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SOME COMMENTS ON THE SEISMICITY OF THE ADRIATIC REGION

Abstract. Current knowledge on the seismicity of the Adriatic region is given. Historical and instrumental data support the idea that the Adria microplate is an almost rigid block with strong activity at the margins. The few earthquakes which have occurred in the sea represent the common intra-plate seismicity, with the exception of some medium magnitude events in the lower central Adriatic sea which are interpreted differently from the seismotectonic point of view. In addition, the present - day seismicity of the most northern sector of the region is investigated in detail and confirms the evidence for transpressive activity on the Dinaric front.

INTRODUCTION

The origin of the Tertiary orogenic systems surrounding the Adriatic sea (Apennines, Alps, Dinarides, and Hellenides), as well as that of the other circum-Mediterranean chains, is related to the convergence between the European and the African plates (Fig. 1). This well known process, which started in uppermost Jurassic - early Cretaceous times, lead to the disappearance of the ancient Thetys ocean which was situated between the two continental margins and whose relics are today the ophiolites and abyssal sediments found in the nappes constituting the orogenic systems. The fronts of the circum-Adriatic chains (i. e. the east-verging Apennines, the south-verging Southern Alps, and the west-verging Dinarides) and the epicentral distribution of the earthquakes show that the Adriatic sea currently represents the foreland of these fold-and-thrust belts. The genesis and the curved shape of the Alps have been explained as being due to the collision between the European and the African plates, with the Adriatic region (Adria) as an African promontory (e.g. Argand, 1924; Channel and Horvath, 1976; Channel et al., 1979; Vanderberg, 1979; D'Argenio et al., 1980). There is still a debate however, as to whether Adria is still linked to the African plate (Dewey et al., 1973; Biju-Duval et al., 1977) or, more likely, is presently a microplate (Hsu, 1977) as is also suggested by the seismicity pattern and focal plane solutions of the largest recent earthquakes (Anderson, 1987; Anderson and Jackson, 1987). The margins of this Adria microplate are the Apennines to the west, the Southern Alps to the north, the Dinaric - Hellenic chain to the east, and possibly the Ionic basin to the south. While the first three are well marked by the earthquake distribution, the last is more poorly identified, and there are different opinions (e. g.: Mele et al., 1990) about the location of its separation from the African plate.

A thrusting with subduction of the Adria lithosphere under the Apennines, Dinarides, and Hellenides has been suggested from geophysical and tectonic data (Favali et al., 1990); but the extensive presence of wrench tectonic deformations in the Dinaric region suggests a lithospheric thickening without subduction (Favali et al., 1992). The Adria microplate is generally considered

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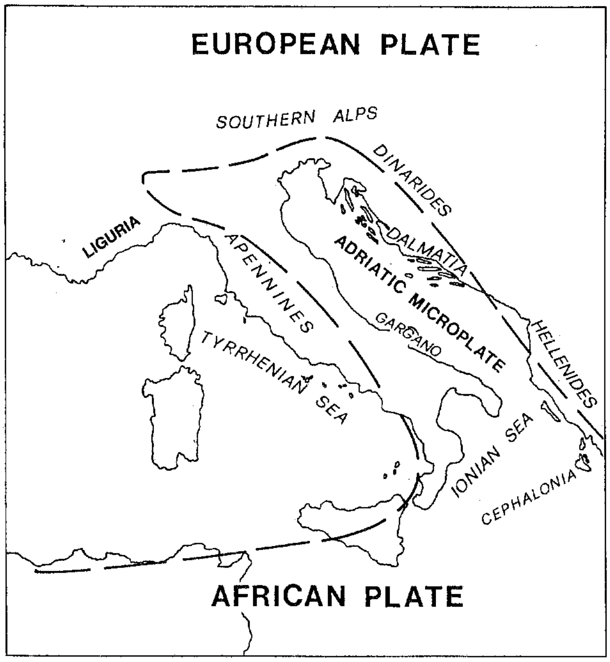

Fig. 1 — Index map of the study region.

subject to a continuing anticlockwise rotation, with pole located near lake Garda (Anderson and Jackson, 1987) while the motion between Africa and Eurasia has been postulated to have its pole located offshore the Canary islands (Anderson, 1987). A more recent analysis of all the available stress indicators in the region supports a location of the Adria microplate rotation pole on the Liguria coast (Meletti and Scandone, 1994, personal communication). Investigations of seismic reflection (Finetti, 1984) and refraction (Morelli, 1984) profiles seem to imply that the movements associated with this rotation produced not only the typical compressional deformation of the peri-Adriatic orogenic chains, but also transcurrent faults often normal to the Adriatic axis, such as the Cephalonia, Gargano (called also Mattinata) and Tremiti islands faults (Finetti, 1982, 1984).

The aim of the present work is to present the current knowledge on the seismicity of Adria, with special attention to the offshore earthquakes, and to give some new data on the seismicity of the study region's northern sector in its seismotectonic setting. For this, the published data on relevant events have been collected, and specific processing of the data recorded by the seismometric network of northeastern Italy has been performed.

SEISMICITY OF ADRIA

The general opinion is that the Adria microplate is a single, rigid, almost aseismic block (e. g. Mantovani et al., 1985; Anderson and Jackson, 1987). Recently, Favali et al. (1993) have analyzed a seismic sequence in central Adria identifying an active zone, at the latitude of Gargano, which is interpreted as being connected to a lithospheric discontinuity (which shows structures outcropping from the southern Dalmatian coastline, in the Kotor zone, to the Split - Sibenik area and, across the Adriatic isles, as far as the Tremiti islands and the Gargano - Murge region, Favali et al., 1992) separating the active southern sector from the aseismic northern one.

Historical seismicity

In Fig. 2 the epicentres of the earthquakes between the years 1000 and 1915 are shown.

The data have been taken from the Italian earthquake data file (GNDT, 1994b) prepared within the framework of the 'Gruppo Nazionale per la Difesa dai Terremoti' (GNDT) of the 'Consiglio Nazionale delle Ricerche' (Stucchi, 1993), from the Slovenian catalogue (Ribaric, 1982), and from the Croatian catalogue (GIZ, 1986). This last catalogue merges data from ten different catalogues for the Balkan region. Fig. 2 should adequately represent what is currently known about the seismicity of Adria, as it collects together most of the information available for the whole studied area: however it gives only a partial idea of the seismicity of the study region because macroseismic information rarely gives good offshore locations and effects are reported on land only for major events (Albini et al., 1994). The main events reported in the map are located NE of Ancona, and around the Gargano promontory on the western coast of the Adriatic sea, and around Rijeka, Zadar, Split, Dubrovnik, and the Kotor bay on the eastern coast. The seismicity in the Middle Ages is linked almost exclusively to the major towns on the coast: in fact, information on earthquakes damaging Zadar is very frequent, and that on events which destroyed Dubrovnik continues till the 18th century. The (poor) seismicity around Venezia in Fig. 2 very likely refers to distant earthquakes strongly felt in the town because of its particular

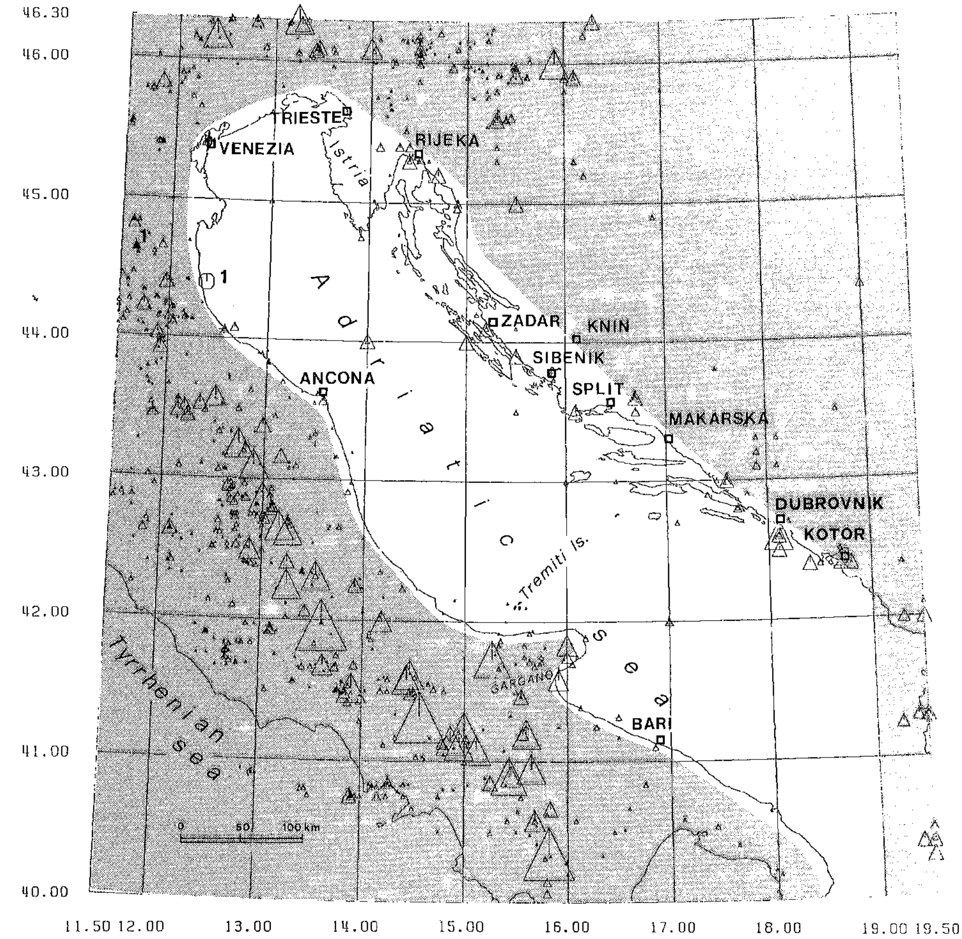

Fig. 2 — Epicentre map of the earthquakes (Ribaric, 1982; GIZ, 1986; GNDT, 1994b) between the years 1000 and 1915 in Adria (non-dotted area) and instrumental location (octagon) of the 1909 event (see Table 3); the size of the events represents their focal volume (Båth and Duda, 1964).

setting. The major events of Fig. 2 (Io ≥IX Mercalli - Cancani - Sieberg, MCS) are reported in Table 1, where the component catalogues of GIZ (1986) are given explicitly. It can be seen that the sources (column marked 'Sources') of the parametric catalogues (column marked 'Cat') from which the epicentral data are taken date back only to the end of the last century. Further compilations analyzed (Milne, 1912; Sieberg, 1932; Morelli, 1942) do not in general refer to more ancient documents either, while Kispatic (1892) and Karnik (1969, 1971) refer only to events which occurred after 1800. An historical investigation is, therefore, required for improving knowledge on the major Balkans earthquakes in previous centuries. Information on the observed intensities during the main earthquakes can be found in Shebalin (1974) and Postpischl (1985a). Table 1 shows that most of the earthquakes seem to have been in Zadar and Dubrovnik, although some of them are considered doubtful by the catalogue compilers (Shebalin et al., 1974) and some have contrasting or poor locations. The only event which has been accurately studied by detailed historical investigation (Guidoboni and Margottini, 1988) is the Dubrovnik earthquake of 1667. This earthquake and the subsequent tsunami destroyed most of the public and private buildings in Dubrovnik, causing 5000 deaths, produced severe damage and deaths in the towns of the Kotor bay, and was felt as far away as Venezia and Istanbul (Guidoboni and Margottini, 1988). Only with the beginning of this century the information

Table 1 - List of the main earthquakes (Io ≥ IX MCS) between the years 1000 and 1915 in Adria with the addition of the 1909 event.
Explanation of symbols
Cat: 1 = Cvijanovic, 1971; 2 = Shebalin et al., 1974; 3 = Postpischl, 1985b; 4 = Cvijanovic, 1981; 5 = GNDT, 1994b.
Sources: a = Kispatic, 1891; b = Baratta, 1901; c = Mihailovic, 1930; d = Staikoff, 1930; e = Mihailovic, 1947; f = Makrovic, 1950; g = Montandon, 1953; h = Trajc, 1961; i = Cvijanovic et al., 1967; j = Cvijanovic and Skoko, 1970; k = Ribaric and Cvjianovic, 1971; l = Cvijanovic, 1972; m = Basovic, 1973; n = GNDT, 1994a.

Cat	Date	Time	Lat N	Lon E	Epic. area	Int.	Sources
3	1223		41.58	15.92	Manfredonia	IX-X	b
2	12800606		44.10	15.20	Zadar	IX	h
2	13000930		44.10	15.20	Zadar	IX	h
1,2	1323		45.20	14.70	Vinodolski	IX	a,c,f,h.j,l
1,2	13430630		44.00	15.00	Zadar	IX	a,c,f,h,l
2	13991106	20	44.10	15.20	Zadar	IX	h
4	14180407		43.90	15.50	Vrana	IX	a,c,f*
2	1451		42.60	18.10	Dubrovnik	IX	h
2	1471		42.60	18.10	Dubrovnik	IX	h
2	14820215		42.60	18.10	Dubrovnik	IX	h
2	144960123	17	43.50	16.10	Trogir	IX	h
1,2	15200517	07	42.60	18.10	Dubrovnik	IX	a,c,e,f,g,h,i,m
2	15300722		42.60	18.10	Dubrovnik	IX	h
1,2	1632		42.40	18.40	Kotor	IX	a,f,k,m
1,2	16390728	18:30	42.50	18.10	Kotor	IX	a,c,f,i,k,m
1,2	16670406	08	42.60	18.10	Dubrovnik	X	a,c,d,f,g,i,k
1,2	17210112		45.30	14.30	Rijeka	IX	g
2	17681128		44.10	15.20	Zadar	IX	h
5	19090113	00:45	44.60	11.67	Po plain	VI-VII	n

(*) sources not cited by Cat 4 but deduced as cited by Cat 1.

is sufficient to locate events in the sea. Considering the years before 1000, only poor information has been found (Kispatic, 1891; Cvijanovic, 1971) and the major event mentioned is dated at 361 A. D., with effects in the Zadar - Pag area: in a recent historical investigation of Mediterranean region seismicity before 1000 A. D. (Guidoboni, 1989), some calamities are reported between 361 and 365 with effects in Greece and Sicily, while the Crete earthquake of July 21, 365 caused a tsunami on the Dalmatian coast also.

Instrumental seismicity

In Fig. 3 the epicentres of the earthquakes between 1916 and 1989 are shown. The data (ISC, 1989) were taken from the earthquake catalogue of the International Seismological Centre (ISC) and consist only of instrumental locations. This figure offers, therefore, a more precise idea of the regional seismicity, although the station distribution around the Adriatic sea was not satisfactory until the Sixties. Only the northern part has been adequately monitored since

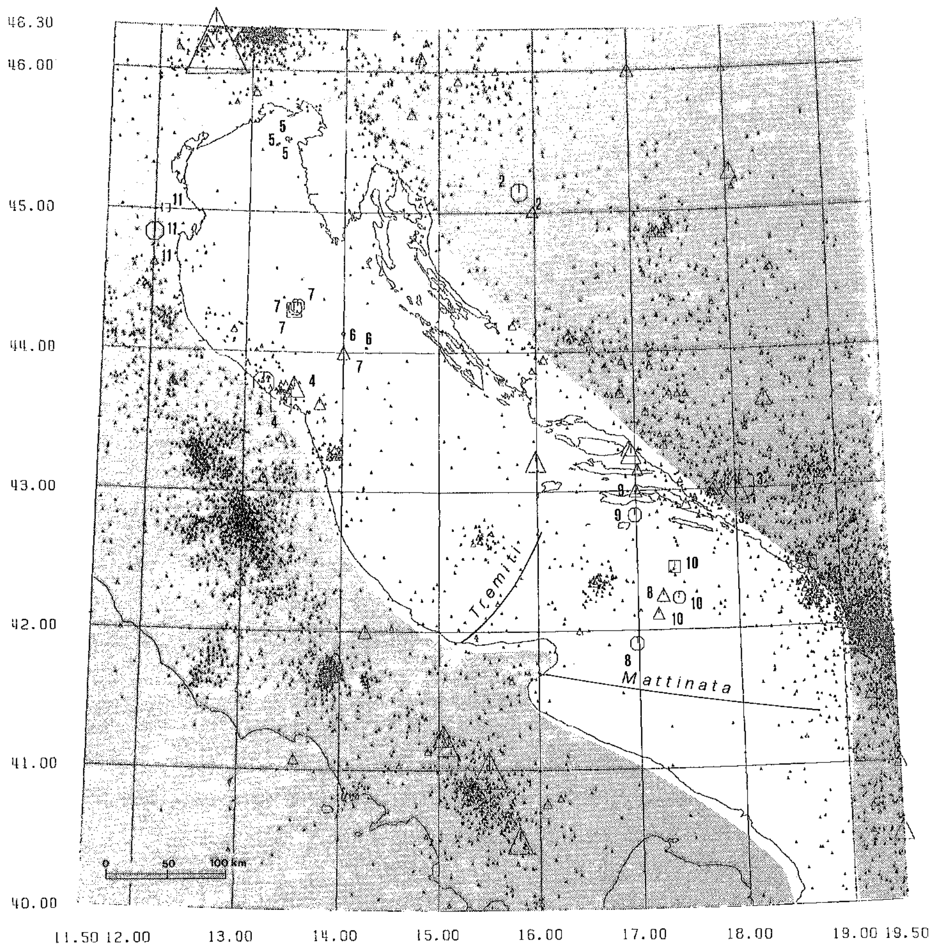

Fig. 3 — Epicentre map of the earthquakes (ISC, 1989) between 1916 and 1989 (triangles) in Adria (non-dotted area) and re-locations of some of the main events (see Table 3); the size of the events represents their focal volume (Båth and Duda, 1964). Symbols for the epicentre locations: triangles = ISC (1989), squares = GIZ (1986) and GNDT (1994b), circles = Caloi (1932, 1937b), octagons = this work. Location of the Mattinata and Tremiti faults from Finetti (1982).

the beginning of the century, with the stations of Trieste, Venezia, Padova, Pula, Rijeka and Ljubljana; but timing problems made it frequently difficult to get good locations. The map in Fig. 3 shows similar features as that in Fig. 2, with the seismicity concentrated around Ancona, offshore Gargano, around Rijeka, on the islands facing the Split - Dubrovnik coast, and around the Kotor bay. The coastal seismicity of the previous map is now mainly shifted offshore and some spots of quakes appear in the central southern Adriatic sea around the Tremiti islands. A few additional quakes, in some cases also of interesting magnitude, can be seen in the northern Adriatic sea.

Events with magnitude larger than, or equal to, 5.5 in the ISC (1989) catalogue are listed in Table 2 (the ISC catalogue quotes Ms, mb, and Ml values as well as magnitudes of undefined type: at the present stage, all have been taken into account in the selection, but with preference for Ms): they are located along the southern Dalmatian coast (Makarska, Kotor bay) with the exception of five located in the middle Adriatic sea. The quake of August 29, 1931 in the northern Adriatic sea was studied using macroseismic data (Agamennone, 1939) and instrumental data (Caloi, 1932) and the location is well constrained at 10 km off the westernmost part of the Istria peninsula; a value of 38 km was proposed for the focal depth. The event was felt on the Istrian coast (Agamennone, 1939) with intensity V MCS at Porec and IV MCS at Koper and Piran. The 1934 quake was interpreted as two events 40 km apart in the middle Adriatic sea north of Ancona (Caloi, 1937b). On the basis of the first polarities recorded, it has been defined as a sinking earthquake caused by inhomogeneity of the crustal structure near the hypocentre (Caloi, 1937b; Ritsema, 1967). Caloi (1937a) interpretes the main seismicity of the northern Adriatic sea as correlatable to a seismic zone off the Rimini - Ancona coast and a secondary small zone in mid-sea north of Ancona. The 1938 quake is located in the mid - southern Adriatic sea north of the Gargano promontory. The 1962 Makarska seismic sequence

Table 2 - List of the main earthquakes ($M \geq 5.5$) which occurred between 1916 and 1989 in Adria.

Date	Time	Lat N	Lon E	Epicentral area	Dep.	Mag.*	Remarks
19160312	03:23	45.00	16.00	Cetin Grad	10	5.8	
19270214	02:14	43.00	18.00	Mostar	50	6.3S	
19301030	07:13	43.75	13.50	Senigallia	22	6.0S	
19330926	03:33	42.00	14.25	Apennines		5.6S	
19340204	09:35	41.50	19.25	Montenegro		5.6S	
19341130	02:58	44.00	14.00	N. Adriatic		5.6S	
19380527	21:23	42.25	17.25	S. Adriatic		5.6S	
19421229	03:42	43.00	17.00	Korcula		5.6S	
19560815	12:02	43.22	15.99	Sibenik		6.0	
19620107	10:03	43.27	16.96	Makarska	41	6.0	
19620111	05:05	43.31	16.94	Makarska	31	5.8	Aftershock
19620121	02:51	43.15	17.02	Makarska	41	5.5	Aftershock
19620417	10:03	42.12	17.20	S. Adriatic		5.5	
19790415	06:19	42.04	19.05	Kotor Bay	4	6.1b	
19790415	14:43	42.28	18.68	Kotor Bay	7	5.6b	Aftershock
19790524	17:23	42.24	18.75	Kotor Bay	5	5.7b	Aftershock
19840513	12:46	43.00	17.77	Makarska	34	5.6S	
19861125	13:59	44.12	16.34	Knin	30	5.5S	

(*) S=Ms, b=mb

caused a few deaths in the epicentral area with heavy damage along the coast. The main shock reached intensity VII MCS and was felt as far away as Trieste. In 1979 a notable seismic sequence occurred off the southernmost sector of the Montenegro coast. It consisted of two aftershocks with magnitude larger than, or equal to, 5.5 which followed the 6.1 magnitude main event. The maximum acceleration of 0.46 g was recorded in Petrovac, about 30 km SE of the Kotor bay (Consiglio Superiore Lavori Pubblici, 1979). The event was associated to interference of the Skadar - Pec fault, an element of contact between the European and the Aegean plates, with the Periadriatic line passing about 30 km offshore and parallel to the coast, and with other active faults of Dinaric orientation, although the character of the Skadar - Pec fault is not clear (dextral strike - slip or reverse). As a clear migration of epicentres from SE to NW (i. e. from offshore Ulcinj, about 70 km SE of the Kotor bay, to the Kotor bay itself, see Console and Favali, 1981) was noted, the main event has been interpreted as being caused by subduction of the Adria microplate under the Dinarides, and most of the following aftershocks to the activation of N - S oriented dextral strike - slip faults (Cvijanovic et al., 1981). The Knin quake of 1986 occurred in a well known seismic area (Herak and Herak, 1990a) which has been studied in the broader context of the Dinara mountains (Herak and Herak, 1990b). It was found that the foci are located in the uppermost sedimentary layer of the crust (20 km) with the strongest events at greater depths. The Dubrovnik offshore seismicity is confirmed also by the well located present - day seismicity (see Markusic et al., 1990).

For events with enough seismographic recordings, an attempt has been made to locate them and to construct their focal mechanisms: a standard location procedure was adopted (Lee and Lahr, 1975) and the mechanisms were constructed using the first polarity motions. Data were taken from the ISC and the other existing bulletins, from special studies (e. g.: Caloi, 1932, 1937b; Agamennone, 1939), and using new seismogram readings for the crucial stations. The location and the mechanism solutions obtained are reported in Table 3. In addition, solutions computed for seven very recent earthquakes of low magnitude (between 3.0 and 3.9) in the northern Dinarides are reported in the same table. The quality of the epicentral locations obtained is very variable depending on the quality and quantity of the data available (and, therefore, according to the period) but a general increase in quality with respect to the data of Table 2 has been obtained. In fact, the standard error in the epicentral solutions is always smaller than 10 km (with the exception of the 1916 earthquake) with gap of station coverage less than 180°, while the depth locations are less well constrained (error less than 30 km). It is worth noting that the error in the origin times remains high until the Sixties in the presence of a notable number of stations: this suggests that the quality of epicentre locations could be improved with methodologies less dependent on timing inaccuracies. Some problems arise in locating the 1909 event, because the poor instrumental data available lead to an epicentre in the sea, while macroseismic information (intensity VI -VII MCS in the Ferrara and Ravenna provinces; Martinelli, 1912; Cavasino, 1935) supports the land epicentre reported in the GNDT (1994b) earthquake file (Table 1, see Fig. 2 for the distance of the locations). In Fig. 3 the new solutions (octagons) have been added to the ISC locations (triangles) and further locations from the literature (circles = Caloi, 1932, 1937b; squares = GNDT, 1994b) for the same eleven large events studied (nos. 1 to 11 in Table 3). It can be seen that the difference between the new locations and those already known is very limited for quakes on land, while it increases for offshore epicentres. Data available for nine of the relocated events have been used for computing their fault plane solution: seven of them are local quakes recorded by a regional network and, therefore, not included in Table 2. The number of first polarities is not always large but the solution seems well enough constrained (see the 'Score' column in Table 3). The new focal mechanisms and further focal mechanisms available in the literature for the study region (Gasparini et al., 1985; Console et al., 1989, 1993; Riguzzi et al., 1989; Favali et al., 1990; Del Ben et al., 1991; Rebez et al., 1992) are reported in Fig. 4. It can be seen that the new solutions confirm the seismotectonic characteristics already pointed out in previous studies. In fact, all the new mechanisms in the northern Dinarides show dextral strike-slip motion or vertical movement and, therefore, are in perfect agreement with the transpressive character of the coastal Croatia tectonic structures (Del Ben et al., 1991). The few new mechanisms for quakes in the Adriatic sea reveal normal dip-slip movement, in agreement with the solutions of Rebez et al. (1992) for quakes in the northern Adriatic and most of those in the central Adriatic from the literature

Table 3 - Location solution and focal mechanism of the earthquakes studied in the present work.

N	Date	Time	rms s	Lat N	Lon E	erh km	Epicentral area	Dep. km	erz km	gap	Num sta	Plane A strike/dip	Plane B strike/dip	P axis strike/dip	T axis strike/dip	B axis strike/dip	Score
1	19090113	00:45:27.9	1.6	44.406	12.372	9.4	Off Ravenna	10.0	7.4	157	14						
2	19160312	03:23:57.6	1.8	45.146	15.841	14.6	Cetin Grad	10.0	25.4	82	8						
3	19270214	03:42:52.6	2.7	43.021	18.039	5.2	Mostar	1.6	7.6	90	28						
4	19301030	07:12:53.9	2.1	43.775	13.186	7.7	Senigallia	22.3	27.6	69	21						
5	19310829	15:56:58.1	0.9	45.481	13.298	4.3	Salvore	14.0	3.1	145	13						
6	19341130	02:58:17.8	1.3	44.034	14.235	3.8	N Adriatic	1.3	6.8	68	23	204/46	32/42	15/76	118/2	209/2	22/23
7	19341130	02:58:19.2	1.1	44.332	13.521	1.9	N Adriatic	15.1	3.6	52	37	122/50	324/38	324/64	226/4	130/10	30/37
8	19380527	21:23:06.1	2.0	41.905	16.980	5.7	S Adriatic	2.9	9.1	91	28						
9	19421229	03:42:01.6	2.0	42.826	16.985	8.0	Korcula	44.5	21.5	162	17						
10	19620417	10:03:03.9	3.0	42.227	17.405	6.7	S. Adriatic	38.3	19.1	67	17						
11	19671230	04:18:20.6	1.7	44.823	11.958	3.9	Po plain	16.0	4.3	87	19						
12	19790505	21:00:00.8	0.7	45.103	14.928	1.7	Senj	3.7	2.3	109	24	308/38	24/80	147/42	258/20	15/37	16/16
13	19830103	05:42:14.9	0.7	45.435	14.535	2.2	Klana	6.2	1.9	148	20	328/70	170/22	230/64	64/24	333/8	13/14
14	19860327	07:25:27.2	0.9	45.252	14.944	1.6	Carevica	8.2	2.3	76	46	288/80	90/10	208/54	18/35	110/4	31/34
15	19860327	07:43:09.8	1.0	45.145	14.904	1.8	Ledenice	8.1	2.3	82	43	287/80	89/10	204/54	14/35	106/4	29/33
16	19920221	20:50:32.2	0.9	45.447	14.372	1.1	Klana	8.3	1.3	61	57	330/84	240/86	205/6	285/6	98/82	41/46
17	19920223	06:15:27.8	0.6	45.456	14.356	1.0	Klana	6.7	1.3	84	24	336/86	246/86	201/4	291/4	118/84	19/20
18	19920311	15:40:32.4	0.6	45.940	14.339	0.9	Borovnica	5.8	1.3	69	32	298/54	57/56	27/9	207/56	85/36	25/25

(Gasperini et al., 1985; Console et al., 1989, 1993). Normal mechanisms are considered characteristic of intra-plate activity in foreland domains (Rebez et al., 1992) which Adria is.

Some recent earthquakes in the central - southern Adriatic sea were investigated in detail using all the available instrumental recordings. A seismic sequence started on July 3, 1987 with a quake of magnitude Md 4.9 offshore Porto S. Giorgio (50 km SE of Ancona) and had two notable late aftershocks on September 4 (Md = 4.0) and September 10 (Md = 3.8). The focal mechanisms of four events from the sequence (see Fig. 4) are in agreement with the NNW - SSE oriented Apenninic thrusts (Riguzzi et al., 1989) and the hypocentre alignment exibits an anti-Apenninic trend with shallow foci (clustered at about 5 km depth) which deepen towards the Apennines (Console et al., 1992). Another active area can be found around the Gargano promontory. A seismic sequence occurred in January 1986 about 50 km north of the Tremiti islands, with a main event of magnitude mb 4.2. In April 1988 another sequence, with an mb 5.3 quake as main event, started ENE of Gargano. In October 1989 an mb 4.7 quake

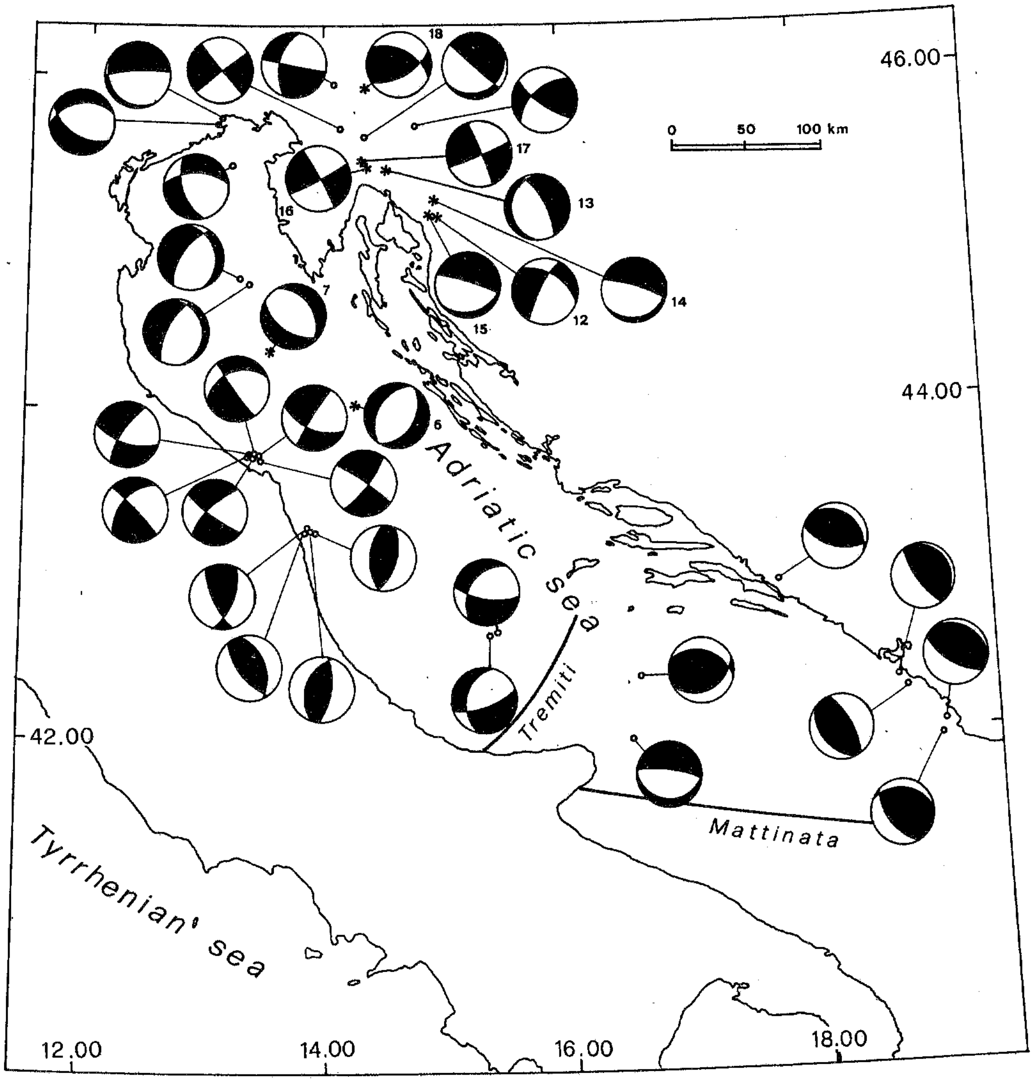

Fig. 4 — Focal mechanisms of the main earthquakes in the Adriatic region. The star indicates the epicentre of the events studied in the present work (see Table 3). Location of the Mattinata and Tremiti faults from Finetti (1982).

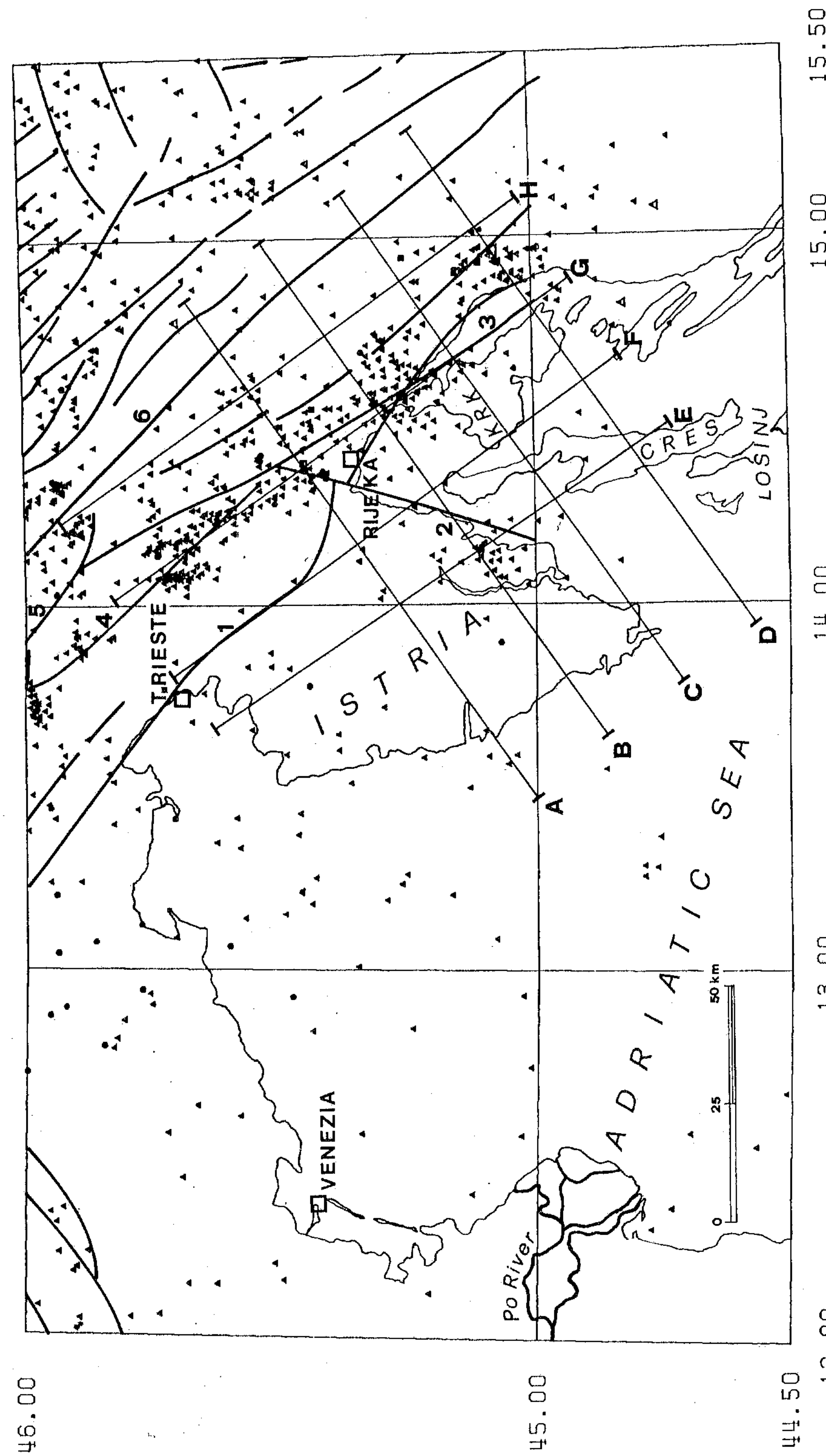

Fig. 5 — Epicentre map of the earthquakes recorded by the OGS seismometric network during the period 1977 - 1992 (triangles) in the northern Adriatic region; additional epicentres of the main local earthquakes in 1975 and 1976 (octagons) are added, and locations of the cross - sections studied are reported. Legenda for the main tectonic structures (from Del Ben et al., 1991): 1 = Trieste line, 2 = Istria line, 3 = Rijeka strike - slip fault, 4 = Rasa line, 5 = Postojna line, 6 = Idrija strike - slip fault.

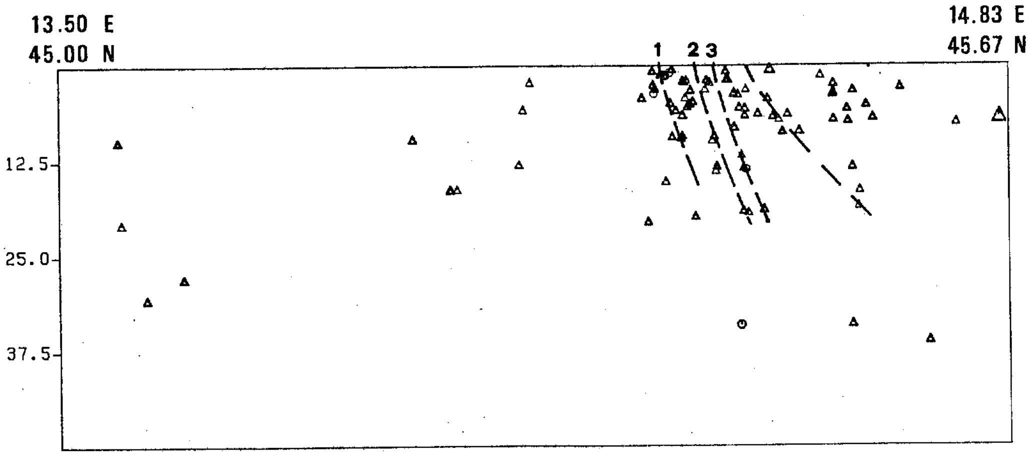

Fig. 6 — 10 - km - wide cross-section A in the northern Adriatic region (see location, symbol, and number explanation in Fig. 5).

was located in the Tremiti islands and aftershocks continued throughout 1990. The focal mechanisms of the two main events of the first sequence (see Fig. 4) show normal motion, with a strike - slip component and NNE - SSW oriented pressure axis (Console et al., 1989). The foci distribution in some vertical cross-sections shows a southward fault dip angle of about 50° (Herak et al., 1988) which is in agreement with the regional fault pattern but not with the focal mechanism of Fig. 4. The main event of the second sequence is located near the NE - SW oriented Tremiti islands fault and its focal mechanism shows reverse faulting with a strike - slip component (Console et al., 1993): the ENE - WSW oriented and SSE dipping plane fits with the geometry of the Tremiti islands fault quite well. The third sequence is located in proximity to the westernmost sector of the Tremiti islands fault. All this evidence was used to answer the question as to whether the activity of this area is either the intra-plate kind, thus preserving the Adriatic block as a whole, or on the contrary, is indicative of active margins; and the existence of a plate boundary between the northern and southern Adriatic microplates has been suggested (Console et al., 1993). This hypothesis is supported by meso-structural data collected from the Gargano promontory and the Tremiti islands (Favali e Mele, 1989; Favali et al., 1993). Different dynamic behaviours with opposite rotations have been proposed for the northern

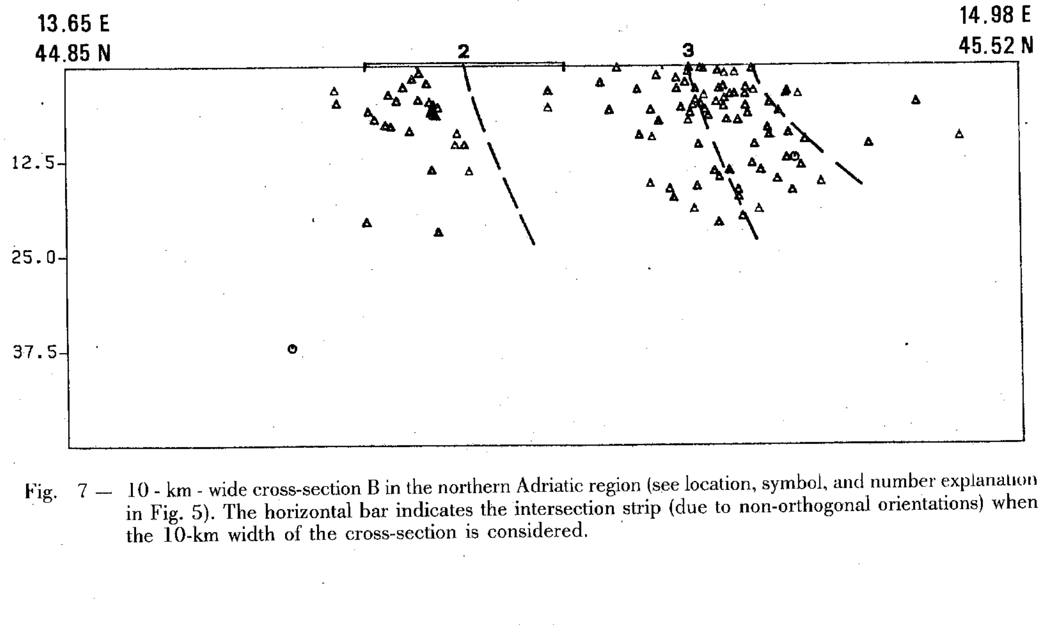

Fig. 7 — 10 - km - wide cross-section B in the northern Adriatic region (see location, symbol, and number explanation in Fig. 5). The horizontal bar indicates the intersection strip (due to non-orthogonal orientations) when the 10-km width of the cross-section is considered.

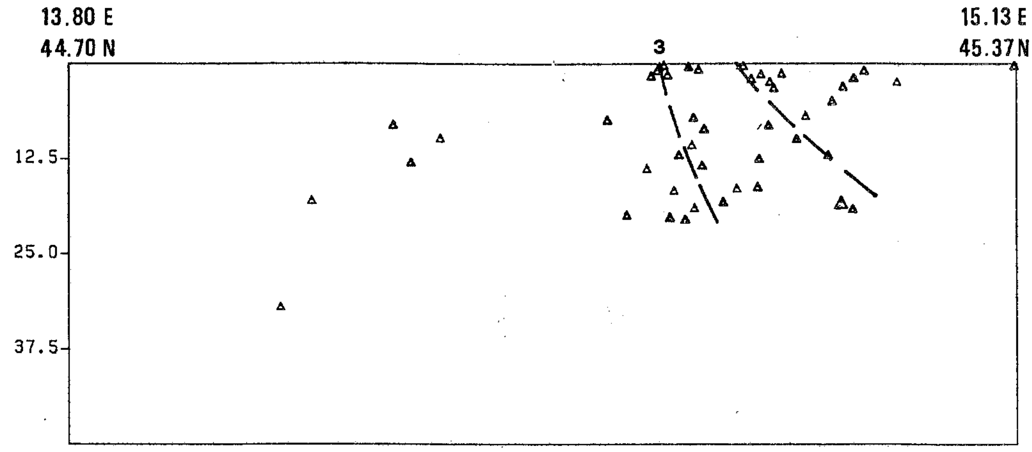

Fig. 8 — 10 - km - wide cross-section C in the northern Adriatic region (see location, symbol, and number explanation in Fig. 5).

(counter-clockwise) and southern (clockwise) blocks (Favali et al., 1990). This derives from different interpretations of the two major tectonic elements of the area: the Mattinata and Tremiti islands fault systems (see also Scandone et al., 1991). They are both considered dextral strike - slip faults from offshore Gargano seismic profile interpretation (Finetti, 1984) and sinistral strike - slip and dextral strike - slip, respectively, from land geology (Funiciello et al., 1988; Montone e Funiciello, 1989). Further seismic profile data confirm the transcurrent activity of the Mattinata fault as well as the evidence that it is no longer active (Brancolini, 1994, personal communication). Argnani et al. (1993) propose a tectonic inversion of Mesozoic extensional faults for explaining the observed geologic features and the regional geologic setting.

RECENT SEISMICITY OF NORTHERN ADRIA

A further analysis was undertaken using the data collected by the seismometric network of northeastern Italy, managed by the Osservatorio Geofisico Sperimentale of Trieste (OGS), during the period 1977 - 1992 (OGS, 1977 - 1982, 1983 - 1992). The information reported in the seismological bulletins of Italian and neibouring country stations was also considered

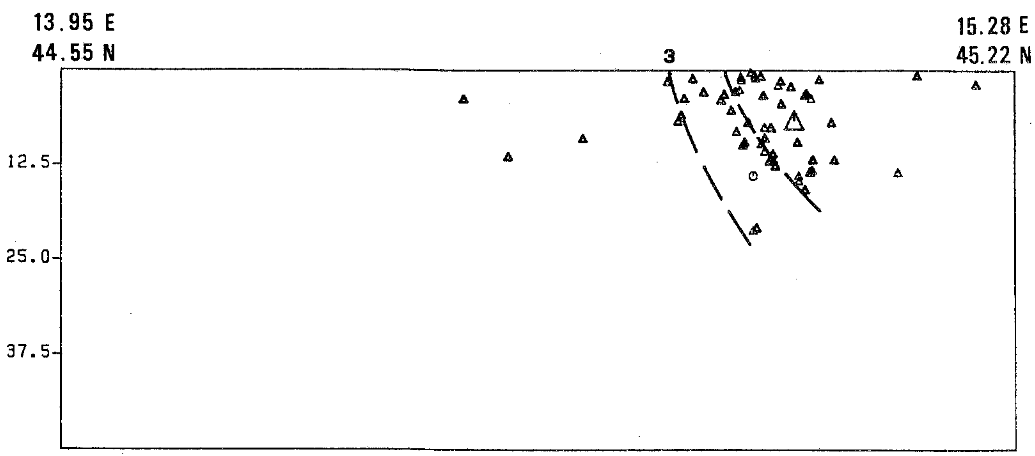

Fig. 9 — 10 - km - wide cross-section D in the northern Adriatic region (see location, symbol, and number explanation in Fig. 5).

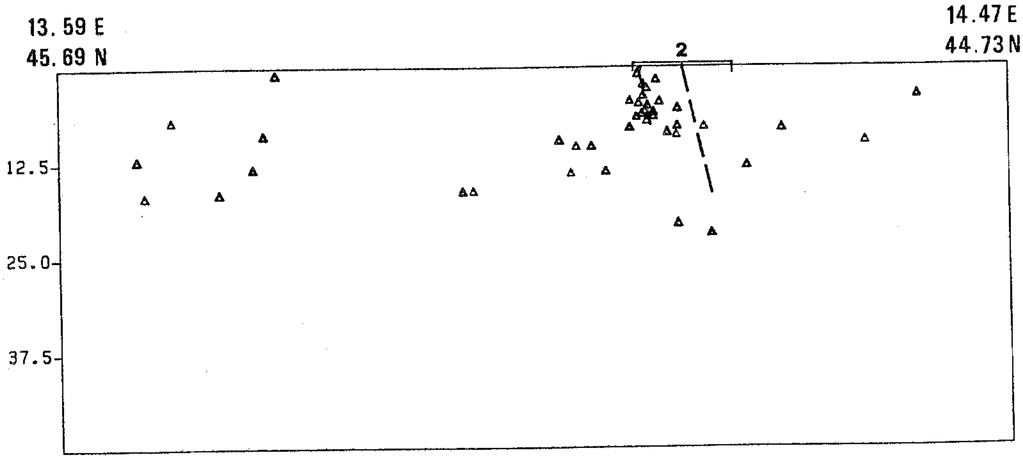

Fig. 10 — 10 - km - wide cross-section E in the northern Adriatic region (see location, symbol, and number explanation in Fig. 5). The horizontal bar indicates the intersection strip (due to non-orthogonal orientations) when the 10-km width of the cross-section is considered.

(see also Renner, 1994). The locations obtained (Lee and Lahr, 1975) refer to quakes in the local magnitude (MAW) range 1.1 - 4.3, with 11 events exceeding magnitude 3.5, and are rather good because of the reasonable station azimuthal coverage. This data set offers, therefore, a complete view of the seismicity, even at low level, in northern Adria, between the Po river mouth and the Dinarides. The located events are reported in Fig. 5 together with the principal tectonic structures deduced from the scheme of Del Ben et al. (1991); the geodynamic activity of the principal tectonic elements is indicated and shows the importance of the Rijeka and Idrija transpressive strike - slip faults (nos. 3 and 6 in Figs. 5 and following) which disconnect the Adria microplate allowing its relative northward motion. Other active transpressive thrust faults with transcurrent component are those of Rasa and Postojna (nos. 4 and 5 in Fig. 5 see also Del Ben et al., 1991). The earthquakes in the sea are low magnitude events which do not show any clear alignment and represent foreland intra-plate activity (Rebez et al., 1992): the most active area is the Trieste gulf, where the 1931 quake (no. 5 in Table 3 and Fig. 3) occurred. The seismicity in Slovenia and on the Croatian coast is concentrated fairly well along the northern Dinaric faults which pass north of the Istria peninsula to the Rijeka area and continue onto Krk island: they represent the present active front (Del Ben et al., 1991). The outer front (Istria,

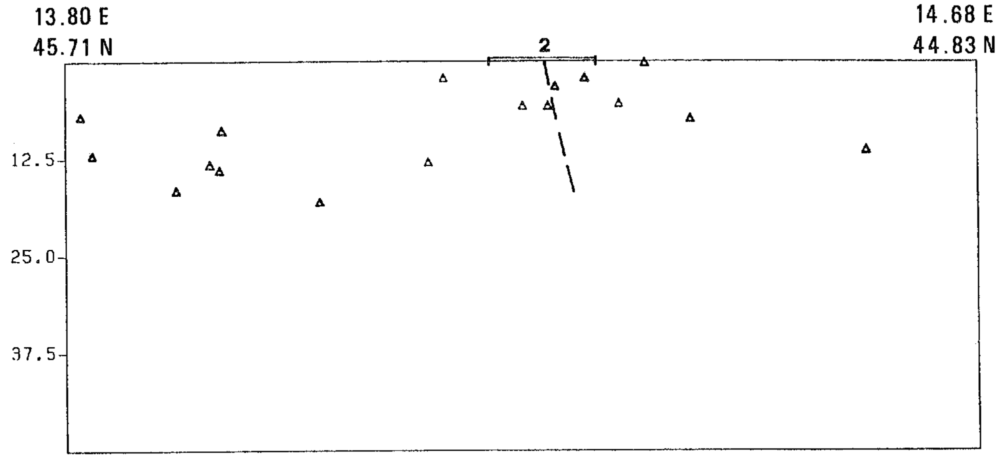

Fig. 11 — 10 - km - wide cross-section F in the northern Adriatic region (see location, symbol, and number explanation in Fig. 5). The horizontal bar indicates the intersection strip (due to non-orthogonal orientations) when the 10-km width of the cross-section is considered.

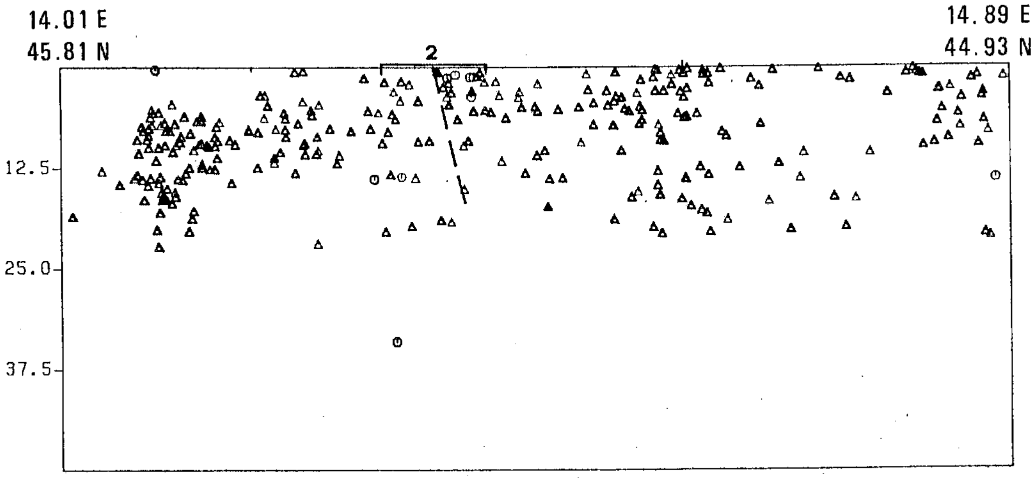

Fig. 12 — 10 - km - wide cross-section G in the northern Adriatic region (see location, symbol, and number explanation in Fig. 5). The horizontal bar indicates the intersection strip (due to non-orthogonal orientations) when the 10-km width of the cross-section is considered.

Cres, and Losinj islands) shows no seismic activity. A spot of epicentres appears on the eastern coast of the Istria peninsula in proximity to the Istria fault (no. 2 in Fig. 5): it may be due to mining activity (Herak, 1994, personal communication). It is interesting to note that no further activity has been detected on the prolongation of this line into the sea.

To indicate better the characteristics of this seismicity, some vertical cross-sections have been constructed (see locations in Fig. 5). Four of them are normal to the Dinaric front (sections A, B, C, and D from NW to SE) and four are parallel (sections E, F, G, and H from SW to NE); a width of 10 km centred on the section track was considered adequate for investigating the section's activity in detail. Section A (Fig. 6) shows a few events on the western coast of the Istria peninsula (SW edge of the section) and the major concentration in correspondence to the Rijeka fault (no. 3). For this latter structure a northeastward steep dip is suggested. Section B (Fig. 7) reveals the seismicity (artificial?) in proximity to the Istria fault (no. 2) on the eastern

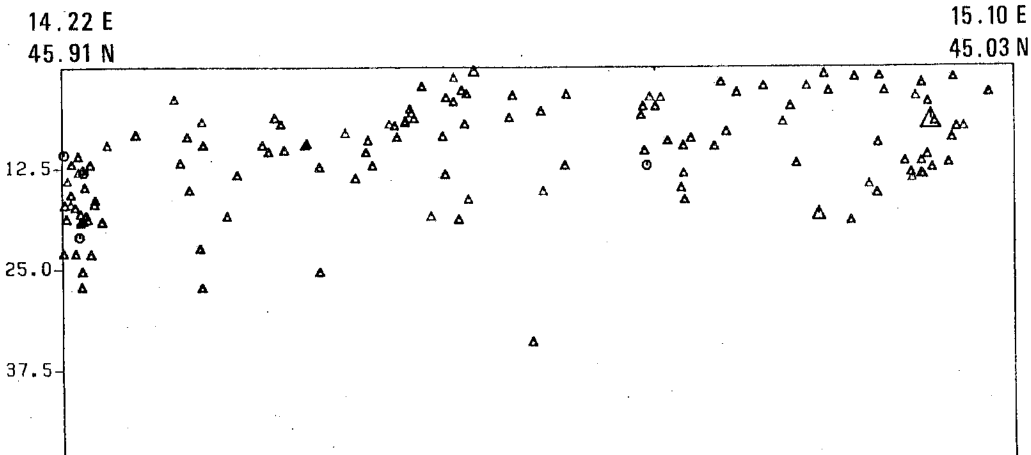

Fig. 13 — 10 - km - wide cross-section H in the northern Adriatic region (see location, symbol, and number explanation in Fig. 5).

coast of the Istria peninsula and that of the Rijeka fault (no. 3). The second is not well concentrated, perhaps because of the presence of other secondary faults. It is worth noting that the major seismicity occurs at the intersection of the Rijeka fault with a secondary fault located along the coast (see Fig. 5). Section C (Fig. 8) shows some foci with a subvertical alignment correlatable to the Rijeka fault (no. 3) near Krk island and further events northeastwards where faults are reported to be parallel to the coast - line. Section D (Fig. 9) shows a clear alignment of foci plunging northeastward (about 60° dip) correlatable with the fault along the coast - line in the Rijeka area. Section E (Fig. 10) is NW - SE oriented and intersects the seismicity (artificial?) near the Istria line: the foci appear well concentrated within the surficial 5 km. Section F (Fig. 11) shows only a few hypocentres near the Istria fault. Section G (Fig. 12) follows the track of the Rijeka fault and shows a uniform presence of foci between the surface and 20 km depth along almost all its length. No concentration in a particular alignment can be seen at the intersection with the Istria line. Section H (Fig. 13) is more internal and reveals a uniform but not very high seismicity correlatable to minor NW - SE oriented faults located here.

DISCUSSION

Much of the current information is well illustrated in the presented general scheme for the Adria seismicity but some notable problems need further investigation.

The main evidence is that the Adria microplate is almost aseismic with the exception of its central sector (area around the Tremiti islands, see Fig. 3), where in 1938, 1962, and 1988 magnitude 5 was exceeded. The meaning of this seismicity can be variously explained: intraplate activity of NW - SE and NE - SW oriented local faults in a rigid block, or connected to an E - W oriented regional transcurrent structure which may even reach the Dalmatian coast. The first interpretation is supported by the reconstructed direction of the slip vector from all the available stress indicators (Meletti and Scandone, 1994, personal communication) and by evidence from seismic profiles (Scandone, 1994, personal communication), the second by seismicity and meso-structural data (Favali et al., 1993). In both interpretations the Mattinata fault plays no or only a small role and can be considered aseismic.

Other evidence is that the seismicity along the Apenninic, South-Alpine, and Dinaric chains defines well the western, northern, and eastern margins of the Adria microplate, but the southern is not clear because of the diffuse seismicity in the Ionian sea (see Fig. 3). The Split - Dubrovnik segment is the most seismic area of the coastal Dinarides and this could be explained by the complex transpressive behaviour of the structures constituting the Dinaric front in the presence of transcurrent faults which cut the front itself normally. The offshore Ancona seismicity is characterized only by the 1972 sequence, with mainly transcurrent mechanisms. The quakes southeastwards on the coast show, on the contrary, reverse dip - slip mechanisms. Both episodes may not be representative of the main geodynamic movements which occur along the Apenninic chain, but could be connected to local tectonic situations.

The recent seismicity of the northern Adriatic region identifies the active front near the Rijeka fault (see Fig. 5); this front consists mainly of subvertical structures with convincing transpressive (and dominant transcurrent) activity, as already pointed out by Cagnetti et al. (1976, 1978), and Del Ben et al. (1991). The Istria fault does not seem to be active, as the located quakes near by could be artificial, and no evidence of dislocation of the active front is shown by the seismicity distribution (see Figs. 5 and 13).

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