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Normal focal mechanisms in the Julian Alps and Prealps: seismotectonic implications for the Italian-Slovenian border region

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Abstract - The instrumental seismicity (earthquakes with 2.4 ≤ MD ≤ 5.6, collected by the Seismometric Network of the Friuli-Venezia Giulia Region) that hit the Italian-Slovenian border region in the period 1974-2000 was analysed and discussed. The study area, which is characterised by medium-high seismicity, is located in the north-eastern portion of the deformed margin of the Adria microplate. Here the SSE-verging Neogene to Quaternary thrust-belt of the Southalpine chain joins with the Paleogene SW-verging thrust-belt of the External Dinarides. In the western Slovenian region, a set of dextral NW-SE strike-slip faults, Neogene to Quaternary in age, seems to act as the easternmost tectonic release for the Southalpine chain. The focal mechanism of 48 events was constructed: their distribution confirms that two distinct seismotectonic zones coexist above the same maximum stress tensor (σ_1 horizontal and about N-S striking). 1) The Gemona area, that shows fault-plane solutions typical of low-angle WNW-ESE trending reverse faults, confirming that it pertains completely to the eastern Southalpine thrust-belt which is propagating southwards deforming the Quaternary deposits of the Friuli plain. 2) The Cividale - NW Slovenia area, that shows two different sets of fault plane solutions. The first indicates NW-SE trending dextral strike-slip faults. This system is connected to the main seismicity of the External Dinarides as testified by the Bovec earthquake of April 1998 (M_D = 5.6) and the Snežnik - Klana events of May 1995 (M_L = 4.7) and February 1992 (M_L = 4.1). The second set presents normal or transtensional fault plane solutions with high angle NNW-SSE trending planes. The inversion technique of Gephart and Forsyth confirms a heterogeneous stress field for the Cividale - NW Slovenia area. The structural model proposed shows that extensional strike-slip duplexes develop together with the main strike-

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slip fault-system of Cividale - NW Slovenia area. Moreover, it is hypothesised that the seismogenic activity of this region is linked to the reactivation of deep inherited structures probably Early Neogene in time.

1. Introduction

The Italian-Slovenian border region is one of the most seismogenic areas inside the Southalpine realm, as the recent destructive earthquakes of Friuli (in May 1976, M_L = 6.4 and September 1976, M_L = 6.1) and Bovec (in April 1998, M_D = 5.6) confirm. This area belongs to the easternmost part of the Neogene to Quaternary Southalpine chain where the present tectonic arrangement is strongly influenced by the Mesozoic and Paleogenic inherited structures. Many Authors (Gutdeutsch and Aric, 1987; Slejko et al., 1989; Carulli et al., 1990; Del Ben et al., 1991; Renner and Slejko, 1994; Bressan et al., 1998; Aoudia et al., 2000; Bernardis et al., 2000; Bajc et al., 2001; Peruzza et al., 2002a, 2002b) studied the region of tectonic contact between the Southern Alps and the External Dinarides and dealt with its local and regional seismotectonic characteristics. According to the National Group for Defense against Earthquakes (GNDT) seismogenic zonation of Italy and neighbouring regions (Meletti et al., 2000), two different seismogenic zones can be distinguished in this area. The first, including the central Friuli region, is characterised by prevailing mechanisms of thrust with P-axis parallel to the slip-vector of Adria Plate, the second, corresponding to western Slovenia presents dextral transpression along NW-SE faults.

In this paper, the seismicity recorded from 1974 to 2000 in the Italian-Slovenian border region is presented and discussed in order to define the seismotectonic characteristics of this area and to contribute to a finer definition of the present crustal deformation.

2. Geological setting and structural evolution

The study area belongs to the easternmost portion of the Southern Alps, south of the Periadriatic lineament (Fig. 1). During the Mesozoic, the region was part of the passive margin of the Adria plate: in the Southern Alps normal faults related to the Mesozoic extensional tectonics were frequently reactivated and inverted during the Cenozoic contraction. In particular, the study region was part of the transition area between the Friuli Carbonate Platform (FCP), located S-SW, and the Slovenian Basin to the east (Buser, 1987). The Late Cretaceous collapse of the FCP (Tunis and Venturini, 1992), and simultaneous filling of the Julian basin by the Upper Cretaceous - Lower Eocene turbiditic sequences, were a consequence of the growth and the westward propagation of the External Dinarides thrust-belt (Mlakar, 1969; Cousin, 1981; Doglioni and Bosellini, 1987). Buried Dinaric compressional structures are still well recognisable in the subsurface of the Friulian Plain (Amato et al., 1976; Venturini, 2002) where low-angle Paleogene lateral ramps are often reutilized as frontal ramps by the Quaternary S-SE verging front of the Eastern Southern Alps (Poli et al., 2002; Zanferrari et al., 2002).

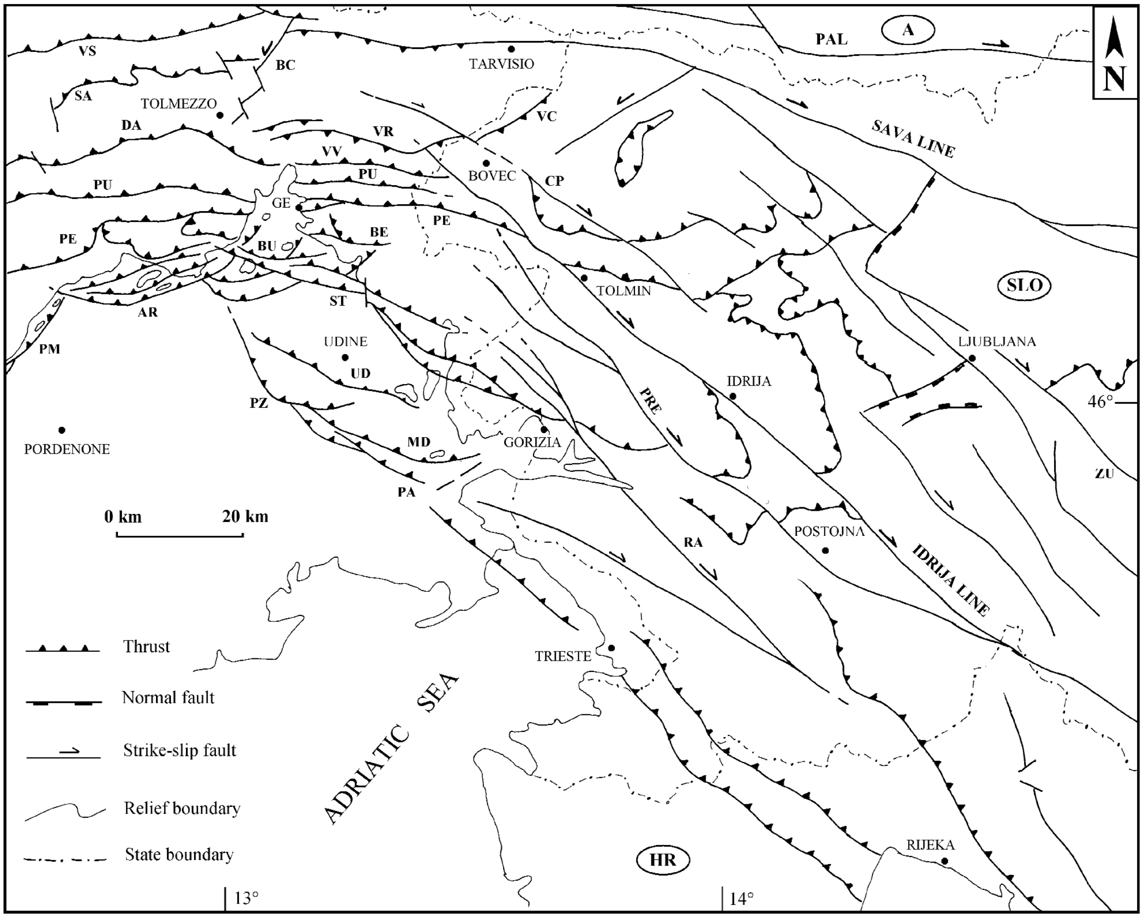

Fig. 1 - Tectonic sketch map of the Italian-Slovenian border region [from: Bigi et al. (1990); Geodetski Zavod Slovenije (1993); Vrabec (2001); sheets 065-Maniago and 066-Udine of Carta Geologica d'Italia (2004a, 2004b)]. Legend: AR: Arba-Ragogna thrust (th.); BC: But-Chiarsò fault (f.); BE: Bernadia th.; BU: Buia th.; CP: Čez-Potoče f.; DA: Dof-Auda th.; MD: Medea th.; PA: Palmanova th.; PAL: Periadriatic lineament; PE: Periadriatic th. (Barcis-Staro Selo line Auct.); PM: Polcenigo-Maniago th.; PU: Pinedo-Uccea th.; PRE: Predjama f.; PZ: Pozzuolo th.; RA: Rasa f.; ST: Susans-Tricesimo th.; SA: Sauris th.; UD: Udine th.; VR-VC: Val Resia-Val Coritenza back-thrust; VS: Valsugana th. VV: Val Venzonassa th.; ZU: Žužemberk f. Towns: GE: Gemona.

During the Late Oligocene - Early Miocene, the eastward escape and extension of the Eastern Alps (Ratschbacher et al., 1991) and the extensional collapse in the Pannonian basin area (Royden, 1988; Doglioni et al., 1999) joined with a broad, mostly dextral wrench fault-system in the Dinarides and Carpathian areas (Horvat, 1993).

Therefore the contemporary Adria northward indentation (Ratschbacher et al., 1991) and the dextral transpressional activity along the Periadriatic lineament (Massari, 1990; Fodor et al., 1998), led to the activation of the S-SE-verging back-thrust chain of the Southern Alps. At present the Eastern Southern Alps are characterised by a set of WSW-ENE to WNW-ESE approximately trending overthrusts extending from the Lessini Mountains to the Italian-Slovenian border area (Doglioni and Bosellini, 1987; Massari, 1990; Venturini, 1990; Castellarin et al., 1992). The southward propagation of the thrust-belt of the Eastern Southern Alps is still active as the high seismicity of the central Friuli and the deformation of the Quaternary deposits confirm (Avigliano et al., 2000; Galadini et al., 2004; Zanferrari et al., 2004a, 2004b). According to Caputo et al. (2002) a NW-SE to NNW-SSE "twist tectonic" characterises the Late Neogene to Quaternary compressive evolution of the Eastern Southern Alps.

The Neogene to Quaternary tectonic evolution of NW-Slovenia is, on the contrary, characterised by the strike-slip activity of WNW-ESE striking faults such as the Periadriatic, Sostanji and Sava ones in the northern sector and, NW-SE dextral striking faults such as Divača, Rasa, Predjama, Idrija, Čez Potoče, Žužemberk (Bled-Mojstrana) in the central-western sector (Mlakar, 1969; Placer, 1981, 1982, 1998; Doglioni and Bosellini, 1987; Geodetski Zavod Slovenije, 1993; Fodor et al., 1998; Bernardis et al., 2000; Poljac et al., 2000; Bajc et al., 2001; Vrabec, 2001).

Concerning the age of activation of these faults, Ratschbacher et al. (1991), Massari (1990), Fodor et al. (1998) and Vrabec (2001) point out that strike-slip tectonics probably associated with normal structures were present in Slovenia starting from early Miocene because it was involved in the Pannonian basin extension and in the lateral extrusion of the Eastern Alps. According to Vrabec (2001) the Quaternary Barje and Gorenjski basins formed at the releasing step between the Sava and the Žužemberk faults. Also Roeder and Lindsey (1992) relate the Neogene extension which characterises the External Dinarides to the orogenic collapse or backarc spreading linked to the formation of the Pannonian basin.

According to Venturini (1990) and Bressan et al. (1998) the NW-SE strike-slip faults of western Slovenia (in particular Idrjia fault) may represent the easternmost tectonic releasing for the Southalpine thrust-belt versus the Pannonian Basin.

3. Seismicity and regional seismotectonics

The Friuli-western Slovenia region is characterised by medium-high seismicity. The historical seismicity of the region is based on the NT4.1 Catalogue (Camassi and Stucchi, 1996) and on the Strong Earthquakes Catalogue by Boschi et al. (1997). Two events with macroseismic intensity higher than grade IX of the Mercalli-Cancani-Sieberg (MCS) scale are recorded in the study area: the so-called Villach earthquake of 1348 and the Cividale-Idrija one of 1511. Both events show an ambiguous epicentre localisation. For the first one, that produced widespread damage in eastern Carinthia and particularly near Villach, but also in the Carnian and Friulian regions, Hammerl (1994) proposed a relocalization in the Italian territory, near Tarvisio. Recently, Galadini et al. (2004), proposed the easternmost segment of the Periadriatic thrust (Gemona- Kobarid segment) as the sismogenic source for the 1348 quake, on the basis of new structural and geological mappings and macroseismic observations by Monachesi and Stucchi (2000).

There is still not any accurate epicentre localisation for the 1511 earthquake, that strongly hit Idrja and Cividale but also Gemona. For example the NT4.1 Catalogue localises the epicentre near Gemona but recently Fizko et al. (2002), on the basis of new structural and geological mappings, on the macroseismic observations by Monachesi and Stucchi (2000) and on the strong motion inversion, proposed a seismogenic source linked to the Idrija fault-system for this quake. Such a solution is also supported by Galadini et al. (2004).

In any case, the failure to accuratly locate the strongest historical quakes of the area, strongly qualifies the reliability of all seismotectonic models still proposed.

Concerning the instrumental seismicity (according to the NT4.1 Catalogue), from 1900 to May 1977 about twenty earthquakes with a magnitude higher than 4.0 have been localised in the area (for example Tarcento, 1931: M = 5.2 and the disastrous earthquakes of Friuli in May 1976 with M_L = 6.4, and September 1976 with M_L 6.1).

From May 1977, with the installation of the Seismometric Network of Friuli-Venezia Giulia (SNFVG), a better monitoring for very low magnitude earthquakes (Fig. 2) was also made possible.

Following the seismotectonic models by Meletti et al. (2000), the study area covers two seismotectonic zones: the Carnian - Friulian area and the External Dinarides. The first zone includes the epicentres of the destructive 1976 Friuli sequence: the major shocks show a compressive stress regime (σ_1 is sub-horizontal and NNW to NNE striking, σ_3 is subvertical) and the fault-plane solutions (FPSs) indicate low-angle WNW-ESE to ENE-WSW trending reverse faults (Slejko et al., 1999; Peruzza et al., 2002a). This framework documents that the deformational activity of this region is linked to the southward migration of the eastern Southalpine front. Seismic activity seems to be concentrated at a depth between 6 and 10 km approximately.

On the contrary, the area of the External Dinarides is characterised by major quakes with transcurrent FPSs (Herak et al., 1995; Polijak et al., 2000). According to Del Ben et al. (1991), Renner and Slejko (1994) and Michelini et al. (1998), these quakes could be linked to ancient Dinaric high-angle thrust-faults, now reactivated as transpressive ones. By contrast, Mlakar (1969), Placer (1981, 1982), Cousin (1981), Roeder and Linsdey (1992) and Jurkovšek et al. (1996), show that the Dinaric low-angle-thrusts are sharply cut by sub-vertical Neogene NW-SE strike-slip faults.

4. Seismological data

The hypocentre localisation (Lee and Lahr, 1975) of the earthquakes (OGS, 1977-2000; Renner, 1995) recorded by the SNFVG managed by the “Istituto Nazionale di Oceanografia e Geofisica Sperimentale” (OGS), were used as a basis for the seismological data. The construction of the FPSs for smaller magnitude events was possible thanks to the data recorded by the SNFVG after 6 May 1977 and obtained from a revision of the seismograms of the ENEL stations for 1974 and 1975. The installation of the SNFVG enabled a better and better monitoring of the region giving also, for medium and low magnitude events, good FPSs.

For this study the focal mechanism of 48 events was constructed (Table 1 and Fig. 3): the considered events do not belong to the 1976 Friuli sequence (Slejko et al., 1999). The magnitude (M_D for the events from n. 3 to n. 48, M_S for n. 1 and n. 2) ranges from 2.4 to 5.6. In Fig. 4 the events with $M_D \geq 3$ have been represented, whereas in Fig. 5 the events with $M_D < 3$: note that

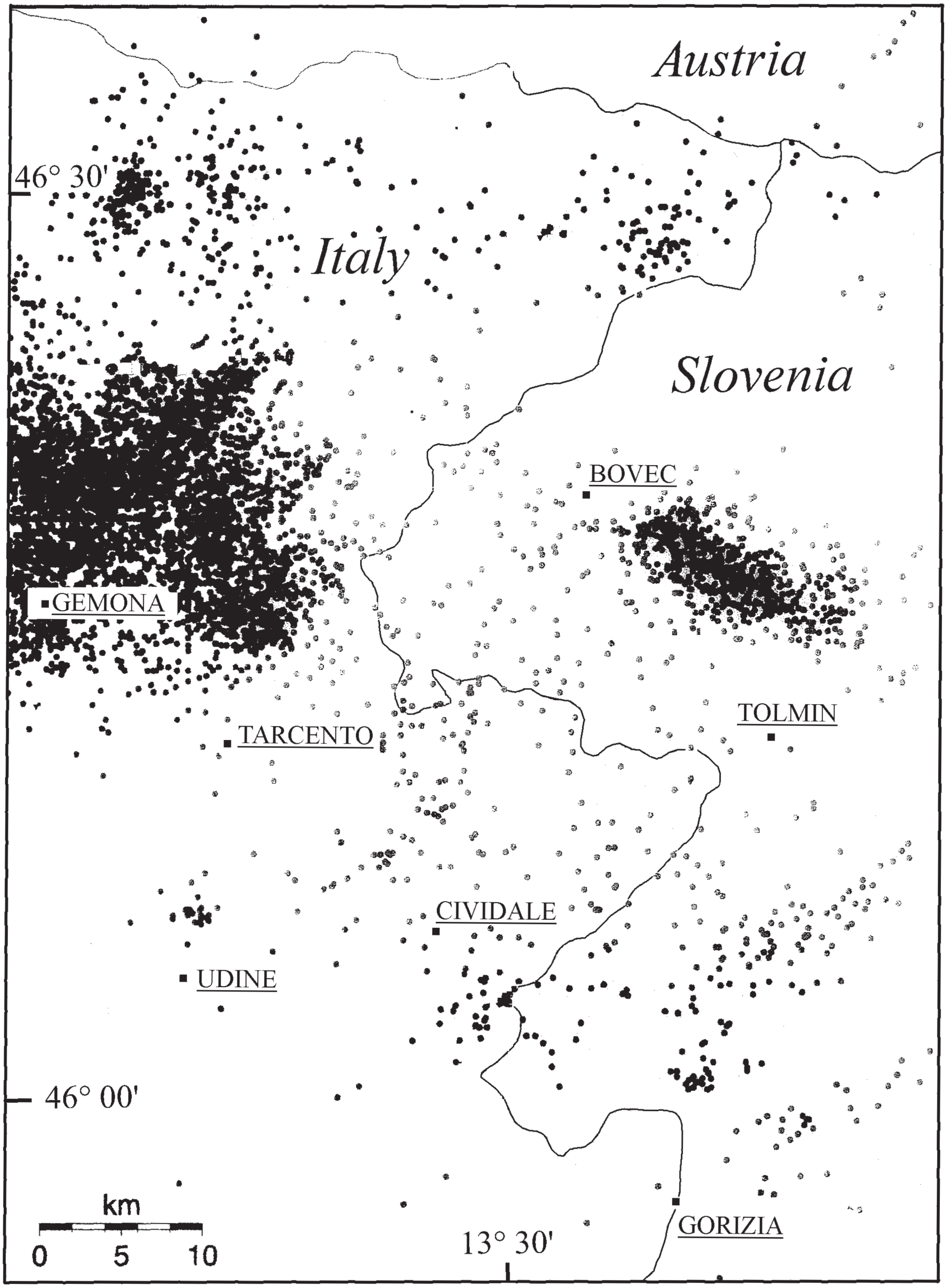

Fig. 2 - Map of epicentres in the study area collected by the OGS Seismometric Network of Friuli-Venezia Giulia from 1977 to 2000.

Table 1 - Focal parameters of analysed earthquakes.

N	Date	Time	rms s	Lat	Long	erh km	Epicentral area	Depth km	erz km	Gap	Num staz.	Mag	Plane A str./dip	Plane B str./dip	P axis str./dip	T axis str./dip	Score good/all
1	19740506	07:50:19,9	0,8	46.341	13.472	1,9	Sella Nevea	10,5	2,2	95	40	4,8	270/40	120/54	082/73	197/07	017/018
2	19750324	02:33:18,4	0,7	46.327	13.148	1,1	Gemona	12,1	1,1	39	61	3,9	290/40	130/52	211/06	091/78	026/028
3	19780423	11:23:03,5	0,8	46.082	13.560	1,3	Prepotto	12,7	1,3	41	35	3,3	110/70	278/20	197/25	026/65	021/032
4	19790418	15:19:19,3	0,7	46.343	13.290	0,9	Chiusaforte	9,3	0,9	30	71	4,8	056/50	296/59	358/05	260/55	059/080
5	19810830	23:30:28,7	0,6	46.321	13.275	1,6	Lusevera	10,7	1,6	48	23	4,0	156/46	290/54	042/04	141/65	020/021
6	19830210	22:30:34,3	0,9	46.251	13.388	1,2	Taipana	10,6	1,2	60	53	4,4	132/50	284/44	209/03	106/75	033/042
7	19850609	23:01:33,3	0,5	46.126	13.554	0,8	S.Pietro al Nat.	15,4	0,7	62	34	3,1	018/70	288/80	335/14	241/14	019/022
8	19870916	13:07:53,9	0,5	45.930	13.876	0,7	Goliaki	13,9	0,6	80	30	3,0	136/80	232/59	187/14	090/29	020/021
9	19880814	02:56:16,4	0,7	46.156	13.416	1,0	Cividale	11,5	1,3	64	34	2,6	134/36	340/57	059/11	290/73	018/023
10	19890814	04:05:58,1	0,4	46.025	13.652	0,5	Plave	11,7	0,7	90	30	2,8	182/74	333/18	104/60	265/28	020/022
11	19890814	04:16:23,9	0,4	46.025	13.658	0,6	Plave	13,2	0,7	91	35	2,7	182/74	348/16	098/61	269/29	022/023
12	19890814	06:34:05,4	0,4	46.023	13.652	0,6	Plave	11,4	0,8	89	32	2,8	182/64	314/36	133/62	253/15	022/025
13	19890814	06:47:40,1	0,5	46.042	13.665	0,7	Plave	12,1	0,8	96	37	2,7	190/70	320/30	131/59	263/22	021/024
14	19890815	00:02:24,8	0,6	46.031	13.667	1,1	Plave	12,6	1,1	150	28	2,7	184/76	308/24	118/55	258/28	016/020
15	19891008	19:34:23,4	0,6	46.168	13.399	1,1	Taipana	9,1	1,1	72	25	2,6	140/60	340/32	024/73	238/14	015/020
16	19900208	11:23:44,6	0,4	46.202	13.664	0,7	Drenchia	12,5	0,7	119	32	2,4	158/40	302/56	161/70	048/08	018/023
17	19911005	05:14:58,5	0,7	46.254	13.350	0,9	Uccea	10,8	0,8	29	51	4,0	066/56	296/46	179/05	279/62	030/035
18	19911005	14:56:29,2	0,6	46.262	13.314	0,9	Lusevera	6,0	1,1	66	43	3,1	118/50	250/51	004/01	095/64	018/023
19	19911102	20:45:30,1	0,6	46.343	13.579	0,7	Sella Nevea	1,1	1,3	74	41	2,8	132/60	242/59	097/46	187/00	018/022
20	19911108	21:50:32,2	0,4	46.309	13.268	0,8	Lusevera	8,0	1,3	43	24	2,8	178/80	276/52	233/18	130/34	013/016
21	19920713	09:34:40,2	0,8	46.019	13.636	1,2	Plave	9,2	1,1	57	42	2,9	178/74	292/35	124/51	244/23	022/030
22	19921225	05:46:02,4	0,3	46.333	13.266	0,7	Lusevera	12,9	1,5	73	15	2,6	063/54	274/40	167/07	280/73	013/013
23	19930722	10:32:42,4	0,4	46.107	13.254	0,6	Tricesimo	11,6	0,7	51	30	3,3	078/02	258/88	168/47	348/43	018/018
24	19930723	19:34:08,6	0,8	46.099	13.244	1,0	Tricesimo	10,0	1,0	32	44	3,6	258/89	350/27	193/41	324/38	018/021
25	19940521	01:25:59,5	0,5	46.027	13.527	0,9	Prepotto	9,3	1,6	98	16	2,7	140/20	328/70	243/65	056/25	011/011
26	19950629	04:02:40,7	0,7	46.140	13.476	1,1	S.Pietro al Nat.	10,9	1,2	68	30	3,0	190/58	322/43	152/63	259/08	017/019
27	19950810	20:44:51,7	0,4	46.128	13.581	1,2	Stregna	15,0	1,1	216	12	3,0	213/80	306/73	169/19	260/04	010/011
28	19960619	07:49:53,0	0,5	46.117	13.580	0,9	Stregna	12,5	0,7	88	30	3,2	196/80	292/59	150/29	247/14	013/016
29	19960725	21:25:56,9	0,5	46.048	13.520	0,7	Prepotto	12,3	0,7	47	40	3,3	312/56	172/41	169/68	060/08	020/025
30	19970215	13:20:22,9	0,5	46.265	13.661	0,7	Kobarid	4,8	1,2	93	30	3,0	290/80	196/68	155/23	061/08	019/023
31	19970401	05:35:43,5	0,6	46.053	13.474	1,4	Prepotto	7,0	1,3	94	25	3,0	322/60	204/51	178/53	081/05	016/017
32	19970425	13:16:05,8	0,5	46.222	13.768	1,0	Tolmin	1,5	1,5	90	31	3,0	262/60	152/59	117/46	027/00	019/026
33	19970802	04:49:23,5	0,4	46.108	13.685	0,7	Stregna	8,2	0,9	73	30	3,2	282/30	164/75	105/53	234/25	019/024
34	19971202	17:18:05,5	0,5	46.074	13.470	0,7	Prepotto	10,2	0,9	53	42	3,2	336/80	190/12	238/55	072/35	026/030
35	19980412	10:55:32,1	0,9	46.320	13.667	1,8	Bovec	16,8	2,3	88	40	5,6	222/82	313/83	178/11	087/01	040/040
36	19980821	13:10:41,1	0,6	46.271	13.704	1,0	Kuk	5,3	1,3	42	55	3,0	156/58	344/32	053/77	249/13	018/021
37	19980830	01:18:22,5	0,5	46.259	13.704	1,0	Kuk	6,7	1,2	45	51	3,0	136/72	020/37	008/52	250/20	021/026
38	19980916	11:09:25,5	0,4	46.320	13.621	0,6	Kobarid	7,5	0,9	48	49	3,1	306/70	040/79	172/06	264/22	017/020
39	19990321	04:07:41,8	0,5	46.431	13.338	0,5	Jof di Montasio	7,0	0,7	35	79	3,5	290/50	066/49	358/00	267/66	034/040
40	19990512	03:41:55,9	0,4	46.274	13.622	0,5	Kobarid	3,3	0,7	54	80	3,3	160/60	248/87	118/23	020/19	026/031
41	19990513	16:06:52,4	0,4	46.282	13.614	0,4	Kobarid	6,5	0,6	31	85	3,8	150/46	047/77	358/41	105/19	037/042
42	19990523	14:23:27,6	0,5	46.267	13.617	0,6	Kobarid	4,2	1,0	37	72	3,2	168/80	078/80	033/14	303/08	027/032
43	19990725	21:07:11,1	0,5	46.314	13.628	0,6	Kobarid	3,4	1,1	38	69	3,3	170/60	350/30	080/75	260/15	022/027
44	19990916	02:57:36,7	0,5	46.323	13.623	0,6	Kobarid	3,4	1,3	55	63	3,0	162/78	358/12	068/57	255/33	021/025
45	19990916	21:46:54,7	0,5	46.356	13.696	0,7	Soca	8,8	1,0	40	64	3,0	130/63	340/30	010/69	231/17	028/032
46	19991001	07:08:58,5	0,5	46.317	13.620	0,6	Kobarid	6,9	0,7	49	85	3,3	170/60	076/83	029/26	127/16	023/029
47	20000203	07:17:09,7	0,5	46.116	13.485	0,6	S.Pietro al Nat.	9,6	0,8	35	72	3,2	190/61	356/30	117/73	275/15	028/031
48	20001015	10:22:54,0	0,4	46.163	13.584	0,6	S.Pietro al Nat.	15,3	0,6	70	62	3,1	290/70	196/79	152/22	244/06	028/032

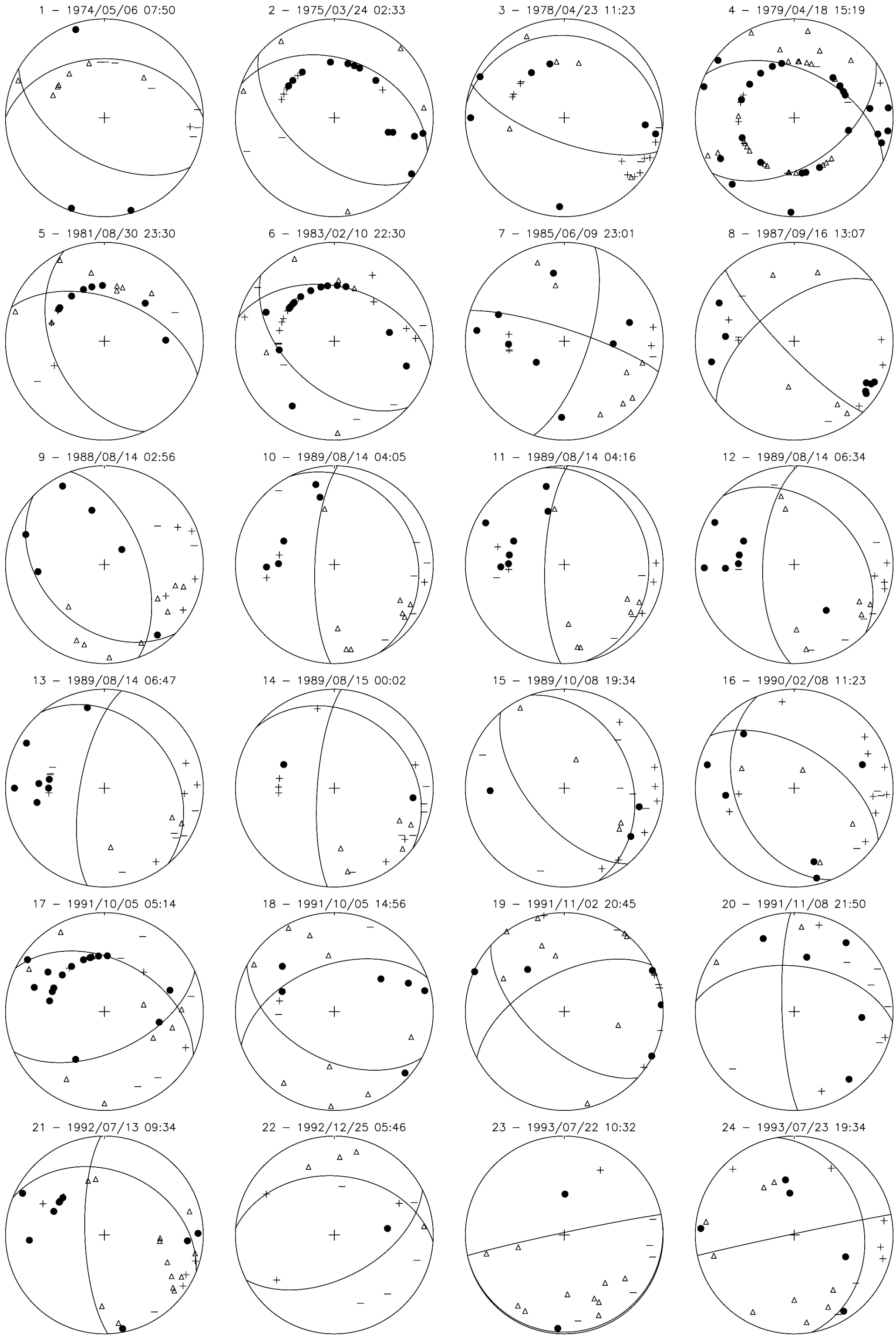

Fig. 3 - Focal mechanisms of the 48 earthquake considered (Table 1) with polarities of first arrivals. Solid circles for compression (+ for low quality), open triangles for dilatation (– for low quality).

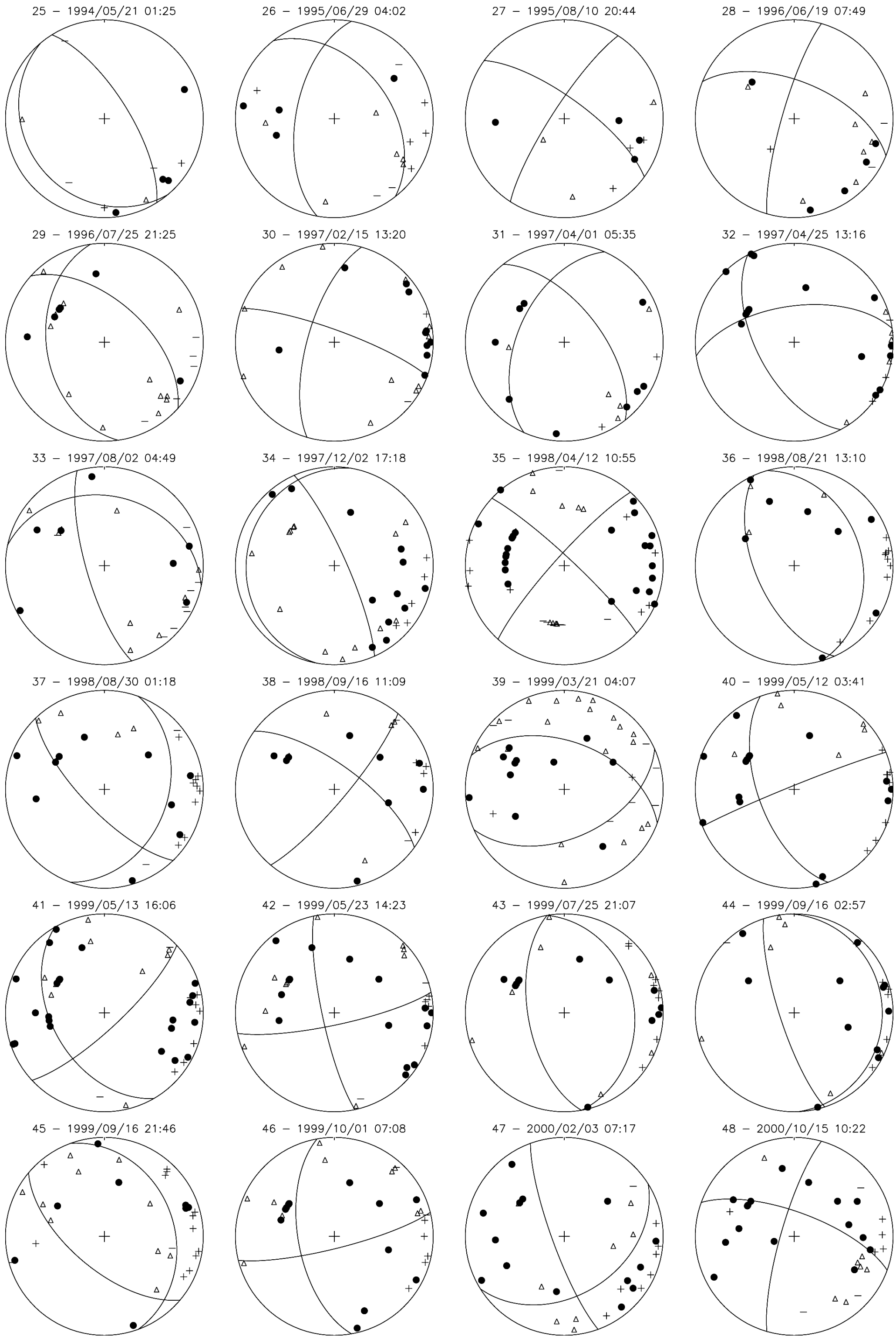

Fig. 3 - continued.

the FPSs spatial arrangement is independent of the magnitude. Moreover, the events with greater magnitude ($M_D > 4$) are generally located in the north-eastern part of the study region (i.e. in the central Friuli area), apart from the Bovec and Sella Nevea earthquakes in April 1998 (n. 35 in Table 1; $M_D = 5.6$) and in May 1974 (n. 1 in Table 1; $M_S = 4.8$) respectively.

The hypocentre locations, obtained from an average number of 52 recording stations, show very small errors on the epicentres, on the depth and on the origin time. As a matter of fact, they have a horizontal error lower than 1.9 km, a vertical one lower than 2.3 km and lower than one second (Table 1) on the origin time.

The construction of the focal mechanisms, with the first impulse technique, shows a good data quality and a good distribution of the polarities. In fact these FPSs have a mean number of polarities equal to 26 and a mean ratio between polarities in agreement with the solution and total number of polarities (score) equal to 0.8 with the maximum score equal to 1 and the minimum equal to 0.66 (Table 1).

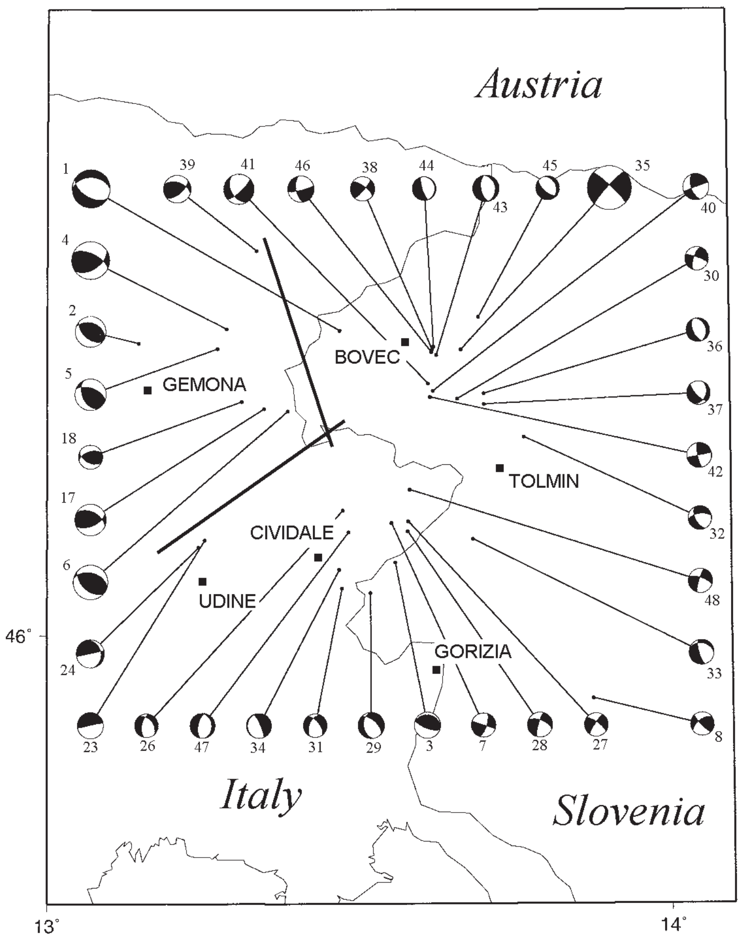

Fig. 4 - FPSs of the earthquakes with $M_D \geq 3.0$ recorded in the study area by the OGS Seismometric Network of Friuli-Venezia Giulia during the period 1977-2000. Black area for compression; numbers refer to Table 1. Heavy lines divide two seismotectonic and kinematic zones: the Gemona area to the NW, and the Cividale-NW Slovenia area to the east.

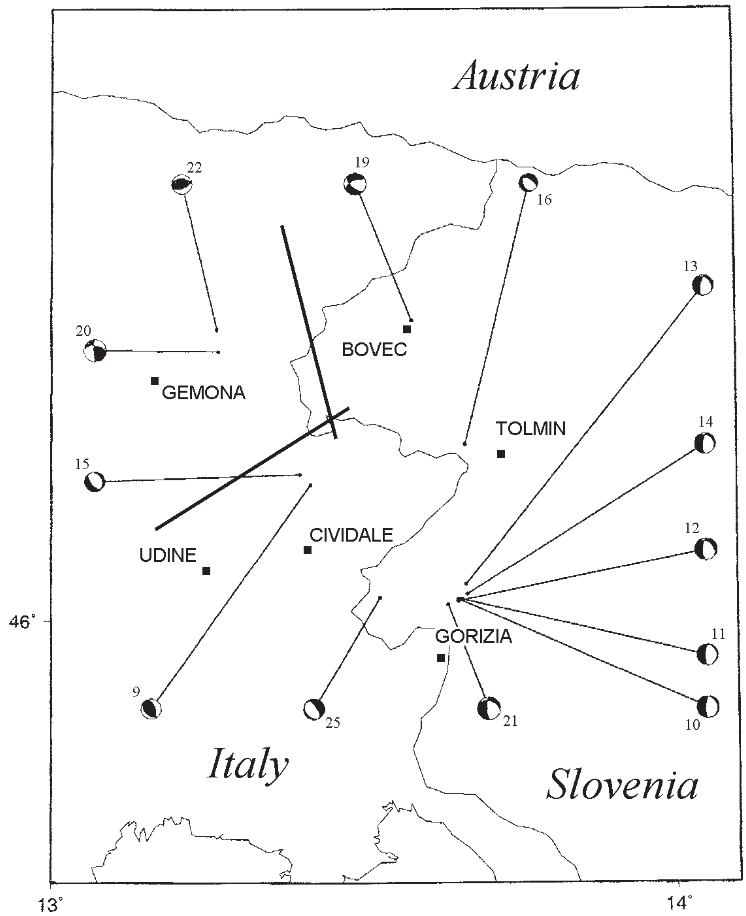

Fig. 5 - FPSs of the earthquakes with MD < 3.0 recorded in the study area by the OGS Seismometric Network of the Friuli-Venezia Giulia during the period 1977-2000. Black area for compression; numbers refer to Table 1. Heavy lines divide two seismotectonic and kinematic zones: the Gemona area to the NW, and the Cividale-NW Slovenia area to the east.

5. Fault-plane solutions

The study area was divided into two zones (Figs. 4 and 5), on the basis of the type of FPS and on the spatial distribution of foci.

1) The Gemona area. This area corresponds to the Friulian sector of the Julian Alps and Julian Prealps. The focal mechanisms (n. 2, 4, 5, 6, 17, 18, 39 in Fig. 4 and 20, 22 in Fig. 5) show reverse fault-plane solutions E-W or NW-SE striking, with horizontal P-axes and vertical or sub-vertical T-axes. Maximum compressive stress axes P range from NNW-SSE to NE-SW. Magnitude ranges from 2.6 to 4.8. The hypocentre depth is about 11 km.

   Comparing these events with the major (M_L > 4) earthquakes of Friuli 1976 (Fig. 6 and Table 2, from Slejko et al., 1999) and with the main quakes that hit central Friuli from 1928 to 1976 (Poli et al., 2000), it is clear that most of the earthquakes show the same type of focal mechanism, apart from the magnitude. Moreover, most of the earthquakes have a hypocentral depth ranging from 5 to 11 km.

Table 2 - Focal parameters of the main shock and aftershocks ($M_L \geq 4.0$) of 1976 Friuli sequence from May to September 1976 (from Slejko et al., 1999).

N	Date	Time	rms s	Lat	Long	erh km	Epicentral area	Depth km	erz km	Gap	Num staz	Mag	Plane A str / dip	Plane B str / dip	P axes str / dip	T axes str / dip	B axes str / dip	Score good/all
1	19760506	19:59:05,8	0.7	46,274	13,325	1,1	Lusevera	10,3	1,2	31	68	4,5	084/70	292/22	182/24	337/64	086/08	072/084
2	19760506	20:00:13,2	0,7	46,262	13,300	1,4	Lusevera	5,7	1,6	33	48	6,4	088/70	294/22	185/25	344/64	092/10	133/165
4	19760506	21:49:41,8	0,9	46,214	13,258	1,9	Tarcento	13,3	2,1	33	45	4,3	058/70	276/25	159/24	305/62	062/14	024/031
5	19760507	00:23:49,5	0,8	46,244	13,298	1,3	Tarcento	8,9	1,5	30	65	4,5	086/70	296/23	184/24	338/63	090/12	069/080
7	19760507	13:42:49,4	0,8	46,320	13,333	1,5	Uccea	12,9	1,6	47	44	4,1	106/74	246/21	186/28	034/59	282/14	027/033
8	19760508	03:10:06,1	0,7	46,267	13,226	1,2	Lusevera	12,6	1,3	43	55	4,1	064/72	296/28	171/24	305/58	070/22	044/048
9	19760508	20:40:31,9	0,9	46,333	13,210	1,5	Lusevera	6,8	1,7	45	49	4,0	078/70	270/20	171/24	341/65	080/04	023/028
10	19760509	00:53:44,6	0,7	46,213	13,323	1,2	Tarcento	13,3	1,1	31	61	5,3	116/56	272/36	196/10	066/75	288/14	110/127
11	19760510	04:35:52,2	0,6	46,264	13,213	0,9	Lusevera	6,8	1,0	44	61	4,4	062/70	242/20	152/25	332/65	—	046/054
18	19760608	12:14:37,6	0,9	46,316	13,260	1,3	Lusevera	9,4	1,3	39	68	4,3	100/70	256/22	183/25	024/64	280/10	047/054
24	19760710	04:11:23,5	0,7	46,307	13,212	1,2	Lusevera	3,5	1,7	38	50	4,2	026/46	208/44	117/01	248/89	027/02	024/031
26	19760714	05:39:34,2	0,9	46,320	13,262	1,3	Lusevera	9,2	1,3	33	70	4,2	104/74	248/20	185/28	030/56	272/10	039/057
32	19760911	16:35:02,4	0,8	46,256	13,233	1,3	Lusevera	4,3	1,5	46	55	5,4	078/60	260/30	169/15	345/75	079/02	050/066
33	19760911	16:48:55,6	0,7	46,272	13,227	1,2	Lusevera	2,5	1,6	55	50	4,3	080/80	248/10	168/55	353/55	263/4	029/036
34	19760912	01:19:58,8	0,6	46,273	13,269	1,0	Lusevera	7,1	1,1	40	67	4,0	104/70	272/20	191/25	021/65	283/06	031/040
35	19760912	19:53:28,5	0,5	46,292	13,225	0,8	Lusevera	7,2	0,8	37	65	4,1	080/50	256/40	168/05	010/85	261/04	041/051
36	19760913	18:54:46,5	0,7	46,277	13,210	1,1	Lusevera	8,2	1,0	37	71	4,3	074/50	248/40	161/05	012/84	252/06	039/048
39	19760915	03:15:19,8	0,5	46,284	13,203	0,9	Lusevera	6,8	0,8	30	66	5,8	058/56	236/34	147/11	332/79	237/02	113/155
43	19760915	09:45:56,3	1,0	46,305	13,256	1,9	Lusevera	11,8	2,0	39	50	4,3	094/54	252/38	175/08	048/77	267/13	036/048
47	19760915	19:31:11,2	0,8	46,294	13,207	1,2	Lusevera	4,3	1,4	30	71	4,1	090/60	286/31	186/15	339/74	092/08	034/044
50	19760920	09:09:58,8	0,8	46,308	13,238	1,3	Lusevera	6,5	1,5	31	55	4,4	086/68	256/22	173/23	003/67	266/06	023/036

2) The Cividale - NW Slovenia area. This area shows two distinct sets of FPSs.
   a) FPSs that indicate NW-SE trending, pure strike-slip faults (n. 7, 8, 27, 28, 30, 35, 38, 40, 42, 46, 48 in Fig. 4). The P and T axes are sub-horizontal and about NNW-SSE and ENE-WSW striking, respectively. Magnitude ranges from 3.0 to 5.6. The hypocentre depth presents two maxima: about 12-16 km in the Cividale area and about 5-7 km in the Bovec area.
   b) FPSs that indicate normal or transtensional faults with N-S to NW-SE striking planes and maximum concentration around NNW-SSE (n. 1, 23, 24, 26, 29, 31, 32, 33, 34, 36, 37, 41, 43, 44, 45, 47 in Fig. 4 and n. 10-14, 15, 16, 19, 21, 25 in Fig. 5). P is always steeply dipping; T presents a low angle. Earthquakes are characterised by a lower magnitude ($2.4 \leq M_D \leq 4.8$). The hypocentre depth is about 10 km in the southern area and about 7 km in the northern one.

6. Stress tensor inversion

According to Bressan et al. (1998) and Poli et al. (2000), the present tectonic stress regime in the Friulian-Slovenian area seems to be non homogeneous, probably strongly conditioned by the inherited geological structural pattern.

In order to determine the maximum stress tensor acting on the study region, the focal mechanism inversion technique proposed by Gephart and Forsyth (1984) and Gephart (1990) was applied to the study area.

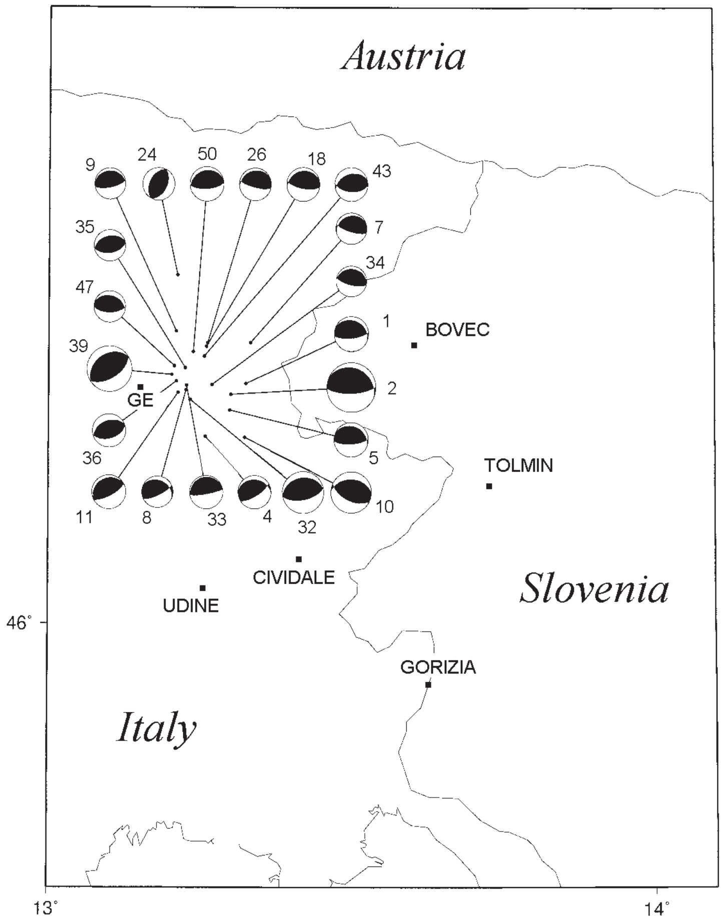

Fig. 6 - Map of focal mechanisms of the main shock and aftershocks with $M_L \geq 4.0$ of the Friuli sequence (May-September 1976: from Slejko et al., 1999). Black area for compression; numbers refer to Table 2.

Because of the scanty number of events in our data set for the Gemona area (see Figs. 4, 5 and Table 1), it was necessary to refer to bibliography, i.e. Bressan et al. (1998) and Slejko et al. (1999). Both papers investigate the present state of the tectonic stress of the Friuli region by applying the Gephart and Forsyth (1984) inversion technique.

According to Bressan et al. (1998), who applied the inversion technique to 107 single events ($2.1 \leq M_D \leq 4.2$) collected from 1988 to 1995 by the SNFVG, the central Friuli region is characterised by a compressional state of stress with σ_1 sub-horizontal ranging from N-S to NW-SE and σ_3 sub-vertical.

As an alternative, Slejko et al. (1999) used the FPSs of 78 aftershocks of the 1976 event collected in a period going from 1976 to 1979 to estimate the orientation of the principal stress axis. In this case too the confidence limits of the stress solution (σ_1 and σ_3) are separate and the misfit value is rather small (F = 4.4°), indicating a homogeneous state of stress. Moreover σ_1 (176°/21°) and σ_3 (5°/69°) values indicate a compressional regime compatible with the tectonic model proposed for the Friuli region.

On the contrary, for the Cividale - NW-Slovenia area, the inversion analysis was applied to our data set considering only single events and not a seismic sequence (i.e. for the Plave seismic sequence of August 1998, only the main shock with M_D = 2.8 was taken into consideration). The results show that:

1) there is no uniform stress distribution, as suggested by the high residual angle (F = 7,86°) and the wide confidence area spectrum at 95% (Fig. 7);
2) the values obtained (azimuth and plunge) for the maximum σ_1 = 103°/71°, intermediate σ_2 = 353°/07° and minimum σ_3 = 261°/18° stress axes, indicate a normal stress regime. Such a regime is hardly acceptable as the regional state of stress because it is in clear disagreement with geological and seismotectonic evidence.

Therefore, it seems to be necessary to distinguish two different stress fields in the Cividale - NW Slovenia area: a pure strike-slip, that represents the main deformation regime, and an extensional one probably connected with the activation of minor structures.

7. Discussion and conclusions

The analysis of the medium-low seismicity collected on the Italian-Slovenian border region during 27 years, confirms that two distinct seismogenic zones coexist: in this area the maximum

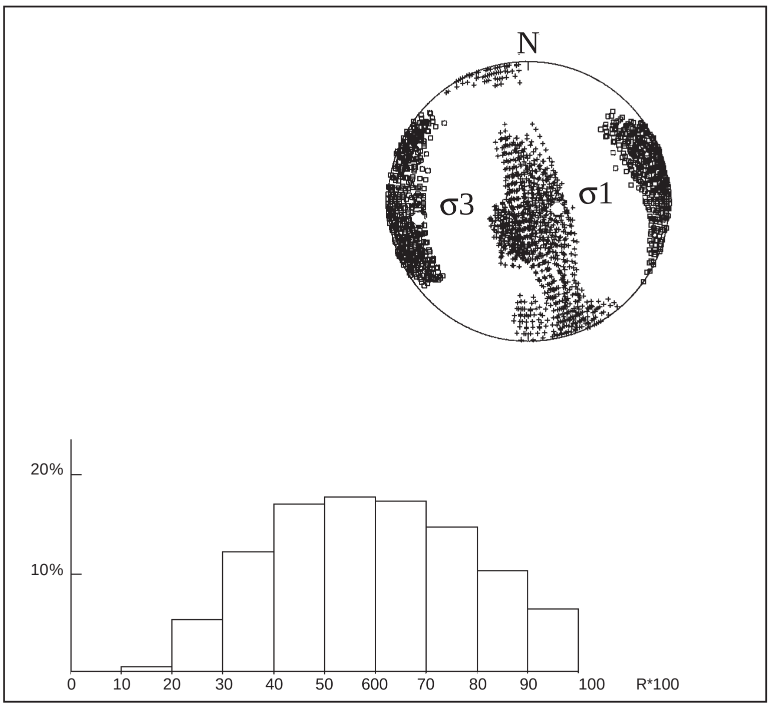

Fig. 7 - Stereographic projection (lower hemisphere) of the confidence areas (95%) as regard to maximum (σ_1 = 103°/71°) and minimum (σ_3 = 261°/18°) calculated stress tensor values for Cividale-NW Slovenia area. Data set = 33 events. The histogram shows the 95% confidence limits of the R-parameter in terms of distributions between the extreme values 0 and 1. F = 7.86°; R = 0.4.

stress tensor (σ_1 is horizontal and NNW-SSE to N-S striking) probably acts on different inherited structural backgrounds developing two distinct kinematics.

1) The Gemona area. All the quakes that occurred in this area present FPSs compatible with the structural pattern of the eastern sector of the Southalpine chain characterised by a SSE-verging, WSW-ENE-trending thrust system. Some reverse FPSs (planes NW-SE and NE-SW striking) are probably connected with a local reactivation of Mesozoic and/or Paleogenic inherited structures (Renner et al., 1991). Consequently, it pertains completely to the eastern Southalpine thrust-belt which is propagating southward deforming the Quaternary deposits of the Friulian plain.
2) The Cividale - NW Slovenia area. The analysis of the focal mechanisms suggests that in this area two sets of structures are active. a) The NW-SE striking, dextral strike-slip fault system linked to the main seismic activity of the External Dinarides from Bovec as far as the Mt. Sneznik-Rijeka area (Herak et al., 1995; Bernardis et al., 2000; Poljac et al. 2000; Bajc et al., 2001). b) A set of normal or transtensional faults mostly NNW-SSE striking showing a lower level of seismicity ($2.4 \leq M_D \leq 4.8$), probably because they act inside the crustal volumes defined by the main strike-slip faults.

Concerning the present tectonic activity of NW-Slovenia, geological evidence of horizontal movements, especially in the Quaternary sediments, are not always distinct.

Kuščer et al. (1974) suggest that the deep Quaternary basins of Bovec (depth of depocentre more than 320 m from the surface) and Tolmin along the Soča valley, might not only be linked to the Pleistocene glacial erosion, but they might be explained as intermontane basins linked to a tectonic subsidence. Cousin (1981) points out two phases with extensional character in the study region: the first (Oligocene?) predates the Neoalpine phase, the second that post-dates it (Plio-Pleistocene?). Poljak (1986), Vrabec (1994) and Placer (1982, 1998) propose the rhomboidal karst basins as being indirect proof of recent transcurrent activity along the Idrija fault. Recently, Benedetti (1999) and Benedetti et al. (2000) confirmed this hypothesis and, on the basis of morphological observations (abrupt changes in fluvial drainage, presence of abandoned valleys, tilted terrace surfaces), attributes evidence of Quaternary deformations to the NW-SE-striking Idrija fault. Finally Bajc et al. (2001), in studying the 1998 Bovec earthquake on the basis of the combining of the hypocentre relocation, the strong motion inversion, the digital elevation model and field geology, interpret the Bovec basin and the Tolminka spring basin as tectonic structures linked to the seismogenic activity of the so-called Bovec-Krn fault (belonging to the Idrija fault system): in particular, the Tolminka spring basin might represent the superficial expression of a restraining step-over basin located at a junction zone between two dextral strike-slip segment faults. Moreover, they suggest that in correspondence to the Bovec basin there could be an important active tectonic barrier at the junction between the strike-slip system of the External Dinarides and the thrust system of the Eastern Southern Alps.

It is common knowledge that transcurrent faults never occur as simple planar faults through the crust. They are usually characterised by complex zones of braided, parallel or *en échelon* faults that are not perfectly straight. Therefore, a variety of accommodation structures can develop. The structural sketch of Fig. 1 clearly shows the complex superficial geometry of the

NW-SE dextral strike-slip faults in the study area. They do not have a straight course but a winding one, sometimes even braided with contractional or releasing bend and stepovers. In particular, bends and stepovers can usually produce a complex zone of deformation with formation of contractional or extensional strike-slip duplexes (Fig. 8) depending on whether it forms at an extensional or contractional bend or stepover.

We suggest that the normal and transtensional focal mechanisms observed in the study area may be linked to the formation of extensional strike-slip duplexes at releasing bends or stepovers of the main dextral strike-slip faults.

Because dextral NW-SE strike-slip faults were already active during the lateral extrusion of the Eastern Alps (i.e. Ratschbacher et al., 1991; Fodor et al., 1998; Vrabec, 2001), we hypothesise that the seismicity that hits western Slovenia is linked to the re-activation of inherited Oligo-Miocene subvertical faults. The present compressive regional stress field (σ_1 about N-S striking) could enable the activation of strike-slip tectonics to which local transtensional (or transpressional) structures may be associated.

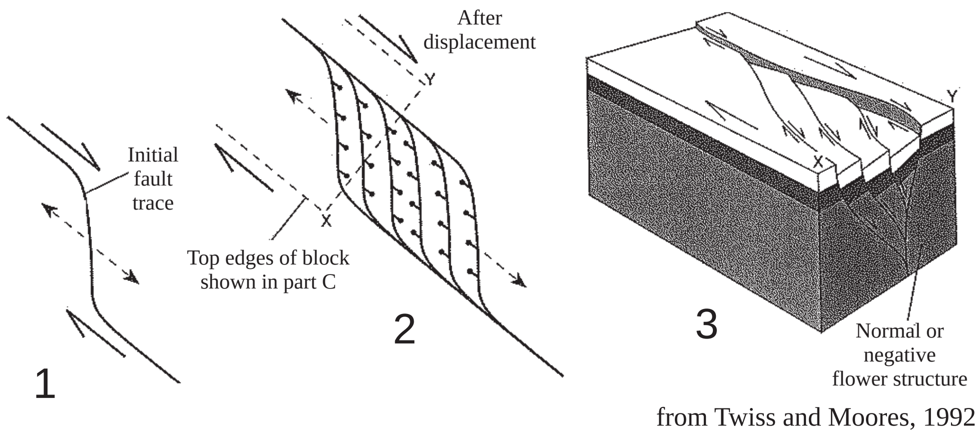

Fig. 8 - Formation of an extensional duplex at a releasing bend. Large arrows indicate dominant shear sense of fault zone; small arrows the sense of strike-slip and normal components of motion on the fault splays. 1) Extensional bend on a dextral strike-slip fault. 2) An extensional duplex developed from the bend in part 1). 3) Block diagram showing a normal, negative, flower structure in three dimensions.

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