and East in the Di-

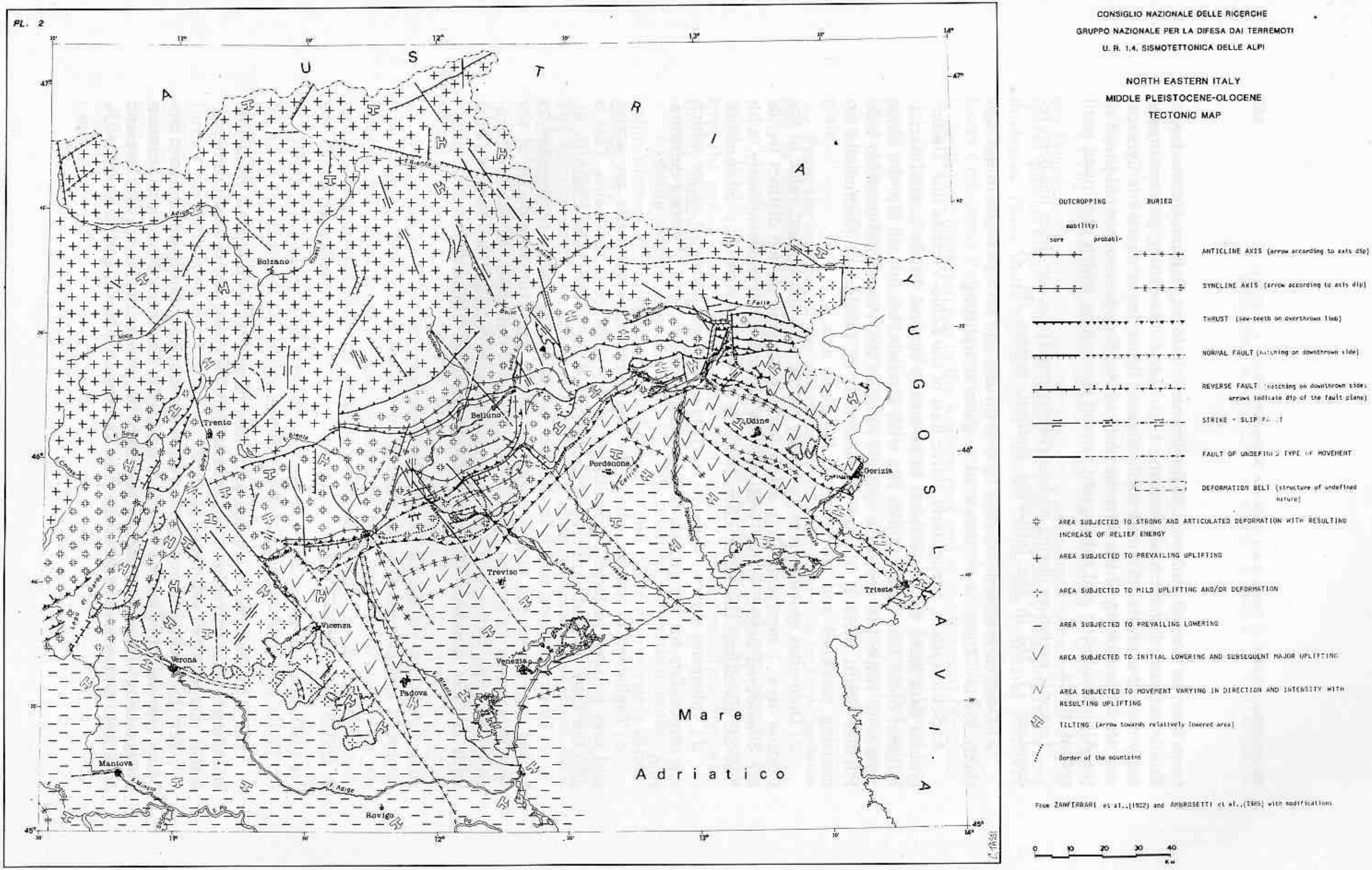

PL. 2
CONSIGLIO NAZIONALE DELLE RICERCHE
GRUPPO NAZIONALE PER LA DIFESA DAI TERREMOTI
U. R. 1.4. SISMOTETTONICA DELLE ALPI
NORTH EASTERN ITALY
MIDDLE PLEISTOCENE-OLOCENE
TECTONIC MAP
OUTCROPPING
BURIED
mobility:
sure
probable
ANTICLINE AXIS (arrow according to axis dip)
SYNCLINE AXIS (arrow according to axis dip)
THRUST (saw-teeth on overthrown limb)
NORMAL FAULT (hatching on downthrown side)
REVERSE FAULT (hatching on downthrown sides arrows indicate dip of the fault plane)
FAULT OF UNDEFINED TYPE OF MOVEMENT
DEFORMATION BELT (structure of undefined nature)
AREA SUBJECTED TO STRONG AND ARTICULATED DEFORMATION WITH RESULTING INCREASE OF RELIEF ENERGY
AREA SUBJECTED TO PREVAILING UPLIFTING
AREA SUBJECTED TO MILD UPLIFTING AND/OR DEFORMATION
AREA SUBJECTED TO PREVAILING LOWERING
AREA SUBJECTED TO INITIAL LOWERING AND SUBSEQUENT MAJOR UPLIFTING
AREA SUBJECTED TO MOVEMENT VARYING IN DIRECTION AND INTENSITY WITH RESULTING UPLIFTING
TILTING (arrow towards relatively lowered area)
Border of the mountains
From ZANFERRARI et al.,(1982) and AMBROSETTI et al.,(1985) with modifications
0 10 20 30 40
Km
A U S T R I A
Y U G O S L A V I A
Mare
Adriatico
Bolzano
Trento
Belluno
Pordenone
Udine
Gorizia
Trieste
Treviso
Vicenza
Verona
Venezia
Padova
Mantova
Rovigo
Lago di Garda
F. Adige
F. Brenta
F. Piave
F. Po
F. Mincio
F. Oglio
F. Isonzo
Tagliamento
Livenza
11°
12°
13°
14°
46°
47°
45°

Plate 2.

naric chain still require a better explanation. Moreover, along the DSS profiles, potential low velocity layers and neighbouring intervals with very high velocity values have been found. They represent outstanding data to connect the superficial tectonic style to the different orogenetic phases which have given rise to the tectonic setting of the deeper crustal layer. Hence there are still doubts when linking the deep crustal structures to the observed seismic activity. A sharp increase in the crustal thickness is observed towards the North along all the DSS profiles. This causes Moho depths of nearly 50 km to be present in the area included from the Venosta valley to Lienz. From here northwards and hence towards the border with Austria and Western Germany the Moho gradually rises up to depths of 35-30 km. The Moho deepening towards the Alps s.s. is supported also by the evidence of a negative trend of the Bouguer anomalies.

The crustal structure reveals a high in the Lessini-Berici ridge (Verona gravimetric high) where the Moho is nearly 30 km deep. Towards the Apenninic foredeep the Moho plunges as a monocline down to depths ranging from 35 to 40 km. Eastwards the transition to the Veneto-Friuli plain appears sharper, taking place in the area of the Schio system. Similar is the situation towards North, in the area of the Valsugana system and westwards, where the boundaries of the Moho high are fixed by the Giudicarie system. Further East another structural high is observed, which belongs to the Po-Adriatic foreland, with the Moho at depths close to 30 km in western Istria (also a gravimetric high). This may be connected with the middle-Adriatic high perhaps also with the Verona high. From here onwards the Moho deepens as a monocline towards southern Friuli and then with a more emphasized flexure at the front of the

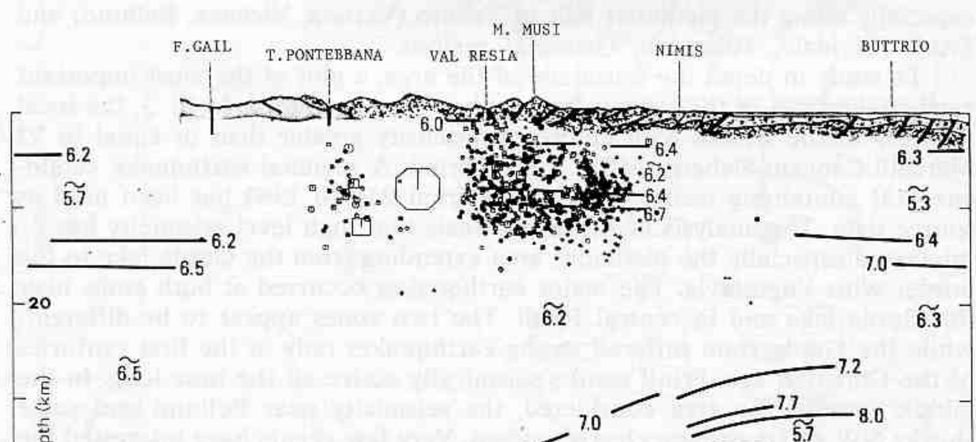


Fig. 1 - Geological and geophysical N-S cross section across central Friuli.

Southern Alps where it exceeds a depth of 40 km (Fig. 1). Another flexure brings the Moho down to depths higher than 50 km towards the Alps s.s. axis.

Furthermore, East of Gorizia a complicated situation exists as further crustal thickenings have been found in the area included roughly between Tolmin and Idrija. Here a deep trough (depth higher than 45 km) is found oriented NW-SE. It is thought to be an extension of similar structures which are present in Dalmatia-Erzegovina and which have been interpreted as a root area of crustal SW-verging overthrusts [1].

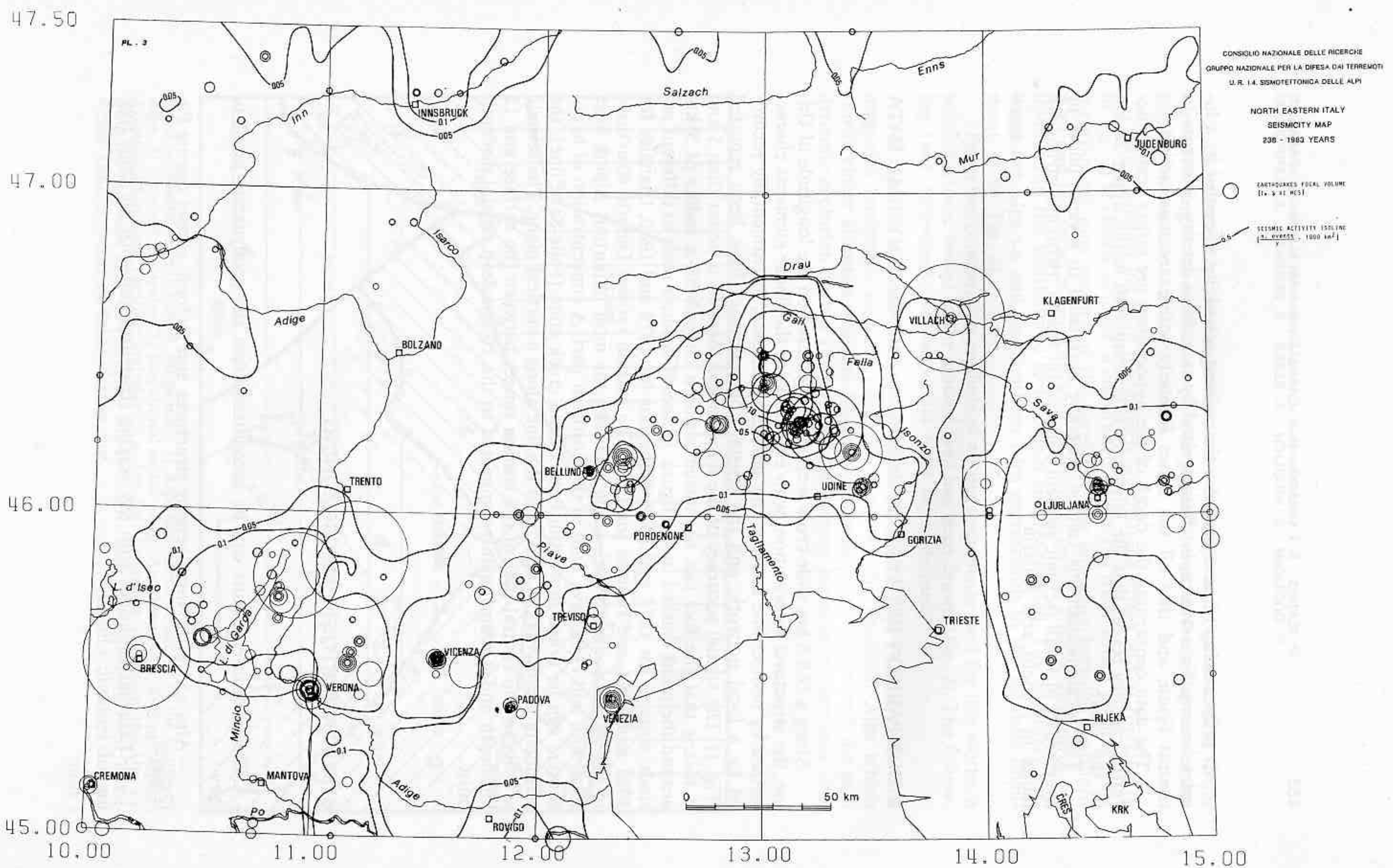
Moreover an interval with velocity values close to 6.7 km/s has been found in central Friuli at depths of nearly 10 km (Fig. 1). It can be significantly correlated with the seismic activity in the area. According to the areomagnetic interpretation of the nature and geometry of the basement [4] it also has to be linked to structures which are present near the top of the basement.

Correlation with aeromagnetic data allows to confirm that the basement, all along the southernalpine front is involved in a complex tectonie situation and in any case displaced and overthrust into the basement of the Adriatic foreland and its cover. This framework occurs in the Valsugana system and further East in the Tagliamento one.

4. SEISMICITY

Northeastern Italy has been hit by numerous destructive earthquakes, especially along the piedmont belt in Veneto (Verona, Vicenza, Belluno) and Friuli (Cividale, Tolmezzo, Gemona) regions.

To study in detail the seismicity of the area, a plot of the most important earthquakes and of the seismic activity has been produced. In Pl. 3, the focal volumes of the shocks with epicentral intensity greater than or equal to VI Mercalli-Cancani-Sieberg (MCS) are reported. A regional earthquake catalogue [13] containing nearly 5000 events from 238 to 1983 has been used as source data. The analysis of the plot reveals that high level seismicity has interested especially the piedmont area extending from the Garda lake to the border with Yugoslavia. The major earthquakes occurred at both ends: near the Garda lake and in central Friuli. The two zones appear to be different: while the Garda zone suffered strong earthquakes only in the first centuries of the Christian age, Friuli results seismically active all the time long. In the middle part of the area considered, the seismicity near Belluno and some shocks NW of Treviso are clearly evident. Very few events have interested the Alpine sector while Slovenjia appears definitely active but with a seismicity lower and less concentrated than in the Veneto - Friuli piedmont belt. Another quantity reported in Pl. 3 is the seismic activity [15] in terms of statistical number of earthquakes of magnitude 3.9 over 1000 km^2 per year. The seismic activity is high in Carnia (values > 1.0) while values greater than 0.1 are to be found along the piedmont belt and in almost all the territory of Slovenija. In this frame, two minima can be observed: the first located between Verona and Vicenza and the second separating Friuli from Slovenija.


PL. 3
CONSIGLIO NAZIONALE DELLE RICERCHE
GRUPPO NAZIONALE PER LA DIFESA DAI TERREMOTI
U.R. 1.4. SISMOTETTONICA DELLE ALPI
NORTH EASTERN ITALY
SEISMICITY MAP
236 - 1983 YEARS
47.50
47.00
46.00
45.00
10.00
11.00
12.00
13.00
14.00
15.00
INNSBRUCK
BOLZANO
TRENTO
BELLUNO
PORDENONE
UDINE
GORIZIA
TRIESTE
VILLACH
KLAGENFURT
JUDENBURG
LJUBLJANA
RIJEKA
KRK
CRES
BRESCIA
VERONA
VICENZA
PADOVA
VENEZIA
TREVISO
MANTOVA
CREMONA
ROVIGO
Inn
Salzach
Enns
Mur
Drau
Gail
Fella
Isonzo
Sava
Isarco
Adige
Piave
Tagliamento
Mincio
Po
L. d'Iseo
L. di Garda
50 km
Plate 3.

It is interesting to note that also the present seismicity, recorded by a local seismometric network, is characterized by maximum density of events in central Friuli, and that all the zones formerly active are now active.

The data concerning the depth of the hypocenters are rather scanty; nevertheless they reveal that the seismicity is concentrated in the upper 20 km of the crust.

The focal mechanisms can be generally correlated to reverse faults or overthrusts in Friuli (seismic sequence started on May 6, 1976) and strike-slip faults in Veneto and Austria.

5. COMPARISON BETWEEN GEOLOGICAL AND GEOPHYSICAL DATA

Along a N-S 5 km wide cross section [5], centered on the longitude of Udine, the structural information, with emphasis for the linear elements characterized by neotectonic activity, the seismological data, instrumentally recorded by a local network, and the crustal characteristics have been reported (Fig. 1). The spatial accuracy of the hypocenters location is better than 3 km: it means that the foci can be moved inside a circle with a radius of 3 km around the point marked in the figure. Different symbols refer to different periods: squares for 1977 and 1978, octhagons for 1979 and 1980, triangles for 1981 and 1982, and rhombs for 1983. The section crosses Dinaric structures in the central-southern part, while it crosses the most important Alpine lines (Gail line and Fella-Sava line) in the northern part. A concentration of hypocenters can be noted down the Pontebbana creek zone (Fella-Sava line): the seismicity represents the activity of the line along a vertical plane. The seismic activity in the central part of the section ranges between the surface and 15 km depth and it seems mainly connected to the 10 km deep crustal discontinuity.

6. SEISMOTECTONIC MACROZONING

Three distinct chains can be recognized from the geodynamic point of view:

– Alps s.s., with North-verging structures and tectonic climax during Paleogene;

– External Dinarides with SW-verging structures and with the same timing of tectonic climax;

– Southern Alps, in the studied area with SE- and South-verging structures evolving from middle-Miocene to present times, and sharing a common foreland with the Apenninic Chain.

The boundary between the eastern Southalpine Chain and its foreland (c in Fig. 2) is clearly defined: a southward advancing front which progressively incorporates new sectors of the foreland. The boundary between Southern Alps and Dinarides is more difficult to trace, as several Dinaric structures are involved in the Southalpine tectogenesis and reactivated. The boundary between the Alps s.s. and the Southern Alps corresponds to the Insubric lineament (a in Fig. 2).

From the comparative analysis of all the documents used for this works, a seismotectonic model of the studied area has been drawn (Fig. 2). The following four seismotectonic megaunits have been defined.

1) Alps s.s. and northern sector of the Southern Alps (1 in Fig. 2). This magaunit comprises also the northern sector of the Southern Alps which shows closer affinities with the Alps s.s. in structural characters and the geodynamic evolution during Tertiary and Quaternary times. It is essentially cha-

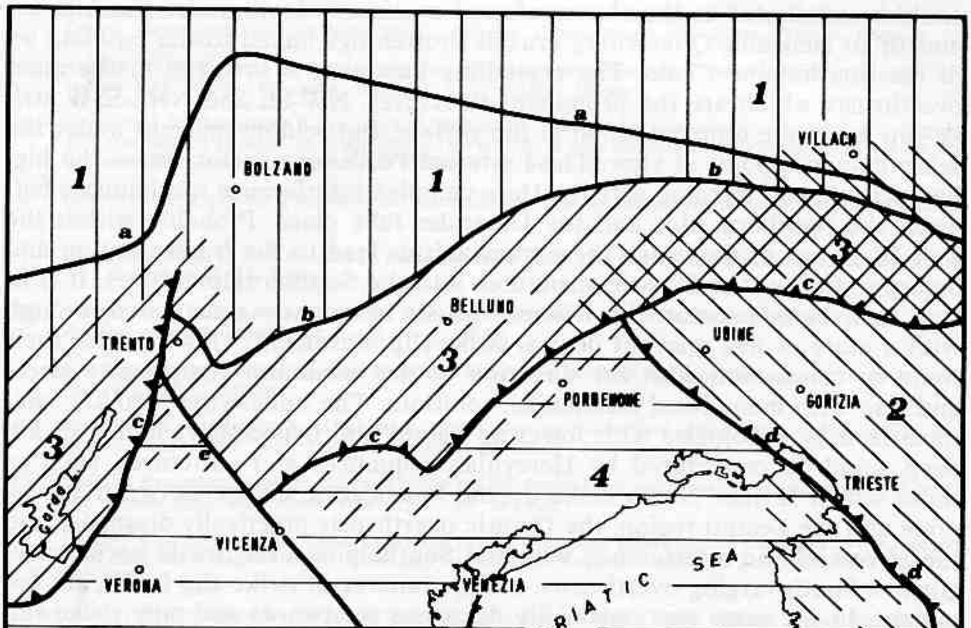


Fig. 2 – Seismotectonic model. Megaunits: 1) Alps and northern sector of the Southern Alps; 2) External Dinarides; 3) Meridional sector of the Southern Alps; 4) Southalpine-Apenninic foreland. Tectonic boundaries: a) Insubric lineament, separating the Alps s.s. from the Southern Alps; b) Valsugana and Fella-Sava lines; c) Southalpine front; d) External Dinaric front; e) Schio-vicenza line.

racterized by a general differential uplifting, with diffuse although minor strike-slip movements along NW-SE and NNE-SSW striking faults. A zone of maximum deepening of the Moho (> 50 km), probably linked of the alpine Cretaceous subduction, is found between the Venosta valley and Lienz with WSW-ENE direction. Seismicity is low throughout the whole sector.

2) External Dinarides (2 in Fig. 2). Dextral strike-slip movements along major faults with NW-SE strike characterize this megaunit. Lesser activity is associated with the overthrusts, which often show relevant strike-slip component or are active in a transpressive frame. The Moho deepens in a elongated zone, (> 45 km) along a NW-SE direction parellel to the surface structures, corresponding to the area of highest earthquake density (M > 4.1). This anomaly was connected to a subduction zone which started in Paleogene, and which is considered as still active [1]. In accordance with the present geodynamic setting, we believe that this zone of crustal thickening is now interested by intracrustal shear and detachment phenomena. It is likely that the same is happening along the Apenninic front. Seismicity is diffuse and locally high.

3) Meridional sector of the Southern Alps (3 in Fig. 2). This megaunit is characterized by the highest neotectonic and seismic activity, though not equally distributed. The depth of the Moho increases towards North: this could be attributed to the above referred maximum depth under the Alps s.s. and/or to Neogenic-Quaternary crustal shortenings linked to the building up of the Southalpine Chain. The crystalline basament is involved in the main overthrusts which are the prominent structures. NW-SE and NNE-SSW strike-slip faults are quite common at the surface, but seldom relevant under the seismotectonic point of view. The Eastward Pordenone sector shows the highest seismic and tectonic activity. Here complex interference mechanisms between the Southern Alps and the Dinarides take place. Probably within the first 10-12 km of the crust, these mechanisms lead to the fragmentation and incorporation of the Dinaric structures into the Southernalpine ones. It is likely that, in this sector, the Dinaric thrusts be anyhow reactivated, though with a more or less relevant dextral strike-slip movement. This fits with their trend in connection with the direction of the maximum compressive stress and also with many focal mechanism solutions. The underlying 5-10 km, characterized by lithologies with lower *vp* values and hypocenters about 15 km deep, coud be constituted by Hercynian sequences and structures, such as those which further North make up the Paleocarnic Chain. Between Pordenone and the Lessini region, the Dinaric overthrusts practically disappear and the effects of the interference with the Southalpine overthrusts become negligible. South-verging overthrusts, cut by transversal strike-slip faults, are dominant. In the same way, seismicity decreases westwards and only strike-slip focal mechanisms have been calculated here, including those in the Cansiglio-Belluno zone. The region around the Garda lake, which belongs to the central sector of the Southern Alps, differs from the eastern one in an earlier tectogenesis, in structural trends (ranging from NNE-SSW to E-W), in a lower degree of seismicity and in strike-slip focal mechanisms with shallower hypocenter depth.

4) Southalpine-Apenninic foreland (4 in Fig. 2). In both the Lessini and the western Istria sectors there is a normal or barely thin crust. The Lessini

sector can be regarded as a northward penetrating wedge into the Southalpine Chain. The thrusts of the Garda-Trento area overlap its western border. In its eastern border the Southalpine overthrusts are laterally drifted along the NW-SE striking Schio-Vicenza line (e in Fig. 2). Seismicity is relatively low but diffuse, and the maximum hypocentral depths (> 20 km) of the whole studied area are reached. In the foredeep basin (northern Adriatic region and eastern Veneto-Friuli plain), the vertical movements are high also during Pleistocene. Seismicity is even lower and sparse.

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