BOLLETTINO DI GEOFISICA TEORICA ED APPLICATA
supported by CNR (National Council of Research)

Vol. XXXI 122 June 1989

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BOLLETTINO DI GEOFISICA TEORICA ED APPLICATA - VOL. XXXI - n. 122

Vol. XXXI 122 June 1989

BOLLETTINO DI GEOFISICA

teorica ed applicata

Boll. Geof. Teor. Appl. OGS Trieste ISSN 0006-6729

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SEISMOTECTONICS OF THE EASTERN SOUTHERN-ALPS: A REVIEW

Abstract. The more significant geological and geophysical data available for northeastern Italy, between lake Garda and the Italian border with Yugoslavia, and between the Italian border with Austria and the river Po are analyzed and compared. From the geological point of view, a structural model showing sectors with different pre-Quaternary evolution, and a neotectonic model showing the tectonic evolution in the Middle Pleistocene-Holocene period, has been developed. Available geophysical information like the gravimetric, magnetic, seismic and seismological data have been analyzed. In particular, the epicentre distributions of the historical and instrumental earthquakes identify the foothills of the area as the most active zone; the main seismicity is related to thrusts and wrench faults of the Southalpine and Dinaric trends. The direction of the tectonic features is coherent with the present known stress field. The seismicity is concentrated in upper crustal levels (5-15 km) in Friuli but hypocentre depths of 25 km were recognized in the Garda area; it is due to the ongoing shortening between the Europe and Adria plates. A seismotectonic model is presented with four major structural units; these units are then further subdivided into ten homogeneous seismogenetic zones.

INTRODUCTION

For assessing the regional seismic hazard, it is necessary to define the seismogenetic zones that determine the seismicity. These zones can be precisely defined in structure and character only when a seismotetonic model is available which explains the neotectonic evolution, and justifies the seismicity of the region.

Seismotectonic modelling was recognized as one of the most prominent research themes by the "Gruppo Nazionale per la Difesa dai Terremoti" of the Italian "Consiglio Nazionale delle Ricerche" (CNR) in the context of which a detailed report has been published (Slejko et al., 1987). The present version represents a synthesis of that work, revised and updated with the most recent geological and geophysical information.

The study area (Fig. 1) is located between lake Garda (to the west) and Yugoslavia (to the east), and between the Po delta (to the south) and Austria (to the north). It is characterized by high seismicity especially in the pre-Alpine belt. Further modern geological and geophysical data were collected, and from a general analysis, a first attempt at a seismotectonic model made. The final results from the CNR's "Progetto Finalizzato Geodinamica" (Ambrosetti et al., 1987;

Manuscript received, April 1, 1989; accepted, June 20, 1989.

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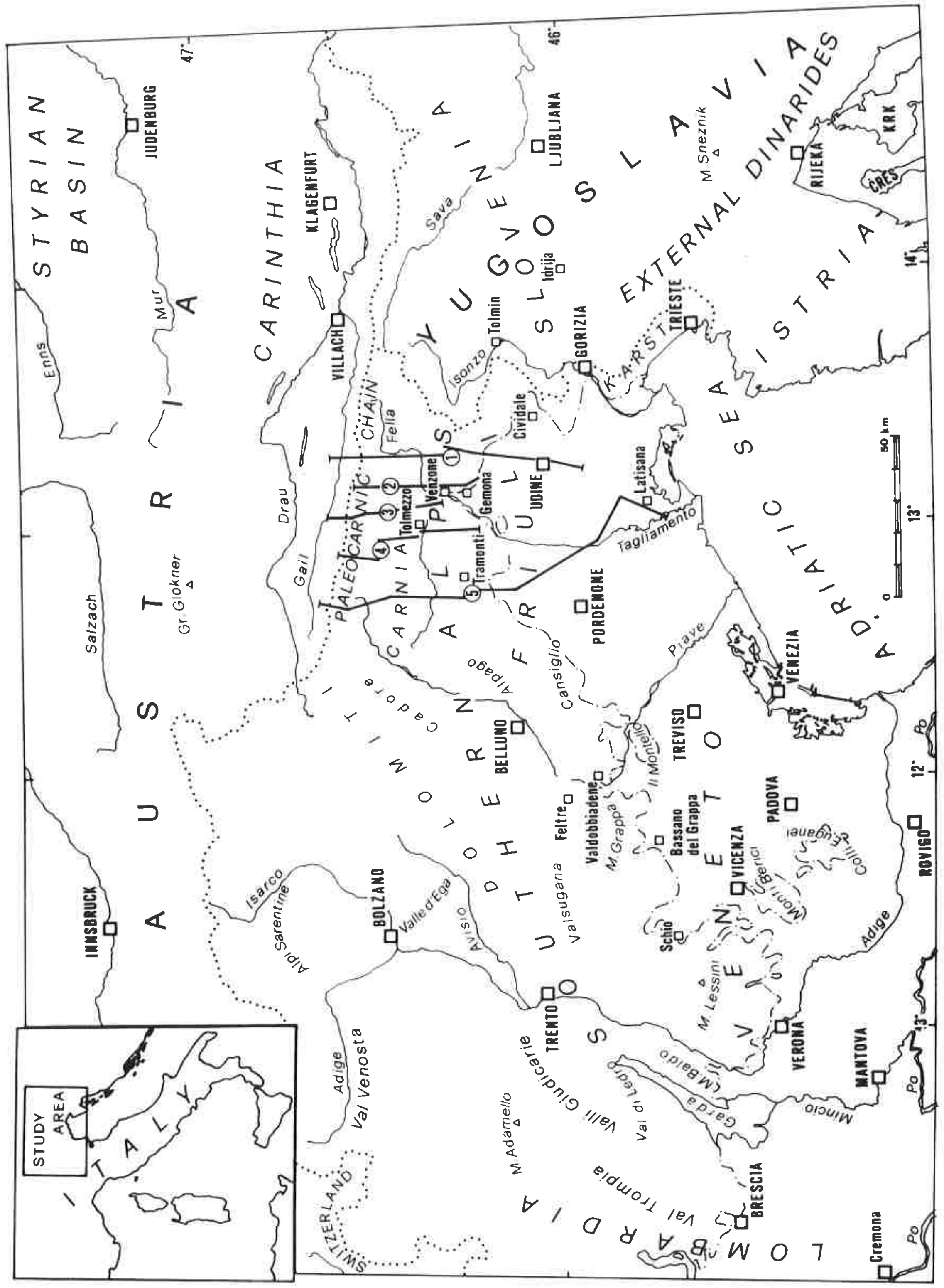

Fig. 1 — Index map of the study area. Solid lines indicate the geological-geophysical vertical cross-section presented in the paper. The dot-dashed line indicates the limit of the relief.

Bigi et al., 1987) as well as the regional seismotectonic studies (Amato et al., 1976; Finetti et al., 1976, 1979; Carulli et al., 1981, 1982, 1989; Panizza et al., 1981; Cavallin et al., 1984; Siro e Slejko, 1984; Slejko et al., 1986) have been used as base documents, while most of the seismological data were obtained from the seismometric network of the Osservatorio Geofisico Sperimentale of Trieste (OGS).

GEOLOGY

The present work focuses on the eastern Southern-Alps and on the Veneto-Friuli plain with only marginal reference to the Austroalpine and Penninic domains and to the External Dinarides.

The Periadriatic (or Insubric) Lineament running west to east (Tonale, Giudicarie, Pusteria, Gail and Karawanken faults) represents the boundary between the Southalpine and Austroalpine units. Its present structural features are related to the neo-Alpine tectonic phases and to the Oligo-Holocene uplifting. This fault system is commonly considered as a crustal discontinuity of at least Hercynian age intruded by late Hercynian and Alpine plutons (Sassi et al., 1985). On the surface, it consists of a system of subvertical faults active at different times and with different mechanisms. The Periadriatic Lineament in the sector studied is presently characterized by vertical movements with a dextral transcurrent component.

The Southalpine crystalline basement consists mainly of pelitic-psammitic sequences with volcanic and volcanoclastic levels of Late Cambrian to Silurian age (Sassi et al., 1979, 1984; Zanferrari, 1985). These rocks were affected by pre-Hercynian (Del Moro et al., 1984) and Hercynian (Del Moro et al., 1980) metamorphism, and intruded by Upper Ordovician (AGIP, 1977) or Permian granitoids (Sassi et al., 1985).

The outcropping Paleozoic non-metamorphic sequences are made up of terrigenous, carbonatic and volcanic rocks yielding Caradoc to Middle Permian ages (Spalletta et al., 1982; Vai et al., 1984; Vai and Cocozza, 1986). Reported as the Paleocarnic chain, they were supposed to be beneath the Mesozoic and Quaternary sediments of the Friuli plain (Castellarin et al., 1980), and were found in a well at a depth of approximately 7 km in the offshore Adriatic (Cati et al., 1987).

The crystalline basement and the Paleocarnic chain are considered the deep part of a Hercynian chain deeply eroded and unconformably covered by Late Paleozoic sequences, representing the base of the Alpine sedimentary cover: the Permo-Triassic units (carbonatic and terrigenous sediments), and the Jurassic-Cretaceous units produced in platform-basin systems depositing on a passive continental margin. They are, from west to east: the Lombard Basin, the Trento Platform, the Belluno Basin, the Friuli Platform and the Slovenian Basin (Cousin, 1981; Castellarin, 1981; Winterer and Bosellini, 1981; Castellarin e Vai, 1982; and references therein).

The Tertiary and Quaternary sediments are mainly flysch and molasse deposits related to the growth of the Dinaric and Alpine chains through the rising of SW- and SE- verging thrusts (Pieri and Groppi, 1981; Zanferrari et al., 1982; Massari et al., 1986; Doglioni and Bosellini, 1987).

Magmatic activity is documented during Middle Triassic times (Dolomites, Recoaro and Carnia) and Tertiary times (Adamello, Lessini, Berici, Euganei hills).

In summary, the area followed a typical Wilson cycle, with the post-Hercynian rifting during Mesozoic times producing crustal thinning (Bernoulli et al., 1979; Bally et al., 1981) and the later Alpine inversion with compression and relative crustal shortening and thickening due to the collision between the Europe and Adria plates (Castellarin, 1979, 1984; Roeder, 1980; Castellarin e Vai, 1982; Finetti, 1984; Doglioni and Bosellini, 1987; Doglioni, 1988).

From an analysis of the structural trends, the following tectonic systems affecting the sedimentary cover and often the basement can be identified (Fig. 2).

a) Giudicarie system, N-S to NNE-SSW trending, with SE-verging folds and thrusts. They are interpreted (Doglioni and Bosellini, 1987; Laubscher, 1988) as positive flower structures and "en échelon" folds and thrusts indicating a sinistral transpression along the belt.

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

c) Dolomites synclinorium, located within a Neogene pop-up of the upper crust and with flexural slip in the sedimentary cover limited to the south by the Valsugana thrust system (Castellarin, 1979; Doglioni, 1987). The orientation of the structures gradually changes northeastwards from ENE-WSW (Valsugana) to E-W (Tagliamento).

d) Valsugana system, with NE-SW to ENE-WSW trending thrusts, which affects the basement along the Valsugana and Bassano-Valdobbiadene lines, and the Oligo-Holocene molasses in its most external part.

e) Tagliamento system, an eastern extension of the previous system, from which it differs in strike (E-W trending) and in being more shortened. It is characterized by low angle south-verging thrusts, which in the external sector involve also the molassic units. Subvertical faults are also present: the Fella-Sava line.

f) Dinaric system, with SW trending thrusts. They are found in the External Dinarides and buried in the Friuli plain with movements that affected the Quaternary molassic units. The Idrija subvertical dextral transcurrent fault is considered an active seismotectonic element of this system (Carulli et al., 1989).

Tectonic activity during Middle Pleistocene-Holocene (Zanferrari et al., 1982; Ambrosetti et al., 1987) is reported in Fig. 3 following the tectonic systems defined above.

a) The Giudicarie system, marked by thrusts and reverse faults in the southern sector, and subjected to a general uplift.

b) The Schio system, particularly active east of the Schio-Vicenza line, shows from subsurface data movements which are mostly vertical. In the Lessini-Berici-Euganei block a complex differentiated uplifting with a general southward tilt occurred; the hinge zone with respect to the subsiding plain appears to be in the Verona deformation belt. Southwards, a zone characterized by subsidence which increases eastwards and towards the Po plain axis has been recognized (e.g. Arca e Berretta, 1985).

c) The Dolomites synclinorium is generally rising, with the highest rate in the Cortina area (1 mm/year: Autori Vari, 1980). Only a few faults are considered active. They have a NE-SW trend or a younger NW-SE trend; the latter characterized by dextral strike-slip movements.

d) The Valsugana system, with thrusts in the southernmost sector responsible for the genesis of the outer uplands, is an area of very important deformations (Beinat et al., 1988).

e) The Tagliamento system, where the southernmost thrusts are active and may be seen in the deformations of the Pleistocene clastic deposits (Carraro e Polino, 1976; Venturini, 1985). The Fella-Sava line shows clear dextral transcurrent movements. The system marks the area of maximum crustal shortening of the eastern sector of the Southalpine chain (Castellarin, 1979).

f) The Dinaric system in the area considered is mainly represented by buried thrusts, the most external of which mark the boundaries of the subsidence area located in the central and lower Friuli plain. In the southernmost mountain sector, which records the strongest deformation, vertical faults with Dinaric direction dislocate the longitudinal Tagliamento structures. The subvertical Idrija fault is part of this system. It is presently characterized by dextral transcurrent tectonics which have affected internal nappes of the External Dinarides belt, separating the active compressional front from the inactive external front situated offshore along the Yugoslav coast, in Istria and in the Friuli plain (Carulli et al., 1989).

Levelling measurements in the area have given relevant results in Hohe Tauern area (Senftl und Exner, 1973) and in Friuli where large variations were associated with the strong earthquakes of 1976 (Talamo et al., 1978).

CRUSTAL STRUCTURE

Detailed seismic investigation is required for a more complete outline of the present connection between the geometry of the deep structures in the Adriatic foreland and those belonging to

the Alps and the Dinaric chain. The Adria microplate acted as hinterland for the Eoalpine orogeny, and its Apulian fragment as foreland for the Dinarides and the successive development of the Southalpine building. The evolution of the Adria microplate conditioned the setting of both the upper and lower crustal features. In this respect, the transition from the area studied to the Pannonian fragment, which represents the hinterland for the Carpathians and Dinarides system (Royden et al., 1983b), is of outstanding importance. The Alps, Dinarides, Apulia and Pannonian basin system has its own peculiar crustal structure and preserves the imprint of its geodynamic history. Significant changes in crustal thicknesses, and probable velocity inversions associated with very high velocity layers, have been found.

The Eastern Alps have been investigated by several Deep Seismic Soundings (DSS) since the fifties, mainly under international cooperation programs (Giese and Prodehl, 1976; Gebrande et al., 1978; Aric et al., 1987; and references in Slejko et al., 1987). A sharp increase in crustal thickness, which causes a Moho depth of more than 50 km in the area included from the Venosta valley to Lienz, has been observed (Fig. 4). Towards the Bavaria region (southern Germany), it gradually rises up to a depth of 35-30 km. This Moho deepening fits the negative trend of the Bouguer anomalies quite well (Fig. 5 and discussion and references in Slejko et al., 1987; Walach and Weber, 1987).

The Apulia unit is characterized by a high Moho (depth < 30 km) in the Adriatic sea-Istria region which is somehow connected to the even more pronounced high of the Lessini-Berici ridge (see also the gravimetric highs of western Istria and Verona in Fig. 5). The Verona high is limited by sharp transitions of the Moho, towards the west in the Giudicarie-Adamello system or along the border of the so called Val Trompia-Giudicarie arc (Castellarin and Vai, 1986), to the north in the Valsugana system, and to the east in the area of the Schio-Vicenza system. Towards the Apenninic foredeep, the Moho plunges as a monocline to depths ranging from 35 to 40 km. From the Adriatic sea northwards, the Moho deepens regularly and attains a depth of 40 km after a pronounced flexure recognized at the Southern Alps-Dinarides transition, beneath the Southern-Alps front.

A seismic marker with velocity values close to 6.7 km/s has been found at depths of nearly 10 km in central Friuli. According to the aereomagnetic interpretations (Cati et al., 1987), this element is linked to structures occurring near the top of the basement. The aereomagnetic data confirm that the basement is involved along the whole Southalpine Friuli arc in a complex tectonic setting, and is displaced and thrust onto the basement of the Adriatic foreland and its sedimentary cover (Valsugana and Tagliamento systems, Slejko et al., 1987). Similar imbrications of the basement have been hypothized for the Dinaric system (Cati et al., 1987). Thus, the 6.7 km/s basement plays the role of a more rigid crustal block which was formerly wedged into the Dinaric system. It then influenced the lateral propagation of "décollement" surfaces in the Southern-Alps producing the arc-shaped arrangement of the external front of Plio-Quaternary age.

The Dinaric unit is characterized by a thick crust with a deep trough (thicking more than 40 km) orientated NW-SE and running from Tolmin-Idrija to Dalmatia-Herzegovina (southern Yugoslavia). It has been interpreted (Aljinovic et al., 1984) as the crustal area root of SW-verging thrusts.

The Pannonian basin forms a crustal unit 25-30 km thick, including up to 4 km of Neogene sedimentary rocks (Horvath and Royden, 1981; Posgay et al., 1981). It comprises the Inner Carpathians, the easternmost parts of the Alps, and the inner zones of the Dinarides. The geodynamic evolution of the Eastern Alps area was strongly conditioned by the extensional tectonics of the Pannonian basin. This basin is the result of the Miocene lithospheric extension and has high thermal gradients which can be explained by a passive upwelling of hot asthenosphere during the extension phase (Royden et al., 1983a).

The characteristics of the Pannonian basin-Alps transition have been studied from DSS profiles, and gravity and magnetic data collected across the Eastern Alps and the Styrian basin (Aric et al., 1987; Walach and Weber, 1987). The transition, which develops through a crustal thickening from less than 30 km east of Graz to more than 40 km towards the Tyrol area, was interpreted as an example of thrust tectonics where the imbrications of the deep crustal

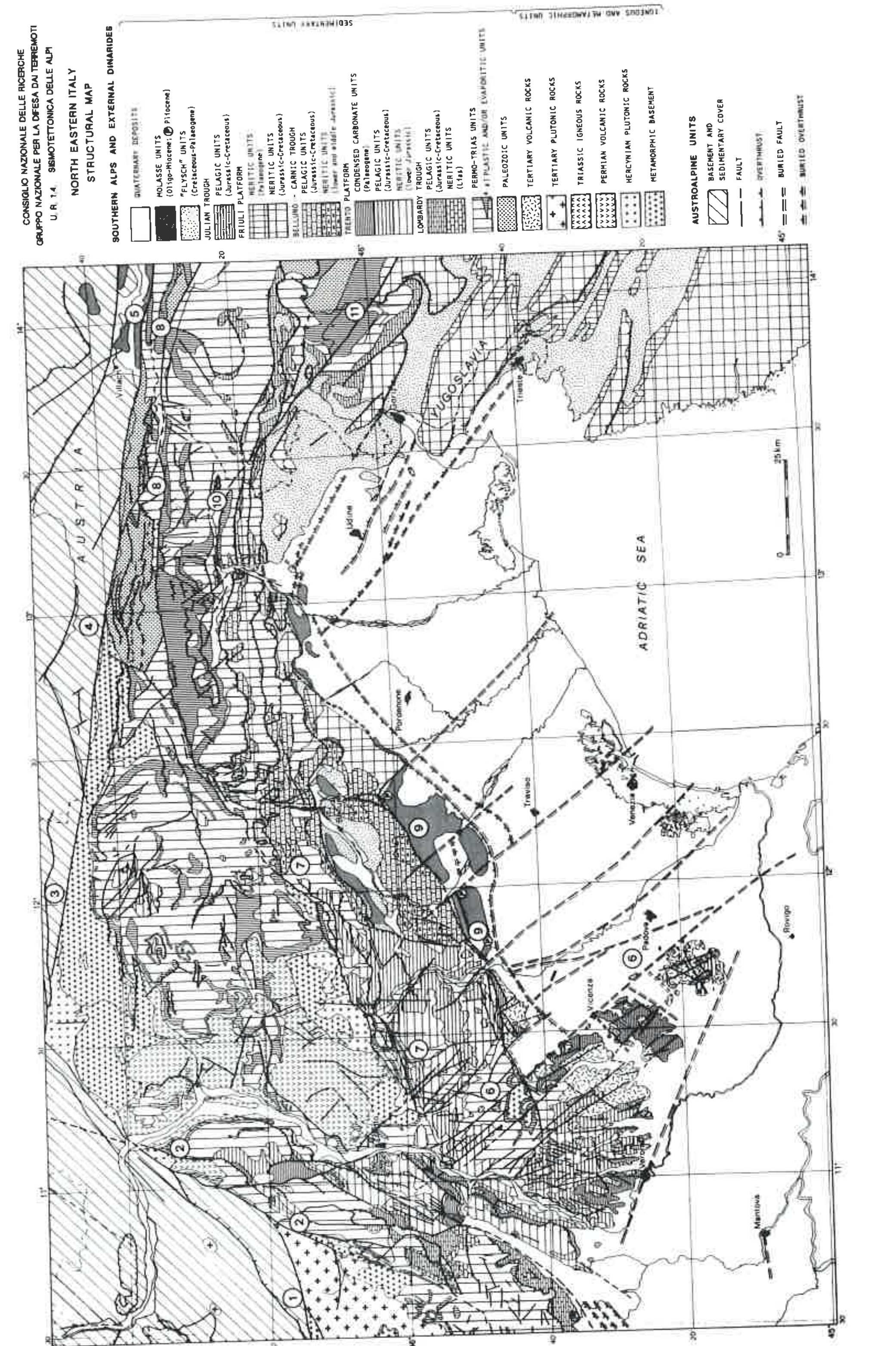

Fig. 2 — Structural map of northeastern Italy (from Slejko et al., 1987). Principal faults: 1 = Tonale line, 2 = Giudicarie line, 3 = Pusteria line, 4 = Gail line, 5 = Karawanken line, 6 = Schio-Vicenza line, 7 = Valsugana line, 8 = Fella-Sava line, 9 = Bassano-Valdobbiadene line, 10 = Resia thrust, 11 = Idrija line.

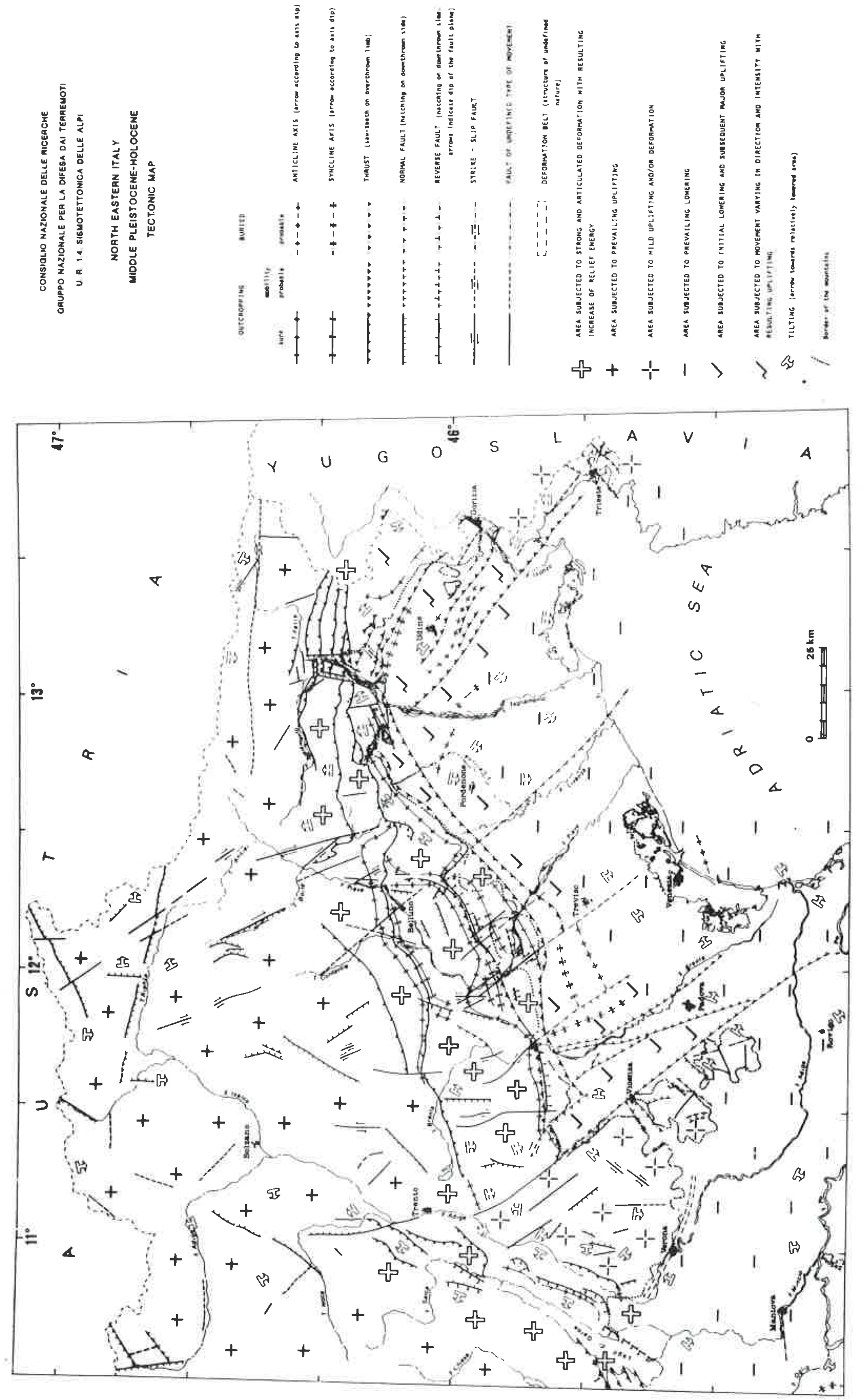

Fig. 3 — Neotectonic map of northeastern Italy (from Slejko et al., 1987).

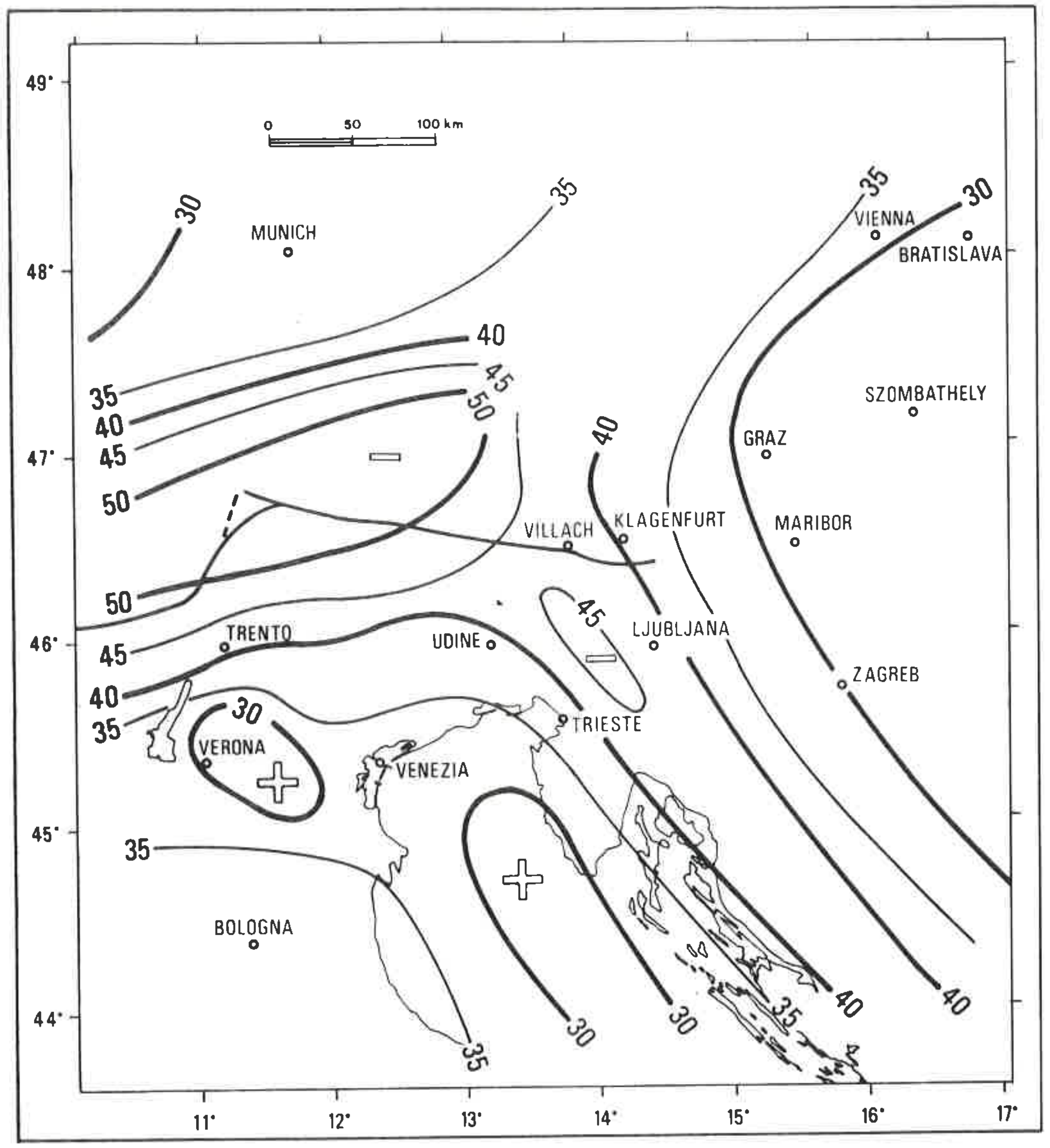

Fig. 4 — Map of the isobathes of the Moho discontinuity (espressed in km) in northeastern Italy and neighbouring zones.

and uppermost mantle materials caused a crustal doubling (Giese, 1980).

Using the gravimetric information from Italy and Austria, a general map of the Bouguer isoanomaly has been obtained (Fig. 5), and from it a N-S profile constructed (Fig. 6). Its interpretation leads to a crustal model similar to that obtained from seismic refraction data.

The gravity minimum corresponding to the Tauern window is controlled by the European Moho deeping towards south, by the north-verging nappes and Southalpine deep crustal structure. However, the relatively short wavelength of the anomalies can be inverted only with a model comprising a low density (low velocity) body at a depth between 10 and 20 km as represented in Fig. 6. In the Southern-Alps domain the gravity trend reflects the transition from the very thick crust, in the Alpine arc to the Adria normal crust with a clear step in central Friuli beneath Gemona.

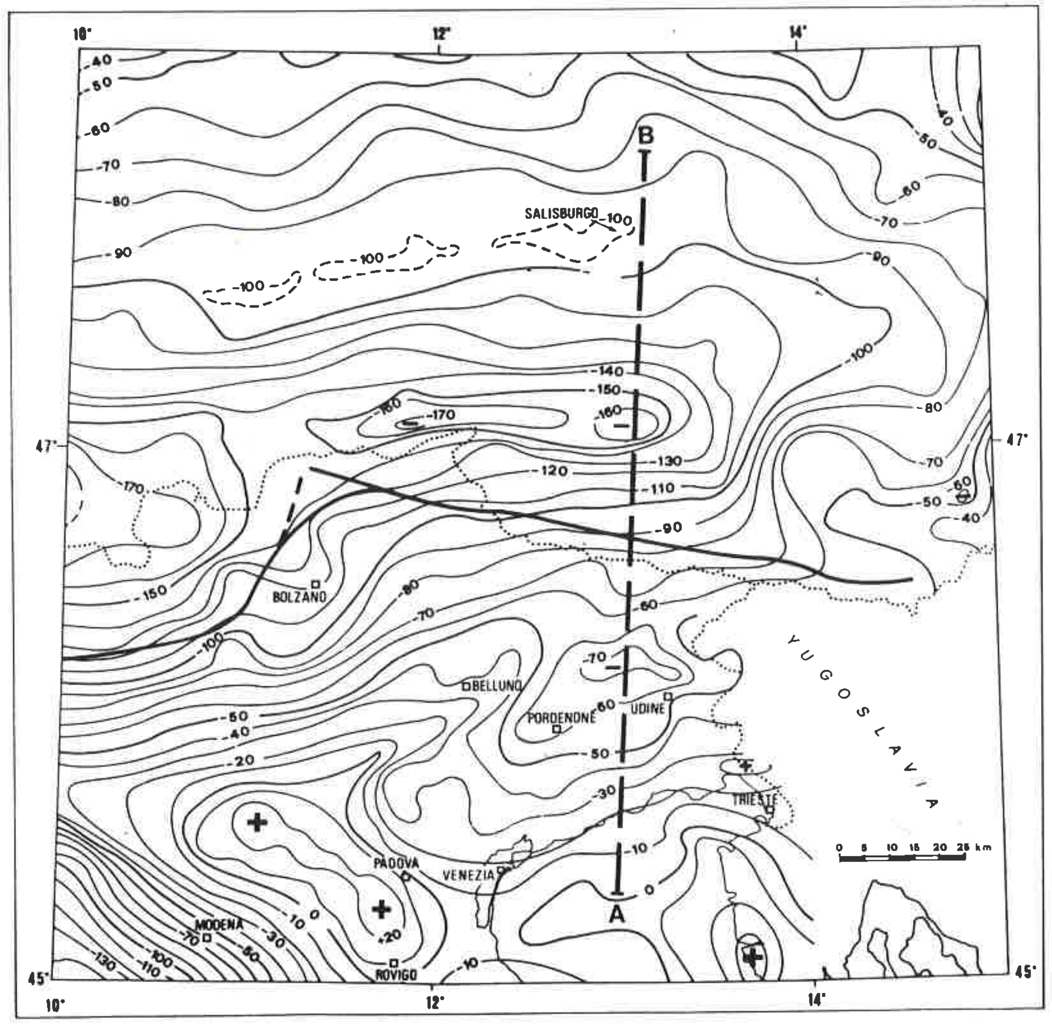

Fig. 5 — Map of the Bouguer anomalies in northeastern Italy and surrounding zones and trace of the gravimetric profile studied (from Slejko et al., 1987).

SEISMICITY

Northeastern Italy has been subjected to numerous destructive earthquakes (Table 1), especially in the Veneto (Verona, Vicenza, Belluno) and Friuli (Tolmezzo, Gemona, Cividale) areas (Slejko et al., 1987). To detail the seismicity of the region, a plot of the most important earthquakes occurred in the period 238-1977 and of the seismic activity according to Riznichenko (1959) has been produced. In Fig. 7, the focal volumes (Båth and Duda, 1964) of the shocks with epicentral intensity greater than, or equal to, degree VI on the Mercalli-Cancani-Sieberg (MCS) scale are given. A regional earthquake catalogue containing nearly 6000 events from 238 to 1984 (OGS, 1987) was used as source data and the intensity, when not reported in the catalogue, was calculated from the magnitude (Karnik, 1969). The plot analysis reveals that high level seismicity has especially affected the piedmont area, extending from lake Garda to the border with Yugoslavia. The major earthquakes occurred at the two ends: near lake Garda and in central Friuli. The two zones appear to be different: while the lake Garda zone suffered

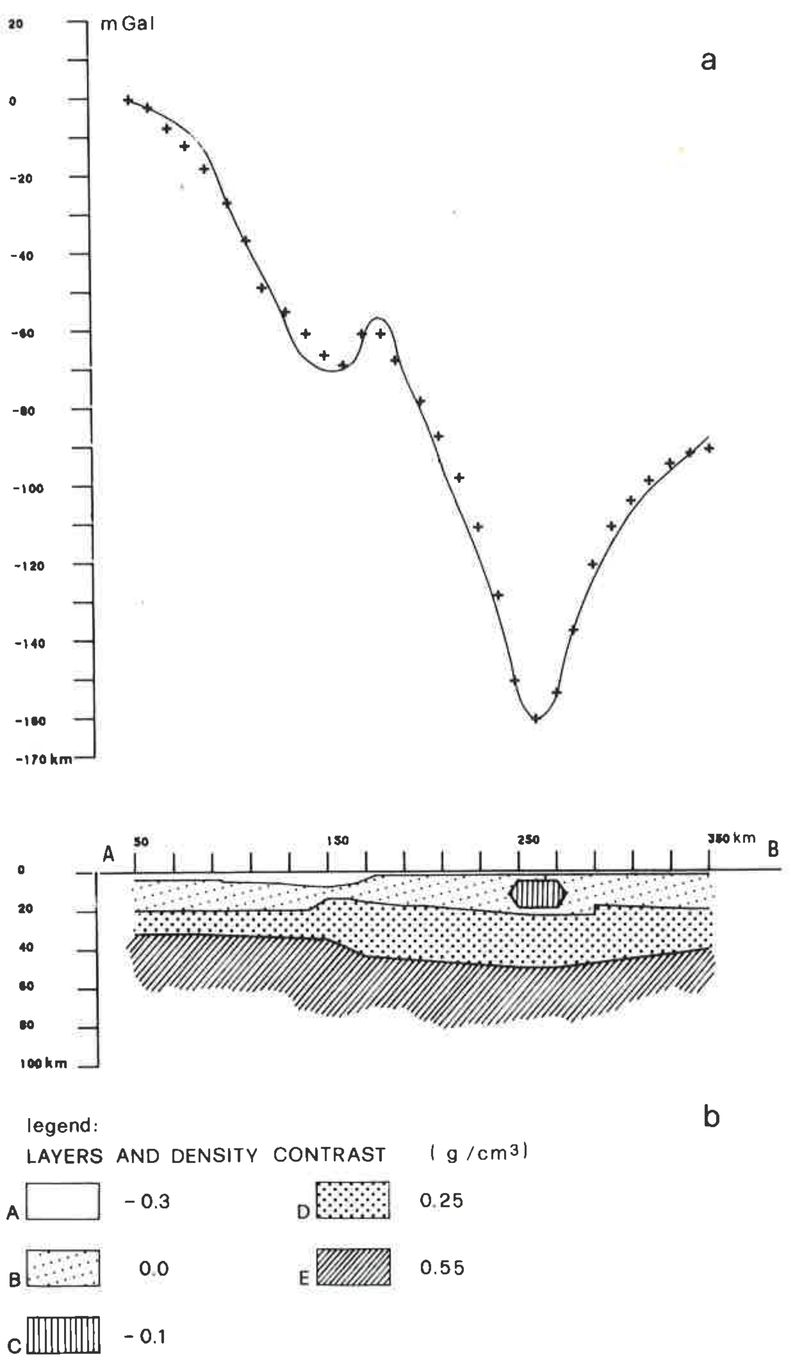

Fig. 6 — Interpreted gravimetric profile (from Slejko et al., 1987; trace reported in Fig. 5):
a) measured (crosses) and calculated anomaly (solid line);
b) density model.

strong earthquakes only in the early centuries of the Christian age and shows only medium intensity recent seismicity, Friuli has been seismically very active all the time. In the central part of the area considered, the seismicity near Belluno and some shocks NW of Treviso are clearly evident. Very few events have affected the Alpine sector, while Slovenia definitely appears active but with a lower and less concentrated seismicity than in the Veneto-Friuli piedmont belt. The historical earthquakes located in the Venezia area, during the period of maximum importance of the town, must be considered as shakings due to events of the Veneto piedmont area or of the Yugoslav coast.

The seismic sequence which started on May 6, 1976 with the destructive shock of Gemona (Io=X MCS: Giorgetti, 1976) has been interpreted (Finetti et al., 1979; Slejko e Renner, 1984; Cavallin et al., 1989) as a phenomenon principally involving Dinaric structures east of the river Tagliamento, with a later westward migration of the seismicity involving Alpine structures with a complex deep mechanism of stress propagation.

Another parameter used in Fig. 7 is the seismic activity given as the statistical number of earthquakes of magnitude 3.3 over 1000 km^2 per year (Riznichenko, 1959) calculated on a $0.5° \times 0.5°$ grid. The earthquake catalogue restricted to the period 1850-1984 and for intensity greater than, or equal to, degree VI MCS was considered resonably complete and homogeneous, and therefore suitable as data source. The seismic activity is high in Carnia and Alpago (values > 1.0), while values greater than 0.2 are localized along the piedmont belt and in almost all the territory of Slovenia. Two minima can be observed: the first located between Verona and Vicenza and the second separating Friuli from Slovenia.

It is interesting to note (Fig. 8) also that the present-day seismicity (1977-1986), recorded by the local OGS network, has a maximum density of events in central Friuli, and that all the zones active in the past are still active: central Friuli, Slovenia and the area around lake Garda. Furthermore, the epicentres in Slovenia assume a well defined NW-SE trend that from central Friuli extends to the Yugoslav coast near Rijeka.

The maximum observed intensities over the last thousand years, as well as over the last four hundred years when the data became more accurate, reveal an E-W trend with the highest values along the pre-Alpine belt (Slejko et al., 1987). Data on the depth of the hypocentres is rather scanty; nevertheless, it reveals that the seismicity is concentrated in the upper crust and never exceeds 25 km depth (Table 2). The events of the Friuli seismic sequence which started in 1976 were localized in the sedimentary cover with a maximum concentration near the top of the crystalline basement approximately 10 km deep (Siro and Slejko, 1982). Their focal mechanisms are correlated to reverse faults or thrusts with maximum pressure axis orientated mainly N-S (Slejko e Renner, 1984). Further mechanisms available for the Eastern Alps (Bossolasco et al., 1974; Cagnetti et al., 1976; Ebblin, 1976; Kunze, 1982; Jimenez and Pavoni, 1984; Renner e Slejko, 1986; Slejko et al., 1987; Slejko e Rebez, 1988) generally show a strike-slip pattern in Veneto and Austria (Table 2 and Fig. 9), vertical movement along the Sava line in Slovenia, and various types around lake Garda. The seismicity of eastern Veneto is associated with the transcurrent activity of NNW-SSE orientated subvertical faults at their interaction with the southernmost Alpine thrusts (Peruzza et al., 1989). The foci deepen moving towards the front of the chain and mainly affect the basement. The structures of the Schio system are seismically active in the region north of lake Garda at their interaction with the Giudicarie system (Slejko e Rebez, 1988). The focus depths involve the whole upper crust (25 km).

In the Dinaric sector, the major seismicity is concentrated along the coastal strip limited northeastwards by the prolongation of the Idrija fault, which plays the role of a disengaging structure (Carulli et al., 1989). In the Slovenian Karst, the historical seismicity is correlatable to transcurrent activity of Dinaric faults and to their interaction with similarly orientated thrusts (Rebez et al., 1987).

Low to medium magnitude seismicity has affected the border area between Italy and Switzerland (Venosta and Engadina valleys) in recent years.

The study of the seismicity of the area has been integrated with paleoseismicity information. For this purpose, two different kinds of phenomena are used: surface faults (Sauro, 1979; Cavallin et al., 1987a) and paleo-landslides (Perna et Sauro, 1979; Girardi et al., 1981; Zardini et

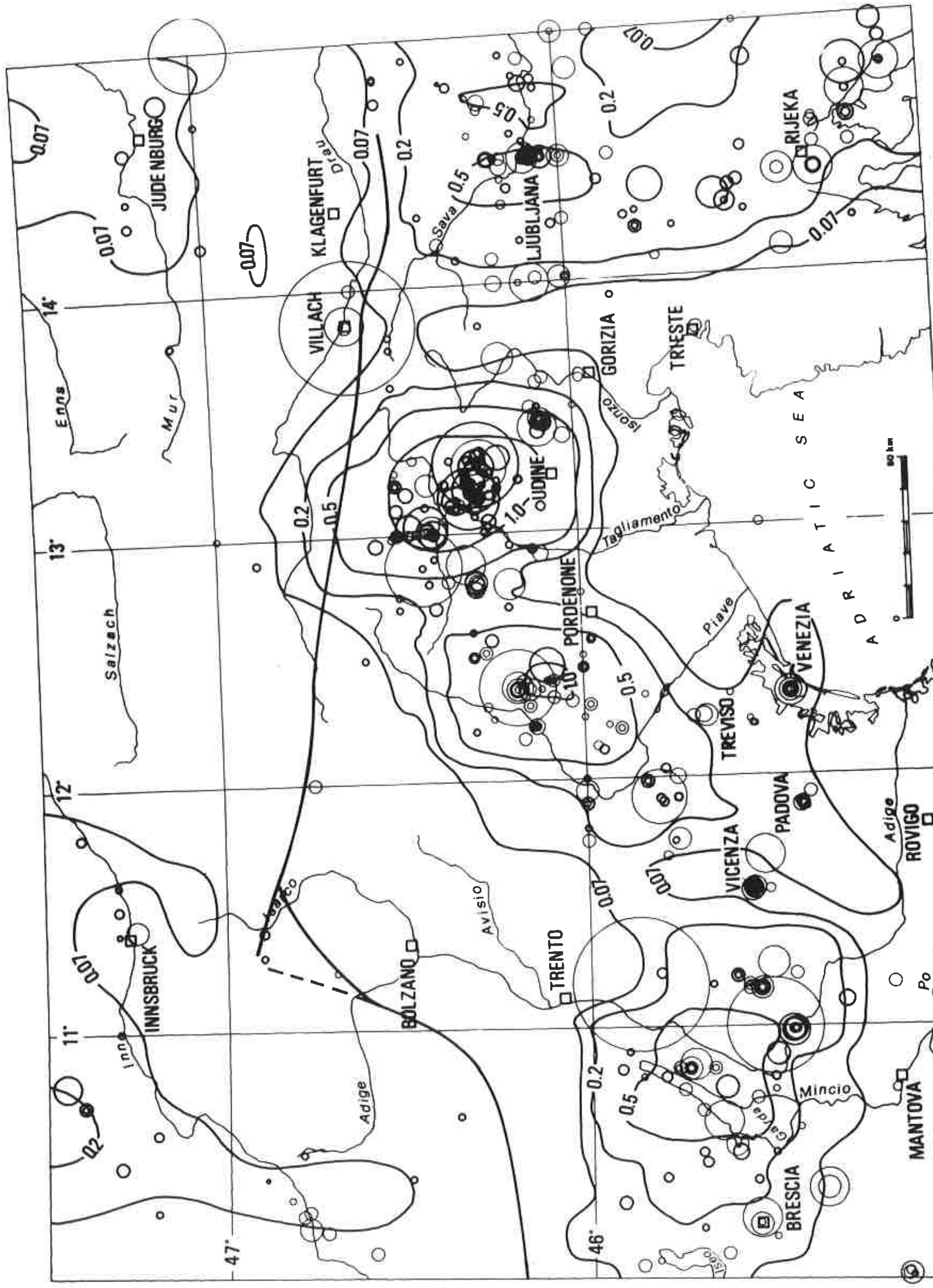

Fig. 7 — Seismicity map of northeastern Italy and surrounding zones (from Slejko et al., 1987) with the epicentres of the earthquakes with intensity greater than, or equal to, degree VI MCS of the period 238-1977 and the isolines of the seismic activity according to Riznichenko (1959).

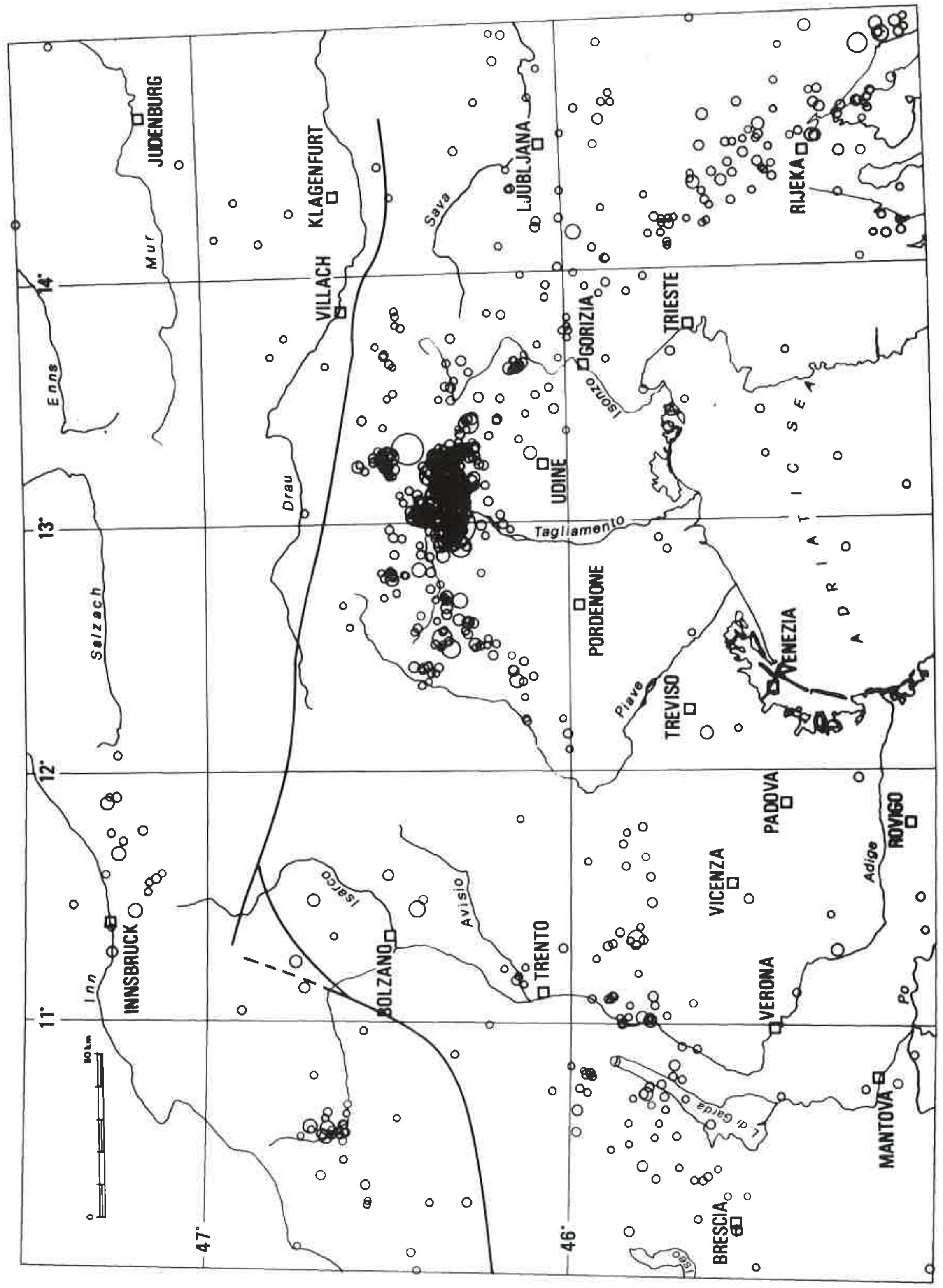

Fig. 8 — Map of the epicentres of the shocks with magnitude greater than 2.6 recorded by the OGS Seismometric Network of Norheastern Italy in the period 1977-1986. Heavier symbols for events with epicentral error smaller than 5 km.

Table 1 — Earthquakes with epicentral intensity greater than, or equal to, degree VIII MCS in the Eastern Alps during the period 238-1984.

h indicates the focal depth, Mag the magnitude and I1, ..., I5 the intensities MCS to which the rays R1, ..., R5, in km, are referred.

Date or time Y D M	H M S	Coordinates Lat N	Lon E	h km	Mag	Int MCS	Epic area	I_1 R_1	I_2 R_2	I_3 R_3	I_4 R_4	I_5 R_5
238		45°32,8'	11°33,0'			8	VICENZA					
243		45°38,7'	10°37,5'			9	LAGO DI GARDA					
254		45°27,0'	10°58,8'			8	VERONA					
260		45°31,0'	11°40,9'			9	VICENZA					
365 07 21		45°52,0'	11°10,2'			11	ROVERETO	9 81				
745		45°26,0'	12°19,9'			8	VENEZIA					
778		45°40,0'	12°14,5'			8	TREVISO					
792 02		46°00	14°30			8	LJUBLJANA					
894		45°26,6'	10°59,1'			8	VERONA					
1000 01		46°00	14°30			8	LJUBLJANA					
1001		45°26,9'	10°58,9'			8-9	VERONA					
1064 04 11		45°32,6'	10°12,9'			8	BRESCIA					
1081 03 26		46°00	15°00			8	LITIJA					
1095 09 10		45°26,8'	10°58,9'			8	VERONA					
1117 01 03	21 30	45°30	11°00			10-11	VERONA	9 133				
1183 01		45°26,9'	10°58,8'			8-9	VERONA					
1197		45°32,6'	10°14,4'			9	BRESCIA					
1222 12 25	11	45°21,5'	10°21,5'			9	BRESCIA	3 660				
1222 12 25	14	45°21,5'	10°21,5'			8	BRESCIA					
1233		45°26,0'	12°19,9'			8-9	VENEZIA					
1268 11 03	23	46°00	11°57			8	FELTRE					
1277 07 20		45°26,8'	10°59,1'			8	VERONA					
1278 04 07		46°05,6'	13°27,0'			8	CIVIDALE					
1279 04 24	17	46°05,6'	13°27,0'			8	CIVIDALE	3 210				
1279 04 24	23	46°05,6'	13°27,0'			8	CIVIDALE					
1282 01 17	17	45°26,0'	12°19,9'			8	VENEZIA					
1287 04 11		45°08,0'	10°01,2'			8	CREMONA					
1298 12		45°26,9'	10°59,2'			8	VERONA					
1303 10 22	23	45°33,2'	11°32,4'			8	VICENZA					
1323		45°12	14°42			9	CRIKVENICA					
1334 12 04	23	45°43,2'	10°51,0'			8-9	LAGO DI GARDA					
1348 01 25	15	46°36,5'	13°51,2'			11	VILLACH	9 53	8 140			
1367 09 21		45°26,7'	10°59,0'			8	VERONA					
1367 09 21		45°26,9'	10°59,1'			8	VERONA					
1389 08 20	18 30	46°24,8'	13°12,0'			8	MOGGIO UDINESE	3 120				
1403 01 03		45°26,5'	10°59,2'			8	VERONA					
1410 06 10	20 30	45°30	11°15			8-9	VERONA/BELLUNO					
1457 12		45°36,6'	10°31,8'			8	LAGO DI GARDA					
1487 01 11	22	45°29,6'	10°53,4'			8	VERONA					
1492		45°29,5'	10°53,2'			8	VERONA					
1504 03		46°47	10°12			8	ARDEZ					
1511 03 26	14	46°06	14°00			9	IDRIJA					
1511 03 26	14 30	46°16	13°16			9-10	GEMONA					
1511 06 25	21	46°01	14°01			8	GEMONA					
1511 08 08		46°06	13°25			9	CIVIDALE					
1551 03 26		46°12	13°42			8-9	TOLMIN					
1556 01 24		47°00	15°00			10	KOFLACH					
1574 08 14		45°24	14°06			8	BUZET					
1574 08 14		45°06	14°48			9	NOVI VINODOLSKI					
1670 07 16	15	47°15	11°25			8	INNSBRUCK					
1689 05 10	03	45°58	14°51	5		8	VISNJA GORA					
1690 12 04	18	46°37,0'	13°51,6'			9	VILLACH	3 500				
1695 02 25	06	45°48,2'	11°55,2'			9-10	ASOLO	10 3	9 10	8 30	7 60	6 148
1700 07 28	03 45	46°25,8'	12°52,1'			10	RAVEO	9 6	8 7			
1721 01 12		45°18	14°24			9	RIJEKA					
1776 07 10	20 15	46°17,2'	12°47,8'			8	TRAMONTI DI SOPRA	7 6	6 21	5 55		
1788 10 20	21 15	46°24,2'	13°00,7'			8-9	TOLMEZZO	8 10	7 19	6 29		
1789 08 03	02	46°17,2'	12°48,2'			8	TRAMONTI DI SOPRA	3 170				
1794 06 06	22 15	46°18,8'	12°52,5'			9	TRAMONTI DI SOPRA	9 6	8 12	7 24	6 48	
1812 10 25	07	46°11,7'	12°47,5'			8-9	MANIAGO	8 21	7 12	6 64	5 72	
1836 06 12	02 30	45°45	11°45			8	BASSANO	8 3	7 6	6 43	5 108	
1870 03 01	19 57	45°24	14°24			8-9	RIJEKA					
1873 06 29	03 55	46°11,0'	12°22,5'			10	ALPAGO	10 2	9 6	8 16	7 30	6 43
1873 06 30		46°09	12°22			8	BELLUNO					
1873 08 08	07 15	46°11	12°22			8	BELLUNO	8 4	7 22	6 31	5 54	
1873 12 25		46°11,0'	12°22,5'			8-9	BELLUNO					
1876 04 29	10 50	45°44	10°50			8	MONTE BALDO					
1891 06 07	01 06 14	45°32	11°09			8	VERONA/VICENZA	8 4	7 11	6 19	5 46	
1895 04 14	20 17 30	46°06	14°30	16		8-9	LJUBLJANA	8 18	7 52	6 110	5 180	4 250
1897 07 15	05 57	46°03	14°30	7		8	LJUBLJANA	3 190				
1908 07 10	02 13 35	46°28,3'	13°09,8'		4,8	8	MOGGIO UDINESE	8 7	7 13	6 23	5 39	
1916 03 12	03 23 59	45°12	14°48	18	5,8	8	CRIKVENICA					
1928 03 27	08 32 31	46°25,2'	13°01,8'	20	5,8	9	TOLMEZZO	9 6	8 9	7 15	6 31	5 46
1932 02 19	12 57 11	45°38,1'	10°45,5'			8	MONTE BALDO	8 1	7 5	6 7	5 15	4 28
1936 10 18	03 10 12	46°06,6'	12°27,7'	17	5,6	9	CANSIGLIO	9 5	8 11	7 20	6 41	5 130
1949 02 03	22 29 20	46°30	13°06	8	4,7	8	PAULARO	3 110				
1959 04 26	14 45 16	46°28	13°00	5	4,4	8	ARTA	8 5	7 13	6 18	5 27	
1976 05 06	20 00 13	46°16,5'	13°16,6'	5	6,4	10	LUSEVERA	10 3	9 9	8 23	7 46	6 91
1976 09 11	16 31 12	46°16,8'	13°13,0'	8	5,1	8	NIMIS					
1976 09 11	16 35 02	46°16,4'	13°16,0'	4	5,6	8	LUSEVERA					
1976 09 15	03 15 20	46°16,9'	13°10,3'	6	5,8	8	ARTEGNA					
1976 09 15	09 21 19	46°17,9'	13°08,3'	9	6,1	9	GEMONA	9 5	8 20	7 38	6 60	5 98
1977 09 16	23 48 08	46°15,2'	13°00,1'	11	5,2	8	FORGARIA					

Table 2 — Focal parameters of the principal earthquakes in the Eastern Alps during the period 1928-1986.
h indicates the focal depth, Mag the magnitude and b the bibliographical reference: 1 = Cagnetti et al., 1976; 2 = Kunze, 1982; 3 = Jimenez and Pavoni, 1984; 4 = Slejko e Renner, 1984; 5 = Renner e Slejko, 1986; 6 = Slejko et al., 1987; 7 = Slejko e Rebez, 1988. A indicates the seismotectonic area (Fig. 17) where the epicentre lies. The Wulff projection on the lower hemisphere was used for the focal mechanisms; directions are expressed clockwise from the north, and inclinations from the horizontal plane with dip on the right side.

N°	Date yr m d	Time h m s	Coordinates Lat N	Lon E	h km	Mag	b	Epic. area	A	Plane A dir/inc	Plane B dir/inc	Axis P dir/inc	Axis T dir/inc	Axis B dir/inc
1	19280327	083231	46°25.2'	13°01.8'	20	5.8	1	TOLMEZZO	8	39°/60°	301°/66°	355°/ 2°	257°/40°	85°/52°
2	19301008	002848	47°27.0'	10°46.8'	8	5.4	1	REUTTE	1	98°/60°	342°/52°	218°/ 4°	313°/50°	125°/40°
3	19340608	031309	46°18.0'	12°30.0'	20	4.5	1	CLAUT	7	27°/88°	295°/88°	340°/ 0°	70°/ 0°	—/90°
4	19361018	031012	46°06.0'	12°27.7'	17	5.6	6	CANSIGLIO	8	193°/62°	294°/80°	153°/22°	55°/21°	308°/60°
5	19561105	194525	46°33.6'	12°57.6'	2	4.8	1	PALUZZA	1	0°/90°	94°/80°	316°/ 7°	47°/ 8°	180°/80°
6	19580930	084526	47°12.0'	10°35.0'	10	4.4	2	IMST	1	226°/70°	326/70°	277°/ 2°	185°/28°	8°/60°
7	19590426	144516	46°28.0'	13°00.0'	5	4.4	2	ARTA	8	209°/70°	306°/76°	168°/23°	75°/ 3°	339°/63°
8	19600219	123014	45°41.4'	10°27.6'	11	4.5	1	IDRO	2	85°/69°	170°/80°	40°/20°	303°/ 4°	194°/68°
9	19610825	122155	47°30.0'	10°48.0'	14	3.7	2	REUTTE	1	228°/56°	316°/86°	88°/21°	187°/27°	327°/55°
10	19630519	100008	46°16.2'	14°31.8'	13	5.3	1	KAMNIK	9	122°/30°	304°/60°	30°/13°	231°/73°	122°/ 0°
11	19670814	101618	46°54.0'	10°24.0'	10	3.6	2	NAUDERS	1	216°/72°	306°/84°	354°/ 8°	261°/16°	108°/71°
12	19680622	122137	45°48.5'	11°12.8'	24	4.5	6	PASUBIO	5	94°/40°	4°/90°	306°/34°	61°/34°	184°/40°
13	19680622	123751	45°45.1'	11°14.4'	23	4.1	6	PASUBIO	5	48°/40°	164°/70°	279°/18°	33°/52°	177°/32°
14	19690601	232029	47°00.0'	14°12.0'	33	4.5	1	METNITZ	1	189°/78°	95°/80°	143°/ 6°	50°/23°	250°/64°
15	19731212	000238	47°03.0'	14°06.0'	5	3.3	2	METNITZ	1	265°/86°	356°/70°	311°/12°	218°/16°	73°/70°
16	19750111	155437	45°38.9'	10°36.5'	12	4.0	6	GARDONE	2	16°/66°	244°/41°	130°/14°	242°/58°	32°/30°
17	19760506	195906	46°16.4'	13°19.1'	9	4.5	4	TAIPANA	8	86°/72°	228°/23°	158°/24°	358°/64°	262°/13°
18	19760506	200013	46°16.5'	13°16.6'	5	6.4	4	GEMONA	8	77°/70°	225°/24°	156°/24°	4°/62°	254°/12°
19	19760507	002350	46°15.8'	13°19.5'	6	4.5	4	TAIPANA	8	87°/70°	205°/36°	155°/19°	32°/56°	266°/56°
20	19760508	031006	46°15.6'	13°11.6'	10	4.1	4	GEMONA	8	83°/59°	254°/32°	167°/14°	4°/75°	261°/ 4°
21	19760509	005345	46°12.9'	13°18.1'	8	5.3	4	TARCENTO	8	101°/56°	264°/34°	185°/10°	40°/77°	277°/ 8°
22	19760510	043552	46°14.5'	13°09.1'	2	4.4	4	ARTEGNA	8	72°/63°	242°/27°	158°/18°	346°/70°	250°/ 4°
23	19760511	224401	46°14.7'	13°02.7'	9	4.8	4	OSOPPO	8	96°/62°	238°/30°	176°/15°	32°/72°	270°/12°
24	19760608	121438	46°18.4'	13°14.7'	10	4.3	4	GEMONA	8	104°/60°	223°/44°	171°/ 4°	64°/69°	264°/32°
25	19760626	111347	46°15.9'	13°08.3'	5	4.3	4	GEMONA	8	90°/70°	208°/34°	158°/25°	34°/56°	258°/26°
26	19760714	053934	46°20.9'	13°17.6'	3	4.2	4	RESIUTTA	8	104°/62°	222°/44°	177°/10°	63°/57°	264°/32°
27	19760911	163111	46°16.8'	13°13.0'	8	5.1	4	NIMIS	8	82°/60°	220°/36°	155°/11°	33°/68°	249°/18°
28	19760911	163502	46°16.4'	13°16.0'	4	5.6	4	LUSEVERA	8	78°/76°	226°/15°	161°/30°	356°/58°	255°/ 7°
29	19760912	195328	46°18.5'	13°12.9'	3	4.1	4	NIMIS	8	89°/65°	250°/25°	172°/20°	10°/68°	266°/ 6°
30	19760913	185446	46°17.4'	13°12.2'	5	4.3	4	NIMIS	8	98°/64°	215°/43°	169°/13°	54°/57°	262°/32°
31	19760915	031520	46°16.9'	13°10.3'	6	5.8	4	ARTEGNA	8	30°/46°	230°/46°	130°/ 1°	223°/80°	42°/10°
32	19760915	043854	46°17.6'	13°09.7'	12	4.7	4	GEMONA	8	52°/80°	182°/15°	133°/34°	335°/53°	229°/11°
33	19760915	092119	46°17.9'	13°08.3'	9	6.1	4	GEMONA	8	86°/46°	261°/43°	171°/ 1°	48°/85°	264°/ 2°
34	19760915	094557	46°17.9'	13°17.6'	15	4.3	4	LUSEVERA	8	104°/50°	284°/64°	162°/ 7°	63°/50°	258°/42°
35	19760915	193111	46°17.4'	13°11.1'	3	4.1	4	GEMONA	8	99°/61°	232°/36°	171°/13°	47°/65°	268°/22°
36	19761213	052403	45°55.2'	10°49.8'	2	4.5	6	RIVA	2	173°/90°	262°/55°	122°/26°	222°/22°	354°/55°
37	19770403	031814	46°17.7'	13°09.8'	5	4.5	4	GEMONA	8	142°/59°	302°/31°	222°/14°	74°/73°	315°/ 8°
38	19770716	131331	46°19.1'	14°21.6'	3	4.3	6	KRANJ	9	170°/18°	348°/72°	77°/26°	263°/64°	167°/ 3°
39	19770916	234808	46°15.2'	13°00.0'	11	5.2	4	FORGARIA	8	93°/72°	231°/23°	170°/25°	25°/60°	270°/14°
40	19780220	121334	46°26.8'	13°16.3'	7	4.0	4	DOGNA	8	185°/12°	275°/90°	357°/45°	197°/45°	90°/12°
41	19780403	104946	46°17.4'	13°10.7'	7	4.2	4	GEMONA	8	145°/57°	281°/42°	215°/ 5°	115°/64°	309°/25°
42	19780423	112304	46°04.9'	13°35.5'	3	3.3	6	CIVIDALE	9	175°/80°	290°/20°	106°/50°	252°/35°	352°/17°
43	19781212	151449	46°19.9'	12°42.7'	8	4.4	4	TRAMONTI	8	81°/66°	248°/25°	165°/21°	0°/68°	260°/ 6°
44	19790306	134606	46°24.5'	13°01.6'	6	3.3	4	TOLMEZZO	8	136°/40°	293°/52°	31°/ 6°	156°/79°	304°/12°
45	19790418	151920	46°20.1'	13°18.7'	9	4.8	4	LUSEVERA	8	67°/57°	316°/62°	11°/ 2°	280°/46°	106°/43°
46	19790619	100315	46°17.0'	13°12.5'	11	3.4	4	GEMONA	8	83°/72°	193°/40°	31°/49°	145°/20°	252°/35°
47	19790814	185858	46°19.3'	13°02.4'	5	3.5	4	TRASAGHIS	8	188°/80°	270°/50°	133°/23°	238°/36°	19°/48°
48	19791112	212314	46°38.0'	10°04.2'	8	2.7	3	ZUOZ	1	138°/90°	48°/90°	183°/ 0°	273°/ 0°	—/90°
49	19801014	133327	46°00.7'	12°08.5'	10	4.0	6	MEL	6	191°/86°	282°/76°	146°/16°	240°/12°	352°/76°
50	19820501	063311	47°15.8'	11°27.8	7	3.8	7	INNSBRUCK	1	38°/70°	310°/90°	356°/14°	264°/14°	140°/70°
51	19830721	133122	45°53.0'	11°19.7'	15	3.9	7	ARSIERO	5	252°/50°	82°/40°	348°/ 4°	130°/81°	262°/12°
52	19830731	205256	46°44.9'	10°27.9'	1	4.3	7	SCHULS	1	38°/80°	310°/90°	356°/ 8°	264°/ 8°	129°/80°
53	19830331	001826	46°42.4'	10°28.4'	2	3.6	7	GLORENZA	1	58°/80°	329°/90°	14°/ 6°	284°/ 6°	149°/80°
54	19840608	024333	46°46.2'	10°28.4'	2	3.8	7	MALLES	1	40°/62°	306°/70°	356°/ 6°	265°/34°	92°/56°
55	19860227	111056	46°30.7'	11°34.3'	17	3.1	5	SIUSI	1	291°/80°	111°/ 8°	19°/35°	209°/55°	111°/ 0°
56	19860415	182040	45°46.5'	10°44.5'	15	3.2	5	TREMOSINE	2	0°/50°	213°/40°	102°/ 4°	209°/70°	13°/16°
57	19860610	050254	46°20.0'	12°30.7'	8	2.9	5	PERAROLO	7	13°/90°	103°/90°	148°/ 0°	58°/ 0°	—/90°
58	19860829	145703	46°22.6'	12°27.8'	6	4.4	5	PERAROLO	7	2°/80°	92°/80°	317°/14°	227°/ 0°	137°/76°
59	19860829	150050	46°22.4'	12°27.4'	3	3.8	5	PERAROLO	7	237°/46°	357°/58°	112°/ 6°	220°/60°	21°/32°
60	19550522	045732	47°18.0'	11°24.0'	10	3.9	2	MITTENWALD	1	231°/66°	326°/60°	192°/40°	285°/ 5°	16°/47°
	19650708	232004	47°18.0'	11°24.0'	5	3.3	2	MITTENWALD	1					

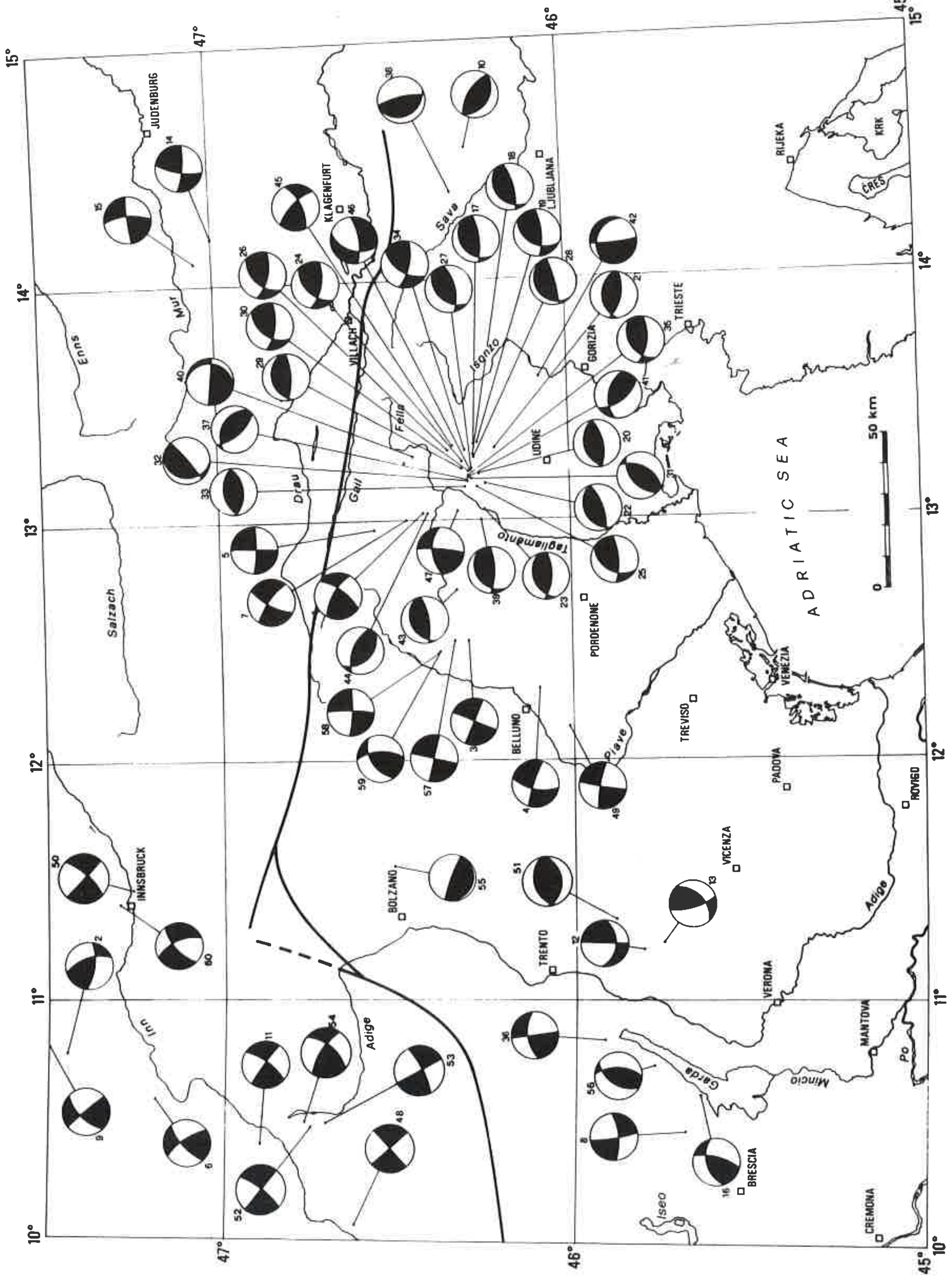

Fig. 9 — Map of the focal mechanisms of the principal earthquakes in northeastern Italy and surrounding zones in the period 1900-1986 with projection on the lower hemisphere; black area for compression; numbers refer to Table 2 (modified from Slejko et al., 1987).

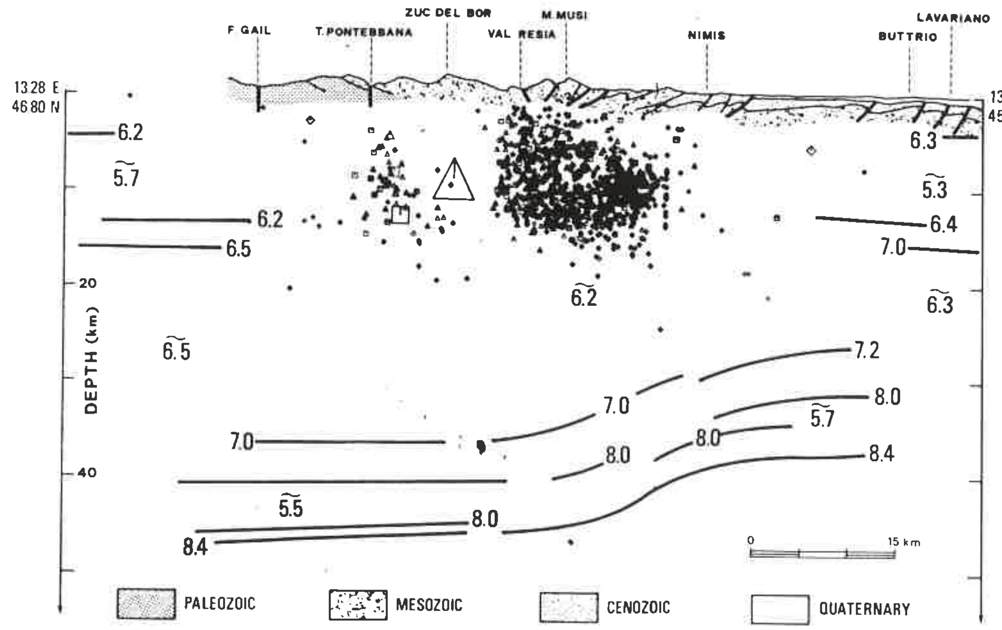

Fig. 10 — Geological-geophysical vertical cross-section n. 1, 10 km wide (modified from Carulli et al. 1982). The line position is given in Fig. 1. Different symbols refer to foci recorded by the OGS Seismometric Network of Northeastern Italy in different periods: squares from 1977 to 1978; triangles from 1979 to 1981; rhomboids from 1982 to 1986. Velocities refer to horizons revealed from refraction seismics.

al., 1984; Cavallin, 1985; Cavallin e Martinis, 1986; Panizza e Zardini, 1986; Cavallin et al., 1987b). In some cases the observed evidence of paleoseismicity can be roughly correlated with the level of the actual seismicity (Friuli and lake Garda zone), in others it is more difficult (i.e. mount Grappa zone).

SEISMOTECTONIC EVIDENCE

The crustal model of the area is poorly defined and different interpretations of the structural setting of the deep structures have been suggested (Barbano et al., 1985; Massari et al., 1986; Doglioni, 1987). Some cross-sections containing structural information, with emphasis on the linear elements characterized by neotectonic activity, the seismological data (instrumentally recorded by the local OGS Friuli network) and the crustal characteristics are proposed for the seismotectonic analysis (Figs. 10-15). The complete crustal model, represented by the lines of isovelocity for the longitudinal waves obtained by refraction seismic profiles, is given only in Fig. 10, as it can be considered representative for the whole Friuli area (Figs. 10-14). Some of the sections cross Dinaric structures in the central and southern part (Figs. 10 and 11), but they cross the most important Alpine lines (the Gail line, as part of the Periadriatic Lineament and the Fella-Sava line) in the northern part. A concentration and alignment of hypocentres can be seen under the Pontebbana creek zone (Fella-Sava line; Figs. 10 and 11): the seismicity represents the present-day activity of the fault in a vertical plane. The seismic activity in the central part of the section ranges between the surface and 15 km depth and seems to be connected mainly to the 10 km crustal discontinuity under the zone of surficial maximum tectonic deformation, where the larger number of shocks were localized. The most surficial seismicity could be caused by some north-verging structures which are considered active (e.g. Resia thrust). The hypocentres for the period 1977-1978 are spatially more concentrated; so it is reasonable to assign them principally to the seismic sequence which started in May 1976. A further observation arising from Fig. 10 is that the major seismicity occurs in correspondence to the northward deepening of the Moho discontinuity. In the western Friuli sections (Figs. 12-14),

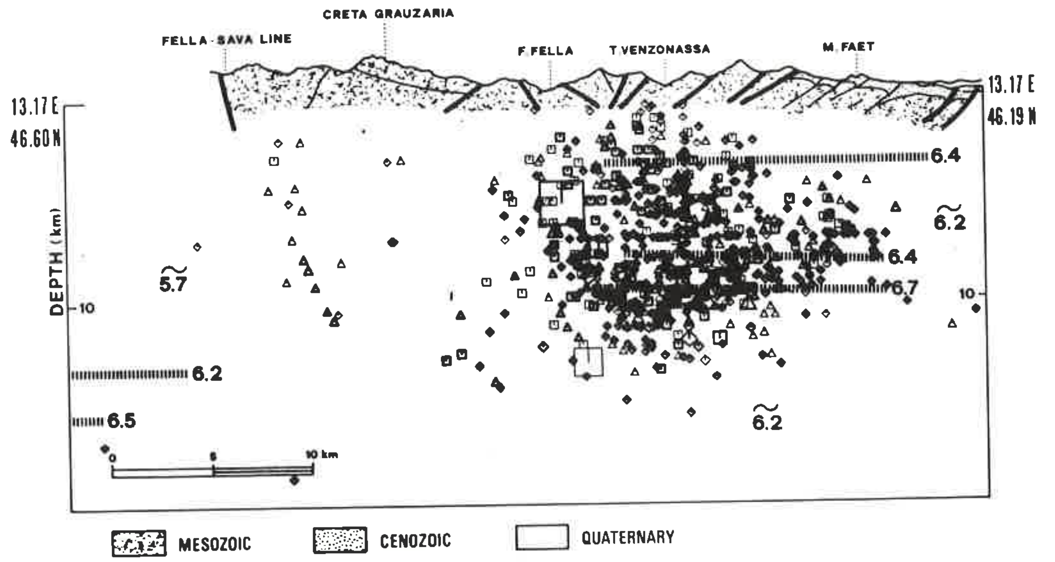

Fig. 11 — Geological-geophysical vertical cross-section n. 2, 6 km wide (modified from Carulli et al., 1982). The line position is given in Fig. 1; for the meaning of the symbols see caption of Fig. 10.

the many quakes are concentrated in the surficial part of the crust and sometimes can be directly connected to the presently active faults emerging at the surface. However, it is quite evident that the strongest Friuli events have deeper foci, definitely in the basement (Fig. 13), and that the average depth of the hypocentres becomes greater westwards. The few shocks in the plain occurred in the basement (Fig. 14). In Veneto, a deeper seismicity is grouped into two main zones: the first under the present compressive front; the second, with stronger events, within discontinuities of the crystalline basement (Slejko et al., 1987).

The seismicity of the Venosta valley is much deeper (reaching 25 km) than that in the Tyrol. From the analysis of cross-sections, the foci seem correlatable to a short NNW-SSE orientated subvertical structure. The available focal mechanisms agree with this hypothesis showing an almost pure strike-slip movement. The earthquakes could therefore be associated with a N-S orientated subvertical fault present in the upper Venosta valley and to its interference with the Engadina line, which is only slightly active from the present-day seismicity (see Fig. 8) and shows strike-slip movements (see Fig. 9) and minor thrusts. In addition, all the focal mechanisms of the area show a well defined N-S compressional axis.

In conclusion, from the analysis and comparison of the geological and geophysical data some observations are clear:

- the zones of maximum seismicity (central Friuli and eastern Veneto) correspond to highly tectonized sectors resulting from the Miocene-Quaternary crustal shortening (Massari et al., 1986) in front of a clear northward crustal thickening;

- the main seismicity occurred in the pre-Alpine sectors, south of the Fella-Sava and Valsugana lines, but some strong historical earthquakes were located around Villach and near lake Garda, in the latter area also the present-day seismicity is notable (see Fig. 8);

- the hypocentres in Friuli seldom exceed 15 km depth, and mainly involve the buried southernmost Paleozoic sequence; the focal mechanisms indicate active Alpine and/or Dinaric thrusts, both systems possibly interacting at depth;

- the earthquakes in eastern Veneto (Cansiglio-Alpago) have foci at a greater depth, in the crystalline basement, and seem to be mainly connected to transcurrent faults reactivating inherited old Mesozoic structures of Dinaric direction;

- the shocks along the Schio line have deeper foci (20 km) and vertical or strike-slip

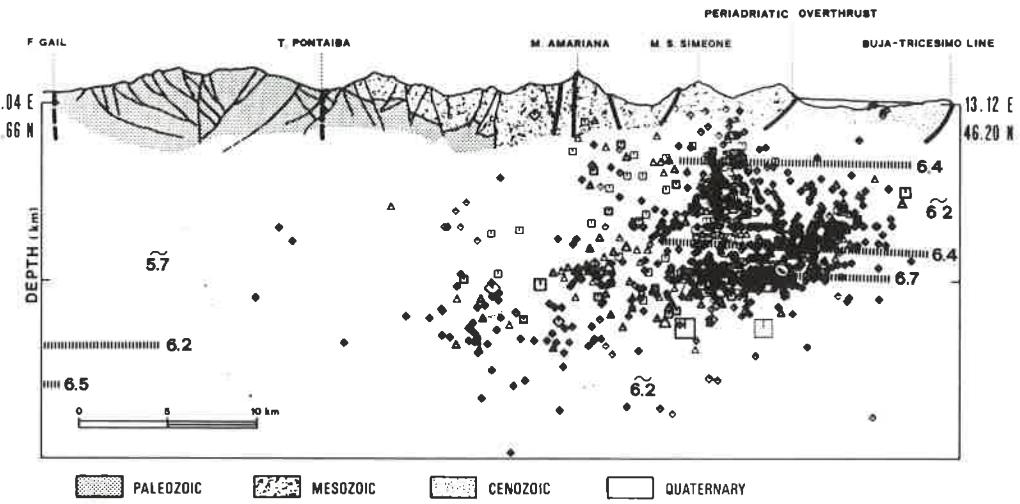

Fig. 12 — Geological-geophysical vertical cross-section n. 3, 6 km wide (modified from Carulli et al., 1982). The line position is given in Fig. 1; for the meaning of the symbols see caption of Fig. 10.

mechanisms; around lake Garda variable hypocentral depths and different focal mechanisms (Peruzza e Slejko, 1988) have been found, indicating activity of structures both longitudinal (with reverse dip-slip movement) and transversal (with transcurrent movement) to the Giudicarie system, in agreement with the hypothesis of a counterclockwise rotation of the Adria microplate with the pole near lake Garda (Anderson and Jackson, 1987).

STRUCTURAL UNITS

Treating it as a Neogene-Quaternary thrust belt, with south-verging thrusts principally active south of the Valsugana and the Fella-Sava lines, various geodynamic models have been proposed for the study region (e.g. Laubscher, 1974, 1988; Van Bemmelen, 1976; Castellarin et al., 1980; Doglioni and Bosellini, 1987).

The geodynamic evolution of the area is conditioned by the tectonic setting and evolution of three distinct chains:

- the Alps s.s., with west- and north-verging compressive structures developed from Cretaceous times to the Neogene;

- the External Dinarides, with SW-verging structures, and tectonic maximum activity during the Paleogene;

- the Southern-Alps, with SE- and south-verging structures in the studied area evolving from the Middle Miocene to the Present, and sharing a common foreland with the Apenninic chain and Dinarides.

The boundary between the eastern Southalpine chain and its foreland (c in Fig. 15) is clearly defined: a southward advancing front which progressively incorporates new sectors of the foreland (Massari et al., 1986). The boundary between the diachronous Southern-Alps and Dinarides is more difficult to trace, as several old Dinaric structures were reactivated in the Southalpine tectogenesis. The boundary between the Alps s.s. and the Southern-Alps corresponds to the Periadriatic Lineament (a in Fig. 15).

A structural model of the study area has been drawn in Fig. 15, and the following four major seismotectonic units defined (Slejko et al., 1986).

1) The Alps s.s. and northern sector of the Southern-Alps (1 in Fig. 15). This unit is essentially characterized by a general differential uplifting, with diffuse although minor strike-slip movements

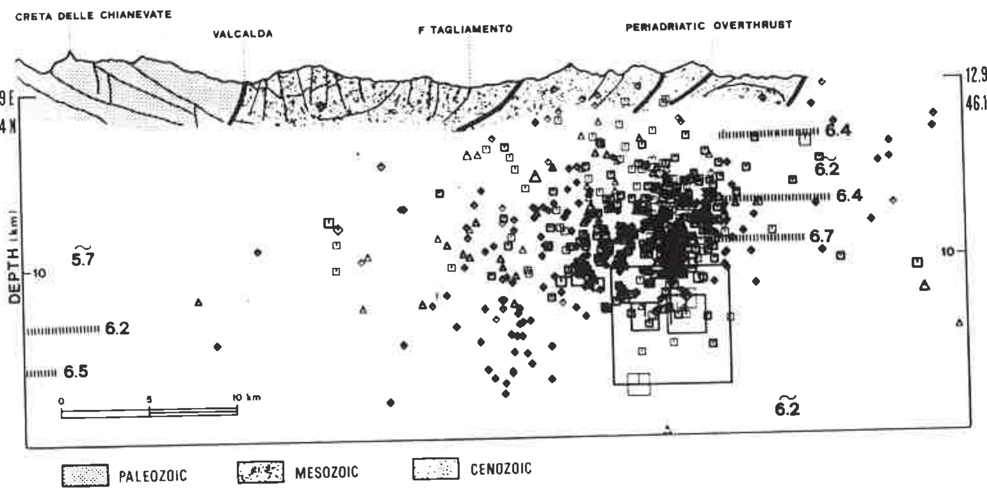

Fig. 13 — Geological-geophysical vertical cross-section n. 4, 10 km wide (modified from Carulli et al., 1981). The line position is given in Fig. 1; for the meaning of the symbols see caption of Fig. 10.

along NW-SE and NNE-SSW striking faults. A zone of maximum deepening of the Moho (depth >50 km) is found with a WSW-ENE direction between the Venosta valley and Lienz (Fig. 4). Seismicity is low throughout the whole sector.

2) The External Dinarides (2 in Fig. 15). Dextral strike-slip movements along major faults with NW-SE strike characterize this unit. Further activity is associated with the thrusts, which often show large strike-slip components or are transpressively active. The Moho deepens to an elongated NW-SE zone (depth >40 km) trending parallel to the surface structures and corresponding to the area of highest earthquake density. This anomaly could be connected to a subduction zone active since the Paleogene (Aljinović et al., 1984). However, in accordance with the present geodynamic setting, this zone of crustal thickening is considered to be affected by intracrustal shear and detachment phenomena. Seismicity seems to be diffuse and locally high (coastal strip: Carulli et al., 1989).

3) The Miocene foredeep belt of the Southern-Alps (3 in Fig. 15). This unit is characterized by the highest neotectonic and seismic activity, though it is not evenly distributed. The depth of the Moho increases towards the north (Fig. 4). This could be attributed to the above mentioned maximum depth under the Alps s.s. and, to a lesser extent, to Neogene-Quaternary crustal shortenings. The crystalline basement is involved in the main thrusts which are the prominent structures. NW-SE and NNE-SSW strike-slip faults are quite common at the surface, but only occasionally relevant for a seismotectonic model. The sector east of Pordenone records a complex interference pattern between the Southern-Alps and the Dinarides and shows the highest seismic and tectonic activity. Probably within the first 10-12 km of the crust, these patterns lead to the fragmentation and incorporation of the Dinaric structures into the Southalpine ones. It is likely that in this sector the Dinaric thrusts have been reactivated with a dextral strike-slip movement, in agreement with many focal mechanism solutions. The underlying 5-10 km, characterized by seismic intervals with lower v_p values (Fig. 10) and hypocentres down to a depth of 15 km, may consist of basement sequences and structures, such as those which outcrop in the Paleocarnic chain. Between Pordenone and the Lessini region, the Dinaric thrusts are not present. Here Neogene-Holocene south-verging thrusts, cut by transverse strike-slip faults, are dominant. Seismicity decreases westwards and only strike-slip focal mechanisms have been calculated here, including those in the Cansiglio-Belluno zone. The region around lake Garda (central sector of the Southern-Alps), differs from the Friuli area in the structural evolution (tectonic climax progressing eastwards from the Late Miocene in the Garda sector to the Pliocene-Pleistocene in the Friuli arc), in structural trends (ranging from NNE-SSW to E-W), in a lower degree of seismicity and in different types of focal mechanisms with variable hypocentre depths.

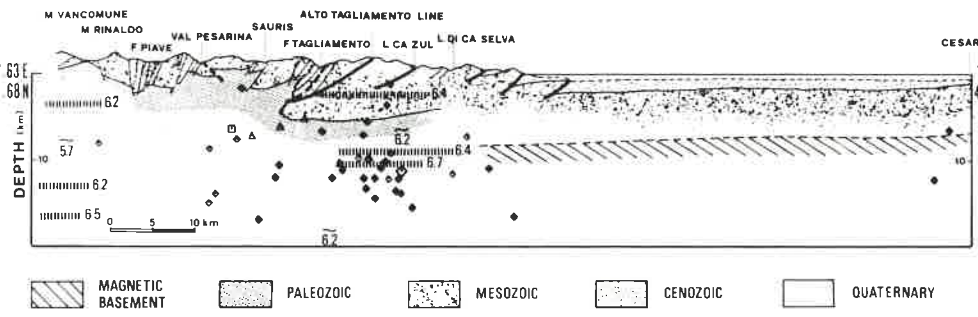

Fig. 14 — Geological-geophysical vertical cross-section n. 5, 10 km wide (from Slejko et al., 1987). The line position is given in Fig. 1; for the meaning of the symbols see caption of Fig. 10.

4) The Southalpine-Apenninic foreland (4 in Fig. 15). In both the Lessini and the western Istria sectors there is a normal or thin crust (less than 30 km). The Lessini sector can be regarded as a rigid block separating the central from the eastern Southalpine chain. The thrusts of the Garda-Trento area mark its western border. Towards the east, the Southalpine thrusts are left-laterally drifted along the NW-SE striking Schio-Vicenza line (e in Fig. 15). Seismicity is relatively low and diffuse, and great hypocentral depths (>20 km) are reached here. In the foredeep basin (northern Adriatic region and eastern Veneto-Friuli plain), the vertical movements were strong also during the Pleistocene, and seismicity is even lower and sparser.

SEISMOTECTONIC MODEL AND SEISMOTECTONIC ZONING OF NORTHEASTERN ITALY

A subdivision of the study area into the four above mentioned units is the first stage in the identification of a seismotectonic model compatible with the present state of the regional geodynamic evolution.

The earthquakes considered are represented in Fig. 16 regardless of their magnitude in order to give a general pattern of the seismic areas. The seismicity is limited towards the Adriatic and Po plain domains by the compressive fronts of the External Dinarides, of the Val Trompia-Giudicarie arc and of the Friuli arc (Carulli et al., 1989). Westwards, northwards and eastwards it is limited by subvertical faults (the Giudicarie, the Valsugana, the Fella-Sava lines in their present structural configuration, and the Idrija line) which act as mechanical disengagement for the external active thrust fronts. In the belt defined by these elements, some notable increases in the crustal thickness from the Adriatic sea towards the Alps and Dinarides can be observed, and they are marked by arrows in the map.

A strict correlation between zones of intersection of tectonic lines (nodes) and seismicity was evidenced in the USSR (Gvishiani et al., 1986) by statistical analyses applied to nodes of different hierarchy.

The concept of node is introduced here on the basis of the seismotectonic evidence described before: nodes are the zones of interference of the seismically active Alpine and Dinaric thrusts with transfer faults dislocating the main systems (the Schio-Vicenza line and the N-S orientated lines in the river Tagliamento valley near Gemona). The maximum concentration of foci is observed in correspondence with the two nodes of Friuli and Garda. Therefore, the seismicity remains limited within compressional fronts and subvertical disengaging tectonic elements in zones of sharp increase of crustal thickness with a maximum concentration at the nodes.

Within this general framework should be mentioned the quasi-aseismic behaviour of the Periadriatic Lineament, with the exception of the Villach zone, where the intersection and bending of tectonic structures might suggest the presence of an "anomalous" (or minor) node with poorly located historical seismicity and weak present-day seismicity only along the Fella-Sava line. The poor information on the very few, but strong, earthquakes in the Villach zone does not allow a convincing demonstration of their correlation with the reputed stable Gail line rather

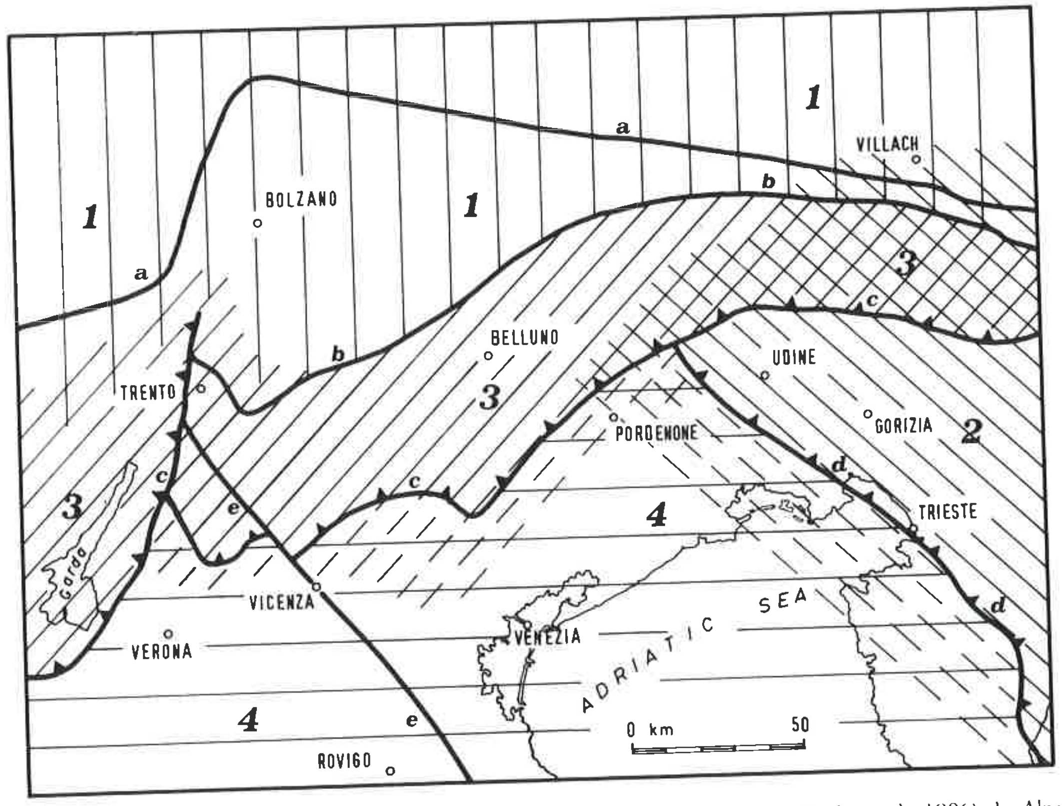

Fig. 15 — Map of structural units in northeastern Italy and surrounding zones (from Slejko et al., 1986): 1 = Alps s.s. and northern sector of the Southern-Alps; 2 = External Dinarides; 3 = southern sector of the Southern-Alps; 4 = Southalpine-Apenninic foreland. Tectonic limits: a = Periadriatic Lineament, separating the Alps s.s. from the Southern-Alps; b = Valsugana (westwards) and Fella-Sava (eastwards) lines; c = front of the Southern-Alps; d = front of the External Dinarides; e = Schio-Vicenza line.

than with the active Fella-Sava line. Moreover, according to Gutdeutsch and Aric (1987), a N-S orientated "seismic lineament" of extensional character can be postulated in the Villach area connecting the Periadriatic Lineament to the Mur-Murz valley sinistral fault. For these reasons, the Carinthia node is represented by a dashed circle in Fig. 16.

The diffuse seismicity in Slovenia must be related to interaction within the External and Internal Dinarides, and the structures of the Pannonian basin.

On the basis of the considerations above described, it is possible to divide the studied region into ten different homogeneous seismotectonic zones (Fig. 17).

1) The Northern Alpine area includes the northern part of the Giudicarie system, the Dolomites synclinorium, the Paleocarnic chain and part of the Alps s.s. Very thick crust and generalized differential uplifting characterize this area. The generally low seismicity has its main concentrations along the Venosta valley.

2) The Garda area comprises the southern part of the Giudicarie system. A large northward and westward deepening of the Moho, and distinct deformations with the tilting of mount Baldo characterize this area. The seismicity is high with various strike-slip and reverse mechanisms probably connected to transverse structures crossing the Giudicarie system (Renner e Slejko, 1986; Slejko e Rebez, 1988). Strong historical earthquakes have been recognized but here the data are insufficient for a detailed study.

3) The Lessini area corresponds to the major part of the Lessini block of normal to thin crust, with small uplifting, deformation and southward tilting. Normal faults seem to be presently active. The seismicity is mainly concentrated in the southern part, and is connected with the

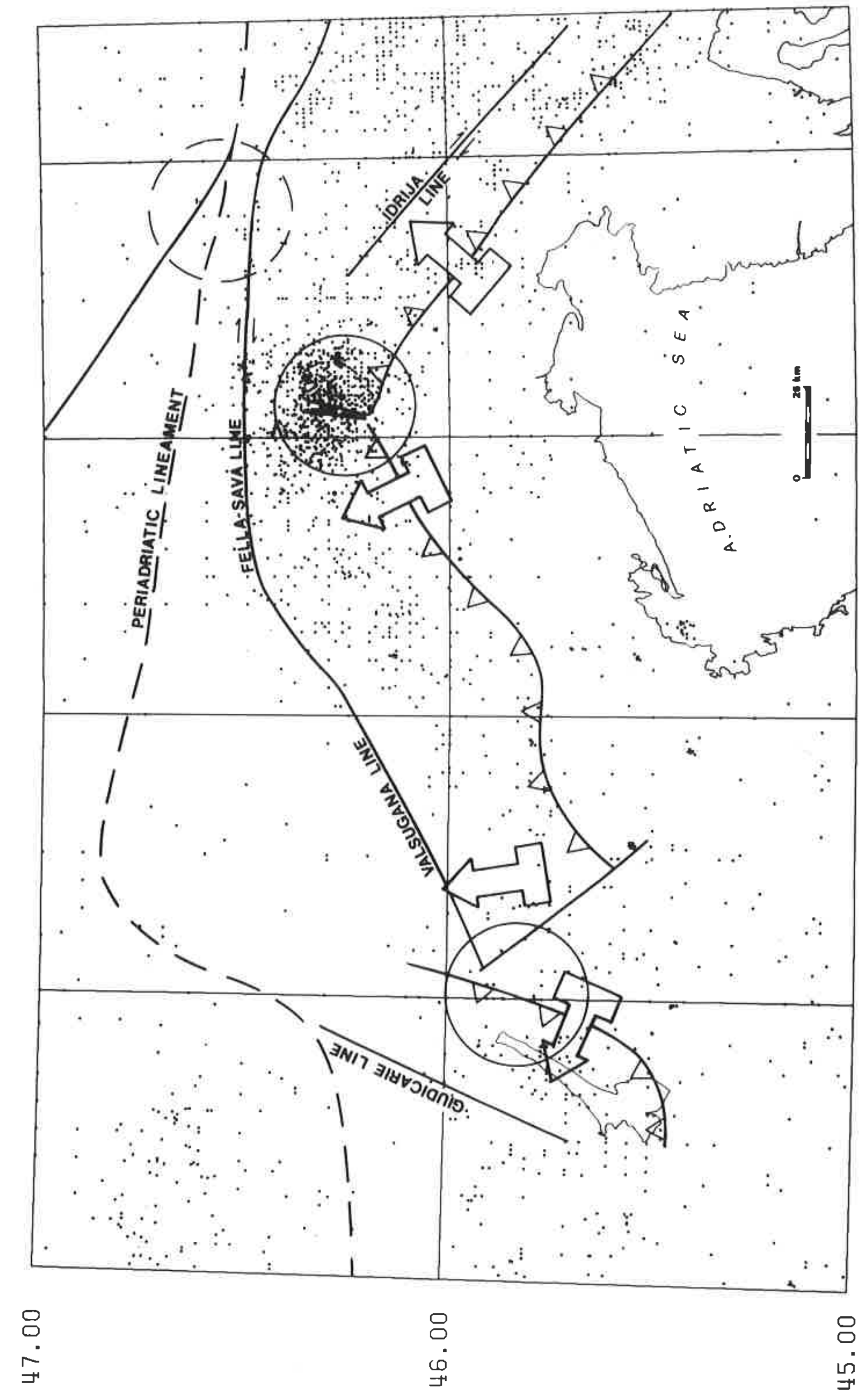

Fig. 16 — Seismotectonic model of northeastern Italy: arrows indicate increases of crustal thickness, circles show nodes and points represent epicentres.

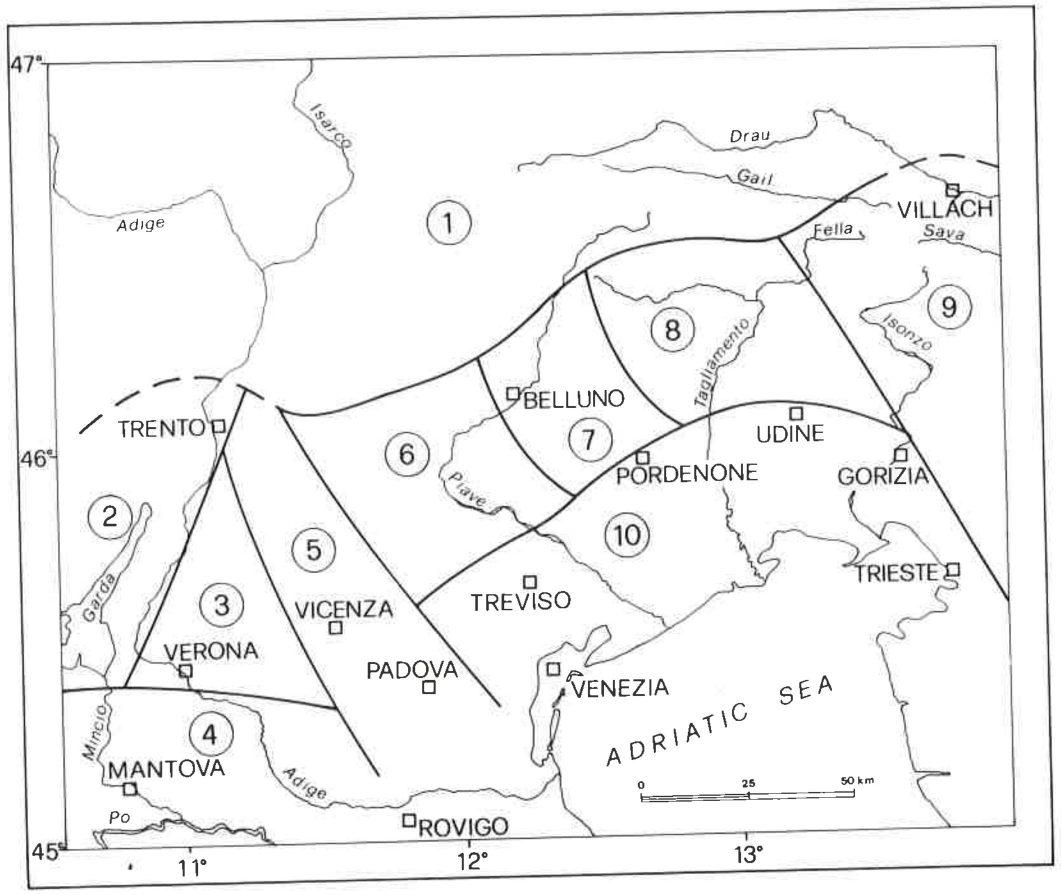

Fig. 17 — Seismotectonic zoning of northeastern Italy (from Slejko et al., 1987): 1 = northern Alps area; 2 = Garda area; 3 = Lessini area; 4 = Po plain area; 5 = Schio line area; 6 = Feltre area; 7 = Belluno area; 8 = Friuli area; 9 = Dinaric area; 10 = southern Veneto-Friuli and Istria area.

Verona deformation hinge at the transition to the subsiding Po plain.

4) The Po plain area, southern prosecution of the Lessini area, has the Moho regularly deepening towards the Apenninic foredeep. The area is downlifted and has very little seismicity.

5) The Schio system area is a transition zone from the Lessini area to the Veneto-Friuli belt and is characterized by the presence of the Schio-Vicenza line which is structurally very important but is not affected by strong seismicity.

6) The Feltre area is characterized by the presence of folds and thrusts dipping NNW, cut by NW-SE transverse transcurrent faults. The area is neotectonically deformed by the activity of the above mentioned structures. The seismicity is rather high especially in the Montello, Bassano and Feltre zones, and is possibly correlated to the activity of the transcurrent faults and of the southernmost thrusts.

7) The Belluno area is a transition zone between the Valsugana system and the Tagliamento system with the presence of transverse Dinaric structures. The neotectonic deformations are related to the evolution and interaction of the above systems. The high seismicity in the Alpago-Cansiglio and Belluno zones seems to be connected with the activity of transcurrent faults (NW-SE orientated) reactivating Mesozoic structures and of the Southalpine thrusts.

8) The Friuli area is characterized by the north dipping thrusts of the Tagliamento system and by N-S and NW-SE orientated transcurrent faults. High neotectonic deformation and a northward deepening of the Moho are seen. The very high seismic activity is mainly due to

the interaction between Alpine and Dinaric structures.

9) The Dinaric area is dominated by NE deepening thrusts and NW-SE orientated transcurrent faults still in evolution. The Moho deepens northeastwards and the seismicity is rather uniformely distributed with a concentration in the Villach, Idrija, Ljubljana and Sneznik mount zones (Carulli et al., 1989).

10) The Veneto-Friuli plain and Istria area includes the Quaternary Southalpine foreland, and is mainly characterized by NW-SE active transcurrent faults. A fair amount of seismicity is located near Treviso and Latisana. In the latter zone, the structure is not known but the aeromagnetic data (Arisi Rota and Fichera, 1985) indicates the presence of a possible discontinuity in the magnetic basement.

CONCLUSIONS

From a comparison of the geological and geophysical data, a first attempt at a seismotectonic model of northeastern Italy has been made. A successive zoning into seismotectonically homogeneous zones is suggested. This zoning has seismogenetic characteristics, although a direct connection between earthquakes and individual tectonic structures is not yet possible.

The proposed seismotectonic model has the following well defined characteristics:

- In the study region the seismicity is concentrated in the zones of maximum recent deformation, primarly at the front of the Southalpine thrusts connected to shortening by compressional tensions responsible for clear variations in the geometries of the deep crustal discontinuities.

- High seismicity occurs in the pre-Alpine belt south of the Valsugana and Fella-Sava lines. The southern limit of this zone roughly corresponds to the present Southalpine deformational margin.

- Concentrations of seismicity can be noted at the zones of interference between the different tectonic systems: Southern-Alps and External Dinarides in Friuli; Giudicarie system, Valsugana and Schio lines in western Veneto.

- Another concentration of seismicity can be connected to the Dinaric transcurrent faults in eastern Veneto (Alpago-Cansiglio).

- The Garda sector as well as the Villach and the Idrija areas have peculiar characteristics: the strong historical seismicity can only be explained by considering the geodynamics of a wider region (Carulli et al., 1989).

- The hypocentral depth never exceeds 20-25 km, and is concentrated in the upper crust. The maximum activity in Friuli is concentrated at the base of the sedimentary cover or at the top of the basement, whilst in Veneto it occurs in the basement.

- The focal mechanisms in Friuli are of the dip-slip type connected to ESE-WNW orientated thrusts, and of strike-slip type with variable orientation in Veneto and in Austria.

The main limits of the proposed model are the following:

- The crustal model is not sufficiently controlled by DSS profiles.

- The gravimetric and magnetic data can only support a previously defined crustal model, and some reference points are necessary.

- The seismological information of the historical events needs revision, especially in the Garda, Villach and Idrija zones.

In conclusion, the seismotectonic model proposed can be considered a tentative scenario for which detailed studies of seismogenesis will have to be performed to arrive at a seismogenetic zoning for seismic hazard purposes.

Acknowledgements. The present work was developed by the Research Unit 1.4. "Seismotectonics of Alps" of the GNDT (Contracts n. 82.01968.54 and n. 83.01340.54) during the years 1983-1986. The Seismometric Network of Northeastern Italy is managed by OGS with financial support from the Regione Autonoma Friuli-Venezia Giulia and the Provincia Autonoma Trento. Many thanks are due to profs. A. Castellarin and G.V. Dal Piaz for critically reading the manuscript.

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