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SEISMOTECTONICS OF THE EASTERN SOUTHERN-ALPS:
A REVIEW

Abstract: The most 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 geomagnetic, magnetic, seismic and seismological data have been analyzed. In particular, the spatiotemporal distributions of the historical and instrumental earthquakes identify the footsills of the area as the most active zone; the main seismicity is related to thrusts and wrench faults of the Southalpine and Dinantic 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 hypocenter 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 seismogenic zones.

INTRODUCTION

For assessing the regional seismic hazard, it is necessary to define the seismogenic zones that determine the seismicity. These zones can be precisely defined in structure and character only when a seismotectonic 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;
Fig. 1 – Index map of the study area. Solid lines indicate the geological and geophysical vertical cross-section presented in the paper. The dot-dashed line indicates the limit of the relief.
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 synclines, located within a Neogene pop-up of the upper crust and with flexural slip in the sedimentary cover limited to the south by the Vallogona thrust system (Casalartini, 1978; Tommasini, 1987). The orientation of the structures gradually changes north-eastwards from ENE-WSW (Vallogona) to E-W (Tagliamento).

d) Vallogona system, with NE-SW to ENE-WSW trending thrusts, which affects the basement along the Vallogona 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 rooted in the External Dinarides and buried in the Friuli plain with movements that affected the Quaternary molassic units. The Idriza subvertical dextral transcurrent fault is considered an active seismotectonic element of this system (Carulli et al., 1989).

Tectonic activity during Middle Pleistocene-Holocene (Zanarcarati 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 generally southward tilt occurred; the hinge zone with respect to the subsiding plain appears to be in the Verona deformation belt. Southwestwards, a zone characterized by subsidence which increases eastwards and towards the Po plain axis has been recognized (e.g. Arca e Beretta, 1985).

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

d) The Vallogona system, with thrusts in the southernmost sector responsible for the genesis of the outer uplands, is an area of very important deformational phenomena (Reinat et al., 1988).

e) The Tagliamento system, where the southernmost thrusts are active and may be seen in the deflections 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 shortening of the eastern sector of the Southalpine chain (Castellani, 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 deformations, vertical faults with Dinaric direction dominate the longitudinal Tagliamento structures. The subvertical Idriza fault is part of this system. It is presently characterized by dextral transcurrent tectonics which have affected internal nappe packages, oblique to 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 Hulse Tausen area (Senfli and Essen, 1975) and in Friuli where large variations were associated with the strong earthquakes of 1976 (Talano et al., 1978).

CRUSTAL STRUCTURE

Detailed seismic investigations are required for a more complete outline of the present connection between the geometry of the deep structures in the Alpide 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 systems (Royden et al., 1983b), is of outstanding importance. The Adria microplate 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 60s, mainly under international cooperation programs (Giese and Prodehl, 1976; Gebrard et al., 1977; Aric et al., 1987; and references in Seyko 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 Bavarian region (southern Germany), it gradually rises up to a depth of 35-30 km. This Moho deepening fits the negative trends of the Bouguer anomalies quite well (Fig. 5 and discussion and references in Seyko et al., 1987; Walach and Weber, 1987).

The Apulian 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 Giudicaries-Adamiello system or along the border of the so called Val Trompia-Giudicarie arc (Castellani and Vai, 1986), to the north in the Vallogona 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 aeromagnetic interpretations (Cati et al., 1987), this element is linked to structures occurring near the top of the basement. The aeromagnetic data confirm that the basement is involved along the whole Southalpine Friulian arc in a complex tectonic setting, and is displaced and thrust onto the basement of the Adriatic foreland and its sedimentary cover (Vallogona and Tagliamento systems, Seyko et al., 1987). Similar interpretations of the basement have been hypothesized for the Dinaric system (Cati et al., 1987).

Thus, the 6.7 km 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 (thickening more than 40 km) orientated NW-SE and running from Tolmin-Istria to Dalmatia-Herzegovina (southern Yugoslavia). It has been interpreted by 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 stratigraphic rocks (Horvath and Royden, 1981; Pesagel 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 Sljšaka et al., 1982). Principal faults: 1 = Torbole line, 2 = Giulianova line, 3 = Pozzuoli line, 4 = Gail line, 5 = Rupazzes fault, 6 = Veneto-Vareso line, 7 = Vallesina line, 8 = Friulian line, 9 = Fiume-Vabresian line, 10 = Bresan thrust, 11 = Ioriana line.

Fig. 3 — Neotectonic map of northeastern Italy (from Sljšaka et al., 1982).
and uppermost mantle materials caused a crustal doubling (Giese, 1980).

Using the gravimetric information from Italy and Austria, a general map of the Bouguer isoasomal 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 Taueran window is controlled by the European Moho deepening 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 Stojko et al., 1987).

SEISMICITY

Northeastern Italy has been subjected to numerous destructive earthquakes (Table 1), especially in the Veretto (Verona, Vicenza, Belluno) and Friuli (Tolmezzo, Gemona, Grivicale) areas (Stojko et al., 1987). To detail the seismicity of the region, a plot of the most important earthquakes occurred in the period 1938-1977 and of the seismic activity according to Rüdenhout (1959) has been produced. In Fig. 7, the focal volumes (Bühl and Budé, 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 1828 to 1964 (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
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; Cavallini 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 km² per year (Ronzoni, 1959) calculated on a 0.5° x 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 reasonably complete and homogenous, 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 oriented mainly N-S (Slejko e Renner, 1984). Further mechanisms available for the Eastern Alps (Boschi et al., 1974; Cagnetti et al., 1976; Ehblin, 1976; Kuno, 1982; Jimenez and Pavana, 1984; Renner and 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 NW-SSW oriented subvertical faults at their interaction with the southermost Alpine thrusts (Peruzza et al., 1989). The foci deepening moving towards the north 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 Garda arc 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 northwards by the prolongation of the Istria fault, which plays the role of a dislocating structure (Carroll et al., 1989). In the Slovenian Karst, the historical seismicity is correlated to the transcurrent activity of Dinaric faults and to their interaction with similarly oriented thrusts (Rebez et al., 1987).

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

The study of the seismicity of the area has been integrated with paleoseismic information. For this purpose, two different kinds of phenomena are used: surface faults (Saura, 1979; Cavallini et al., 1987a) and paleo-landslides (Perna et Saura, 1979; Girardi et al., 1981; Zardini et
Fig. 7 - Seismicity map of northeastern Italy and surrounding areas (from Siroli et al., 1987) with the epicenters of the earthquakes with intensity greater than, or equal to, degree VI MCS of the period 228-1977 and the minimum of the seismic activity according to Illia and Chiarizia (1985).

Fig. 8 - Map of the epicenters of the shocks with magnitude greater than 2.6 recorded by the OGS Seismometric Network of Northeastern Italy in the period 1977-1986. Heavier symbols for events with epicentral error smaller than 3 km.
Table 1. Earthquakes with epicentral intensity greater than, or equal to, degree VIII MCS in the Eastern Alps during the period 1928-1984.

<table>
<thead>
<tr>
<th>Date of year</th>
<th>Coefficient of intensity</th>
<th>b</th>
<th>Magnitude</th>
<th>Epicentral area</th>
<th>Average instrument cm</th>
</tr>
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<tr>
<td>1928-1931</td>
<td>4.08</td>
<td>17.00</td>
<td>5.0</td>
<td>VICENZA</td>
<td>14</td>
</tr>
<tr>
<td>1932-1935</td>
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<td>17.00</td>
<td>5.0</td>
<td>VICTORIO</td>
<td>14</td>
</tr>
<tr>
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<td>17.00</td>
<td>5.0</td>
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<td>14</td>
</tr>
<tr>
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</tr>
<tr>
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</tr>
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<tr>
<td>1981-1984</td>
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</tbody>
</table>

Table 2. Focal parameters of the principal earthquakes in the Eastern Alps during the period 1928-1984. a) indicates the focal depth, b) indicates the focal magnitude and b) the hypocentral reference.

<table>
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<tr>
<th>N°</th>
<th>Date of year</th>
<th>Coefficient of intensity</th>
<th>b</th>
<th>Magnitude</th>
<th>Epicentral area</th>
<th>J</th>
<th>P</th>
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<td>VICTORIO</td>
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<td>8</td>
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</table>

Using the same formula, the epicentral area at which the epicenter lies is also determined.
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., 1965; Massari et al., 1996; Doglioni, 1987). Some cross-sections containing structural information, with emphasis on the 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. 10-13). 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 Gall line, as part of the Periodic Lineament and the Fella-Sava line) in the northern part. A concentration and alignment of hypocentres can be seen under the Punteibiana 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 superficial 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),
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 noses: 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 Veneto 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 NW-SE oriented 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 Veneto valley and to its interference with the Eugadina 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 Valugana 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 Dinarian thrusts, both systems possibly interacting at depth;
- the earthquakes in eastern Veneto (Cassiglio-Abano) have foci at a greater depth, in the crystalline basement, and seem to be mainly connected to transient faults reactivating inherited old Mesozoic structures of Dinarian direction;
- the shocks along the Sobio line have deeper foci (20 km) and vertical or strike-slip mechanisms; around lake Garda variable hypocentral depths and different focal mechanisms (Perego and Slejko, 1986) 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 Valugana and the Fella-Sava lines, various geodynamic models have been proposed for the study region (e.g. Laubscher, 1974, 1988; Van Bemmelen, 1976; Castellari et al., 1980; Doglioni and Baselli, 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 Periodic Lineament (a in Fig. 15).

A structural model of the study area has been drawn in Fig. 15, and the following four major seismicotectonic 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 characterised 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 (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 characteristic this unit. Further activity is associated with the thrusts which often show large strike-slip components or are transformally active. The Moho descends 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 (Alpinov et al., 1984). However, in accordance with the present geodynamic setting, this zone of crustal shortening 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 seismic and tectonic activity, though it is not evenly distributed. The depth of the Moho increases towards the north (Fig. 4). This could be attributed to the absence mentioned above of the maximum depth under the Alps s.s. and, to a lesser extent, to Neogene-Quaternary crustal shortening. 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 area. 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 $v_s$ values (Fig. 10) and hypocentres down to a depth of 13 km, may consist of basement sequences and structures, such as those which outcrop in the Paleochains. Between Pordenone and the Lessini region, the Dinaric thrusts are not present. Here Neogene-Quaternary south-verging thrusts, are dominant. Seismicity decreases westwards and only strike-slip focal mechanisms have been calculated here, including those in the Carnic-Belluno zone. The region around Lake Garda (central sector of the Southern Alps), differs from the Friuli area in the structural evolution (transcurrent thrusts progressing eastwards from the Late Miocene in the Garda sector to the Pleistocene in the Friuli area), 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.

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 Scho-Vicenza line (c 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 Valugana, the Fella-Sava lines) in their present structural configuration, and the Idrìa 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 (Krishin 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 Scho-Vicenza line and the N-S oriented 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-asismic behaviour of the Periodic 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 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 Gall line rather.
Fig. 15 — Map of structural units in northeastern Italy and surrounding areas (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 Apennine foreland, Tectonic limits: a = Periadriatic Lineament, separating the Alps s.s. from the Southern Alps, b = Val Varcoe (co-seismic), c = Fella-Sava (transverse) lines, d = front of the Southern Alps, e = front of the External Dinarides, f = Stico-Venosa line.

than with the active Fella-Sava line. Moreover, according to Godtisch and Aric (1987), a N-S oriented "seismic lineament" of extensional character can be postulated in the Villach area connecting the Periadriatic Lineament to the Mur-Mura 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 Giulianian system, the Dolomites synclinorium, the Paleocarpathian 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 concentration along the Venosta valley.

2) The Garda area comprises the southern part of the Giulianian 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 Giulianian system (Renner & Slejko, 1986; Slejko & Rehak, 1988). Strong historical earthquakes have been recognized but here the data are insufficient for a detailed study.

3) The Lessinia area corresponds to the major part of the Lessinia block of normal to thin crust, with small uplifting, deformation and southward tilting. Normal faults seem to be present 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 epicenters.
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 northward with the seismicity rather uniformly distributed with a concentration in the Villach, Istrija, Ljubljana and Snejnik mountain zones (Carulli et al., 1989).

10) The Veneto-Friuli plain and Istrija 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 Istrija. In the latter zone, the structure is not known but the aeromagnetic data (Ainsi 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 seismotectonic 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, primarily at the front of the Southalpine thrusts connected to shortening by compressional tectons 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-Carsiglio).
- The Garda sector as well as the Villach and the Istrija 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/NNE 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 models are only supported by 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 Istrija 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 seismotectonic zoning for seismic hazard purposes.

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