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New seismotectonic evidence from the analysis of the 1976-1977 and 1977-1999 seismicity in Friuli (NE Italy)

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Abstract - The seismicity collected during the sequence that struck Friuli in 1976 and 1977 has been compared with that collected by the regional seismometric network in the following years (1977-1999). A standard approach was used to elaborate the seismological data recorded during the first year of the seismic sequence. A good quality data set of 479 hypocentral locations and 123 fault-plane solutions was obtained and used to check the seismogenic interpretation. Some vertical cross-sections representing the hypocentral probability, that takes into account the errors in the locations, have been constructed. These sections show two high-probability volumes: one is gently north-dipping and the second is steeply south-dipping. The fault-plane solutions have been projected onto the sections, and their nodal planes are in agreement with both elongations of the hypocentral probability volume. A similar elaboration was also carried out for the subsequent seismicity confirming the previous pieces of evidence. Thus, an improvement was obtained for the seismotectonic interpretation of the 1976-1977 seismic sequence as well as that of the present Friuli seismicity. On the basis of new geological data, a 2D structural model for the Southalpine chain has been constructed. According to the classical tectonic setting suggested for the Eastern Southalpine chain, the cross-section shows a south-verging thrust-belt arranged in an embricate fan geometry. At the Gemona latitude, at a depth of 5-8 km, a north-verging steep back-thrusting system becomes active: there seems to be a concentration of cracks in the carbonatic rocks. On the contrary, the 1977-1999 seismicity appears distributed in a larger crustal volume, with an evident westward shift of the maximum seismic activity. The relatively low level of the HP in the 1976 source zone is interpreted as a temporary and partial equilibrium reached by this crustal volume after the main ruptures. The stress redistribution caused by the 1976 sequence possibly produced a transfer of the deformation to the western sector.

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1. Introduction

The eastern sector of the Southern Alps is quite well known from the seismotectonic point of view, as several strong earthquakes occurred there and they have been studied extensively. Furthermore, a regional seismometric network, operating in this area since 1977, has collected a huge quantity of good quality data. Nevertheless, a clear association of the main earthquakes to their causative fault has not been established yet, although some attempts have been made recently (Aoudia et al., 2000; Fitzko et al., 2001; Peruzza et. al., 2002a). Consequently, even though twenty-five years have past since then, the 1976 Friuli earthquake, very likely the strongest quake ever occurred in this region, is still a key event in Italian seismology because some seismogenic aspects have not been clarified yet (see the state-of-the-art in Slejko, 2000).

The Friuli 1976 earthquake was the first, strong, Italian event for which a substantial amount of instrumental data was collected, especially by the temporary stations installed by several Italian and foreign institutions. In spite of this, all the available data, which sometimes present some instrumental problems (e.g. time synchronisation), were never elaborated in a systematic and homogeneous way. The seismicity during the first year after the May 6, 1976 earthquake is crucial for the understanding of the seismic sequence. The main shock (Wood Anderson magnitude MAW 6.4) was followed by a long series of aftershocks, the largest of which, the MAW 5.3 quake on May 9, was followed by a quiescence period in August. Seismicity increased in September when four strong quakes occurred (MAW 5.1 and 5.6 on September 11 and MAW 5.8 and 6.1 on September 15) with additional damage and a few victims, mainly in the Gemona area. Seismicity decreased progressively with time from then on, however a strong event (MAW 5.2) still occurred on September 16, 1977.

The first interpretations of the early part of the 1976 seismic sequence were based upon data collected either by stations more than 60 km away from the epicentre (the WWSSN Trieste station was the closest, Colautti et al., 1976, without considering the ENEL stations located in proximity to the main dams), or stations that operated only for limited time periods (see e.g. Finetti et al., 1979). Further investigations were carried out using data of European permanent (e.g. Zonno and Kind, 1984) or temporary (Barbreau et al., 1978; Wittlinger et al., 1978; Cagnetti and Pasquale, 1979; Briole et al., 1986) stations. The whole 1976 seismic sequence has been re-evaluated only recently using traditional techniques, after a detailed data collection (Slejko et al., 1999) or by applying modern techniques to source modelling (Aoudia et al., 2000; Pondrelli et al., 2001). On the basis of these findings, different source locations and interpretations of the phenomenon were proposed (see Peruzza et al., 2002b for more details).

In this context, the understanding of the main seismic events that hit the region is essential, as they represent the major energy release: the best candidates are the earthquakes with instrumental recordings, i. e. the 1928 earthquake which hit Tolmezzo and the 1976 quake which ruined Gemona, Venzone, Osoppo and many other villages of Friuli. The information collected for the 1928 event gives only a general image of the seismic process (Barbano et al., 1986), for the 1976 quake, on the contrary, several seismotectonic interpretations were suggested soon after the event as well as later, after detailed investigations. In fact, the seismic source, that produced two destructive quakes on May 6 (MAW 6.4) and September 15 (MAW 6.1) 1976 and their long queues of aftershocks, was associated either to NW-SE trending (Dinaric) faults (Amato et al., 1976; Finetti et al., 1979), or to E-W trending blind Neoalpine faults (Aoudia et al., 2000). The Alpine character of the fault-plane solutions of the main quakes does not support the first interpretation and the mechanical link between the two major events has not been modelled yet either. On the other hand, the seismotectonic and kinematic model proposed by Aoudia et al. (2000) is not detailed about the geometry of the seismogenic faults because it is based only on not updated geological data, while those regarding the crustal structure are limited or dated. The surficial cracks (Ambraseys, 1976; Bosi et al., 1976; Martinis and Cavallin, 1978) were not linked to any seismogenic fault because of the complexity of the regional tectonics and their long reactivation history, which is testified by the geometry of the structural elements (see e.g. Carulli, 2000).

On May 6, 1977 the first stations of a local seismometric network started recording in Friuli and good quality data have been collected since then. In the following years the number of stations increased, reaching 15, in addition to the historical Trieste station: they cover the territory of the Friuli - Venezia Giulia region. The analysis of the collected data has shown that the bulk of the seismicity is located in central Friuli (epicentral area of the 1976 earthquakes) and affects both the sedimentary cover and the top of the crystalline basement (Slejko et al., 1989), but the role played by the individual faults remains, anyway, not clear.

The aim of this paper is to re-evaluate most of the seismological data, collected during the first year after the main shock (May 6, 1976 - May 5, 1977) and during the following years (May 6, 1977 - December 31, 1999), to merge this information with that coming from the knowledge of surficial and especially crustal geology, and to propose a new interpretation for the 1976 seismic sequence.

2. Tectonic framework

The study area (Fig. 1) includes the central Friuli plain, the Julian Prealps and Alps, the Carnic Alps as far as the Italian Austrian border. Therefore, this area comprehends the whole eastern Southalpine chain (ESC) starting from its frontal zone, located in the Friulian Plain south of Udine, to the Gailtal line, a segment of the Periadriatic Lineament.

The Palaeozoic basement together with its about 10 km-thick Mesozoic to Recent sedimentary cover, have been thrusting southwards from Miocene to Present forming a WSW-ENE to WNW-ESE trending thrust-belt showing fault propagation folding and fault-bend folding as typical mechanisms of imbrication and shortening.

Mesozoic extensional and Paleogenic compressional tectonics played a fundamental role in controlling the structural evolution and the present framework of the ESC. Mesozoic N-S trending normal faults and about E-W transfer faults were re-utilised by Paleogene and Neogene compressional tectonics as inversion structures. On the other hand, for example, east of the river Tagliamento the present frontal thrust system re-utilises, as south-vergent frontal ramp, the lateral ramp of the buried west-vergent Dinaric thrust (i.e. Palmanova line Auct.).

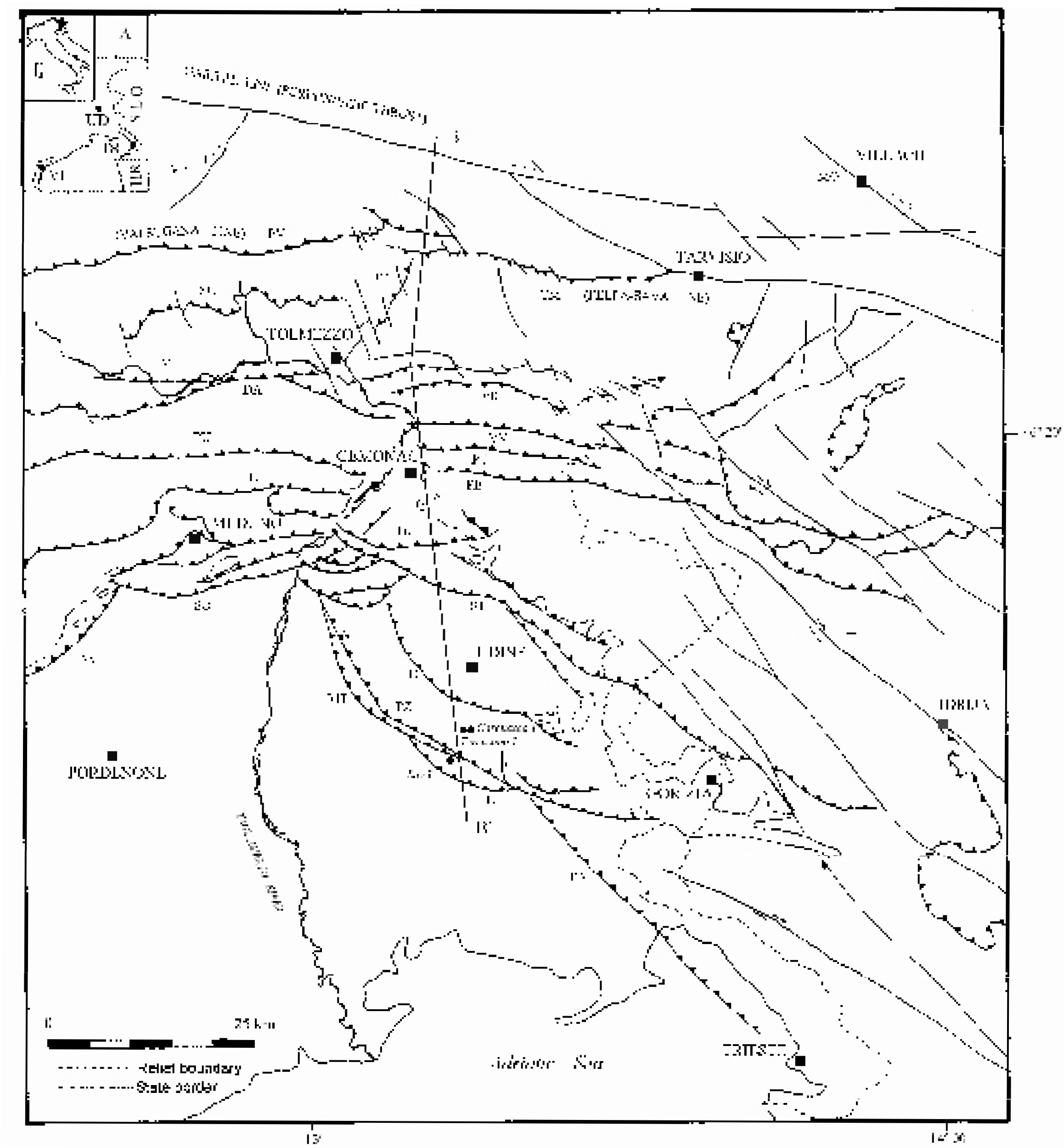

Fig. 1 - Tectonic map of Friuli and neighbouring regions. Legend: AT: Alto Tagliamento fault; AV: Aviano thrust; BC: But-Chiarsò lines; BI: Bicinicco thrust; BU: Buia thrust; DA: Dof-Auda thrust; ID: Idrija fault; MT: Mereto di Tomba thrust; PA: Palmanova thrust; PE: Periadriatic thrust (Barcis-Staro Selo line Auct.); PU: Pinedo-Uccea thrust; PV: Pontaiba –Villamezzo thrust (eastern continuation of the Valsugana line); PZ: Pozzuolo thrust; SQ: Sequals thrust; ST: Susans-Tricesimo thrust; SU: Sauris thrust; TM: Turriea-Minischitte line (western continuation of the Fella - Sava line); UD: Udine thrust; VB: Val Bordaglia line; VR: Val Resia back-thrust; VV: Val Venzonassa thrust. Full dots indicate oil wells; Lav1: Lavariano 1 well. BB': trace of the cross-section of Fig. 2.

2.1. Stratigraphy

The stratigraphic column of the ESC (see Fig. 2) comprehends a pre-Permian magnetic basement and an Alpine sedimentary cover (Permian to Present). The pre-Permian magnetic basement includes both the unmetamorphosed Paleozoic series of the Paleocarnic Chain (Venturini, 1990) and the low-grade Variscan methamorphic basement of the Eastern Alps (Poli et al., 1996).

A mostly clastic Permian and Lower Triassic series unconformably covers the metamorphic basement and the Paleozoic series, beginning the Alpine sedimentary cycle (Val Gardena Sandstone and Bellerophon Formations). A 5 km or more thick complex of carbonates, shales and volcanics deposited during the Middle Triassic.

The "Carnic unconformity" (Cu in Fig. 2) underlines the onset of the deposition of a widespread carbonatic platform of Dolomia Principale and Dachstein Limestone (Upper Triassic). This unit is overlined by the thick shelf complex of the Friulian carbonatic Platform (Jurassic and Cretaceous) that passes northwards to thinner basin facies.

The thick sequence of prevailing seismoturbidites of the Flysch del Grivò (Upper-Paleocene-Lower Eocene) and the unconformably turbiditic sequence of the Flysch di Cormons (Lower p.p.-Middle Eocene) filled the west-migrating Paleocene-Eocene foredeep, testifying the growth and the propagation of the external Dinaric chain.

The onset of sedimentation in the Eastern Southalpine foredeep is represented by the clastic sequences of the Cavanella Group (Aquitanian to Langhian in the Friuli area, but also Chattian in the Venetian region) that form a clastic wedge thickening northwards (Fantoni et al., 2000). In the Neogenic sequence, the Cavanella Group has been pinpointed (dark level in Fig. 2) as it represents a key horizon. Also the younger epibathial to continental deposits, from Serravalian to Messinian, thicken northwards: they are formed by a set of clastic sequences prograding in the foredeep outwards.

Continental Quaternary deposits seal the Alpine succession (thickness south of the Lavariano 1 well is about 400 m).

2.2. Tectonic units and geological cross-section

A N-S geological section crossing the ESC is proposed in Fig. 2 (for location see Fig. 1): the southern sector coincides with the geological cross-section of Peruzza et al. (2002a). The data set for the northern sector is mainly based on bibliographic data, while for the southern one it is based on new field geological observations, the revised stratigraphy of AGIP oil wells in eastern Friuli (Lavariano 1, Cargnacco 1 and Terenzano 1), and on the re-analysis of AGIP seismic lines crossing the Friuli plain.

The most ancient terrains outcrop along the Gailtal line, a lithospheric discontinuity already active during the Early Paleozoic (Visonà and Zanferrari, 2000) that played a fundamental role in the Cenozoic evolution of the ESC starting from the Upper Oligocene (Massari, 1990; Ratschbacker et al., 1991).

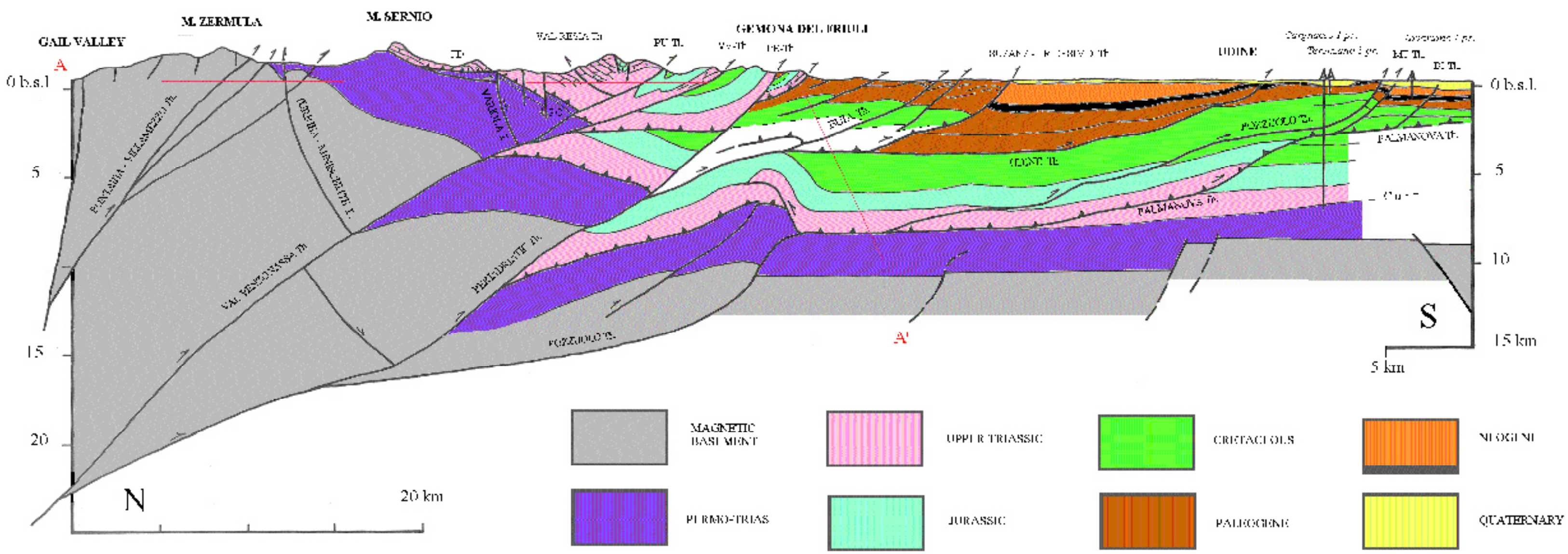

Fig. 2 - Geological cross-section of ESC in Friuli (trace in Fig. 1). AA' line divides the section into two parts with diverse reliability: the right side is constrained by reflection seismic profiles and oil well data; the left side is mostly interpretative, and benefits of modelling of geophysical data (magnetic basement, by Cati et al., 1987) and of seismological imaging presented here. Legend: BI-Th: Bicinicco thrust; MT-Th: Mereto di Tomba thrust; PE-Th: Periadriatic thrust (Barcis-Staro Selo line Auct.); PO: Posselie line; FD: Forcella Dagna line; PU-Th: Pinedo-Uccea thrust; VV-Th: Val Venzonassa thrust; Cu: Carnic unconformity. Traces of Dinaric thrusts marked by black triangles. The undifferentiated Jurassic and Cretaceous platform facies, in the southern part, gradually pass northwards to basin facies. Dark level: Cavanella Group (Aquitanian-Langhian).

South of the Gailtal line, the ESC shows a south-vergent thrust belt arranged in an imbricate fan geometry that propagates, involving the magnetic basement, into an upper crust already strongly deformed during the Dinaric tectogenesis (Fig. 2).

Later on the most important structural elements of the ESC are described.

THE PONTAIBA-VILLAMEZZO THRUST. - This high-angle north-dipping thrust is considered the eastern continuation of the Valsugana line (Carulli and Ponton, 1988a) and represents the most ancient thrust of the ESC (Early Miocene in age according to Venzo, 1939; Castellarin et al., 1992; Carulli and Ponton, 1992; Selli, 1998). In the Carnic area the Pontaiba-Villamezzo thrust (or Forca Pizzul line in Venturini, 1990) superposes the sequences of the Paleocarnic Chain on the Permian ones.

THE MINISCHITTE - TURRIEA LINE. - South of the Pontaiba-Villamezzo thrust, a high-angle south-dipping reverse fault, the Minischitte - Turriea line, forms a triangle zone (Carulli and Ponton, 1988b). Also the Minischitte - Turriea line, which is considered the western continuation of the Fella - Sava line, played a fundamental role during the Alpine evolution of the ESC. Differences in facies and thickness between coeval terrains located south and north of the line and the presence of extensional paleo-lines suggest a Permian-Triassic activity as major normal fault for the Minischitte - Turriea line. Moreover, it clearly shows evidence of Cenozoic superimposed reverse and dextral transcurrent movements (Carulli and Ponton 1988b).

THE DOF-AUDA (MONTE S. SIMEONE - VAL VENZONASSA) THRUST. - It represents the most important regional Neolpine element, in the Tolmezzo area. It presents a W-E striking and north-dipping fault plane that in the eastern sector (i.e. along the Val Venzonassa) overthrusts the Upper Triassic platform carbonates on the basin Cretaceous facies. Its hangingwall comprehends the complex structure of Mount Sernio - Mount Amariana, which is cut by a series of subvertical faults on the south (Gialinars Line, Variola Line and Posselie Line in Fig. 2), and is limited by a series of extensional paleo-lines to the west, i.e. the But Chiarsò fault-system (Carulli et al., 1982, 1987) acting as left transpressive faults in Neoalpine times.

THE PERIADRIATIC THRUST. - The Periadriatic thrust Auct. (or Barcis-Staro Selo thrust) is the most important south-vergent Neoalpine thrust in the Julian Prealps, where it overlaps the Dolomia Principale on the Eocene Flysch. It involves the magnetic basement probably causing its raising to a depth of about 7.9 km (Cati et al., 1987) and cuts Paleogenic Dinaric units.

THE SUSANS-TRICESIMO AND THE BUIA THRUSTS. - They are the two major Neoalpine contractional structures in the Julian Prealpine sector: in particular, the Susans-Tricesimo thrust presents a minimum vertical throw on the Cavanella Group of about 1200 m. On the basis of regional structural considerations, we suggest that the Susans-Tricesimo thrust had a Dinaric history too.

THE POZZUOLO THRUST. - It is the main structure of the ESC front (Peruzza et al., 2002a): it deforms the present Friulian plain surface with a set of splays and brings to light the Cavanella

Group near Pozzuolo del Friuli hill. It is a Neogene south-verging thrust with a staircase trajectory: where the Pozzuolo thrust cuts the magnetic basement, it forms a frontal ramp causing a notable crustal thickening of Mesozoic limestones and dolomites. Here, the activation of a north-vergent steeply deepening backthrust partially accommodates the shortening and causes a local thickening and the rising of a wedge of rigid carbonatic rocks.

THE UDINE THRUST. - This is a thin-skinned thrust flatting on the top of the Mesozoic carbonates by inversion of the slope of a Paleogenic turbiditic basin. Near Udine it ramps deforming the Friulian plain surface.

THE INHERITED DINARIC STRUCTURES. - The Neogene to Quaternary geometries of the ESC frontal thrusts have been strongly controlled by the former Dinaric structures: for example, the Paleogenic lateral ramp of the west-verging Paleogenic (Dinaric) Palmanova thrust (Amato et al., 1976) has been reactivated as frontal ramp by a set of south-vergent, WNW-ESE trending splays deforming the Neogenic to Quaternary deposits.

In the cross-section of Fig. 2, also the so-called Forcella Dagna Line (Carulli et al., 1987) has been interpreted as a Paleogenic contractional west-verging low-angle line.

3. The 1976 - 1977 Friuli earthquake sequence

The 1976 Friuli earthquake occurred at a particular moment for Italian seismology: a considerable number of stations with good quality instrumental equipment were operating on the national territory but neither a centralised data collection nor a fast data exchange were efficient; similarly, the main seismological institutions were ready to operate with portable stations in the epicentral area but a co-ordinating body for this operation did not exist. Furthermore, a few international institutions (as the International Seismological Centre ISC, the European Mediterranean Seismological Centre, the United States Geological Survey) were collecting seismological data from all around the world and were locating events, but with a notable delay, because of the lack of fast communications.

The ISC located 426 events during the first year of the Friuli sequence, but only 142 of them have a magnitude estimate (ISC, 1976-1977). The Trieste station located 446 quakes with magnitude larger than, or equal to, 2.6 (OGS, 1978) and the Istituto Nazionale di Geofisica 1015 events with magnitude larger than, or equal to, 1.6 using the data collected by its own and the CNEN temporary stations, in addition to the ENEL permanent stations on the dams (Istituto Nazionale di Geofisica, 1976a, 1976b).

3.1. Seismological data collection and processing

The existing seismometric data (phase arrivals and first motion polarities from direct seismogram readings or, when the seismograms were not available, from bulletins) for events with Trieste MAW larger than, or equal to, 3.0 were collected over the years, elaborated in an homogeneous way and the fault-plane solution was constructed for the strongest (Slejko and Renner, 1984; Slejko et al., 1989; 1999; Peruzza et al., 2002a, 2002b). A similar data collection was recently made also for the lower magnitude events of the sequence (MAW larger than 2.8) and additional data were added for the already studied events. In the end, 479 earthquakes were re-located or located for the first time and the fault plane solutions were controlled or computed for the first time for 123 of them (Table 1).

The procedure used for locating earthquakes is a standard one (Lee and Lahr, 1975) and the crustal model considered is an average regional model with 4 parallel strata over a halfspace (European Mediterranean Seismological Centre Working Group on the Friuli Earthquakes, 1976). Fault-plane solutions have been constructed with a graphical procedure based on the first arrival polarities. Figs. 3 and 4 summarise the quality of the locations computed and of the focal mechanisms constructed: they definitely look pretty good with horizontal errors smaller than 2.5 km and vertical errors lower than 3.0 km and a huge number of recording stations (the average number is 33), good azimuthal coverage (only in a few cases the gap exceeds 150°), general presence of close recording stations (after the first 2 days at least one station is closer than 20 km, with a few exceptions). The quality of the solutions increased in late September, when additional data were collected by a French mobile network and were used in our relocations. It is reasonable to think that no specific bias was introduced in the data set by the variability of the station number because the geometry of the network changed notably with time. Also the fault-plane solutions calculated show a good quality with a large number of polarities used (more than 40 except a few cases) and a large percentage of polarities in agreement with the solution proposed (more than 75% except a few cases).

3.2. Space distribution of the seismicity and seismotectonic interpretation

Fig. 5 shows the epicentral distribution of the seismicity during the first year, as it appears after revision, and the fault-plane solutions of the major events (MAW larger than, or equal to, 4.5): the north-westward migration from May to September is evident, and continued also in September 1977, when it reached the eastern sector of the Carnic Prealps (Slejko et al., 1999). The active bulk remains well identified although the main May event and a few others are shifted south-eastwards and several epicentres are spread to the west and, even more evidently, to the south. All the fault-plane solutions of the main events (see Table 1) refer to a thrusting mechanism with one plane dipping northwards.

Two series of cross-sections (for their location see Fig. 5) have been computed for a detailed 3D analysis of the hypocentral distribution (Fig. 6). These sections represent the hypocentral probability (HP), i.e. the probability that at least one earthquake had its hypocentre inside a unit crustal volume (see more details on the method in Peruzza et al., 1991; Gresta et al., 1998). Taking into account the statistical errors of the hypocentral locations, the HP correctly displays the seismological information to be correlated to the geological evidence. Although the energy of the events was not taken into account in this elaboration, the zones with high HP represent

Table 1 - Hypocentral locations and fault-plane solutions of the main earthquakes in Friuli between 1976 and 1999.

N	Date	Time	Lat	Long	Dept	Mag	No	Gap	Dmin	Rms	Erh	Erz	Plane A	Plane B	P axis	T axis	Score
1	19760506	195905.8	46-16.47	13-19.48	10.3	4.5	68	31	29	0.7	1.1	1.2	292/22	084/70	182/24	337/64	072/084
2	19760506	200013.2	46-15.74	13-17.99	5.7	6.4	48	33	48	0.7	1.4	1.6	294/22	088/70	185/24	342/68	133/165
3	19760506	202501.5	46-23.17	13-16.66	14.7	4.2	31	46	42	0.9	2.2	2.4	258/20	072/70	164/25	339/65	025/031
4	19760506	214214.0	46-15.71	13-16.91	4.2	3.9	52	45	72	0.8	1.4	1.5	260/26	100/65	184/20	027/68	023/024
5	19760506	214941.8	46-12.83	13-15.46	13.4	4.3	45	33	48	0.9	1.9	2.1	276/24	058/70	159/24	305/62	024/031
6	19760506	222042.3	46-20.04	13-21.26	9.5	3.5	45	47	49	0.6	1.1	1.3	272/46	074/45	353/00	261/81	020/021
7	19760506	230703.0	46-14.93	13-17.81	8.4	3.9	51	45	49	0.8	1.6	1.8	266/44	076/46	171/01	275/85	019/019
8	19760507	001443.5	46-16.76	13-11.66	7.0	3.1	36	41	40	0.8	1.9	2.3	240/40	078/51	160/06	037/79	019/019
9	19760507	002349.5	46-14.65	13-17.88	8.9	4.5	65	30	49	0.8	1.3	1.5	296/23	086/70	185/24	338/63	069/080
10	19760507	010025.7	46-22.95	13-18.66	7.0	3.7	45	62	45	1.0	1.6	2.2	260/44	100/50	186/03	084/74	021/021
11	19760507	060203.8	46-16.26	13-19.72	3.6	3.9	44	46	71	0.6	1.1	1.4	256/44	086/46	171/01	067/85	016/016
12	19760507	063931.9	46-22.48	13-23.28	7.0	3.4	36	59	51	0.8	1.7	1.8	238/46	066/44	332/01	074/86	017/017
13	19760507	094118.0	46-24.78	13-01.56	6.9	3.8	40	44	23	0.7	1.5	1.9	296/28	070/70	175/23	312/60	015/018
14	19760507	111529.8	46-14.27	13-04.90	11.7	3.5	24	113	18	0.3	1.0	1.0	254/50	120/50	187/00	097/65	013/013
15	19760507	124142.4	46-16.43	13-18.56	3.8	3.5	38	64	28	0.6	1.2	1.6	262/50	102/42	001/04	114/79	016/016
16	19760507	134249.4	46-19.18	13-20.00	12.9	4.1	44	47	48	0.8	1.5	1.6	246/21	106/74	186/28	034/59	027/033
17	19760507	155441.3	46-20.33	13-15.08	7.0	3.5	45	99	22	0.6	1.0	1.5	260/46	088/44	354/01	097/86	018/019
18	19760507	201251.7	46-24.29	13-12.13	13.7	3.4	49	47	18	0.5	1.0	1.1	270/44	070/48	170/02	271/80	024/025
19	19760507	205235.2	46-17.00	13-18.96	2.5	3.2	44	59	28	0.6	1.1	1.5	262/44	082/46	172/01	352/89	019/019
20	19760508	031006.1	46-16.04	13-13.58	12.6	4.1	55	43	43	0.7	1.2	1.3	296/28	064/72	171/24	305/58	044/048
21	19760508	095626.2	46-21.82	13-07.17	7.0	3.5	46	63	9	0.4	0.9	1.1	262/44	094/47	178/01	076/84	019/019
22	19760508	204031.9	46-20.00	13-12.59	6.8	4.0	49	45	19	0.9	1.5	1.7	270/20	078/70	171/25	341/65	023/028
23	19760509	005344.6	46-12.78	13-19.38	13.3	5.3	61	31	7	0.7	1.2	1.1	272/36	116/56	196/10	066/75	110/127
24	19760510	043552.2	46-15.82	13-12.80	6.8	4.4	61	44	14	0.6	0.9	1.0	242/20	062/70	152/25	332/65	046/054
25	19760510	050850.4	46-17.96	13-15.48	6.6	3.7	56	45	14	0.5	0.9	1.0	280/46	080/46	360/00	268/80	026/027
26	19760510	160148.2	46-17.30	13-12.38	6.4	3.1	37	80	6	0.3	0.8	1.0	255/44	112/52	185/04	082/70	017/019
27	19760511	005428.0	46-14.68	13-15.61	10.6	3.0	33	91	8	0.3	0.8	0.7	246/40	072/50	159/05	010/84	016/018
28	19760511	053156.5	46-12.96	13-09.04	7.2	3.9	49	42	23	0.6	1.3	1.3	258/26	086/62	173/17	005/73	032/036
29	19760511	095728.9	46-21.82	13-13.93	7.9	3.7	48	46	11	0.5	1.0	1.1	266/48	100/43	003/03	113/77	019/019
30	19760511	100622.3	46-14.40	13-10.67	4.4	3.4	42	83	1	0.3	0.6	0.8	274/58	102/32	007/13	171/77	018/020
31	19760511	221803.8	46-21.39	13-15.65	6.7	3.8	60	46	12	0.5	0.9	1.1	270/46	100/44	005/01	104/85	024/024
32	19760511	224400.7	46-14.02	13-03.21	12.3	4.8	73	40	13	0.7	1.1	0.9	296/24	078/70	179/24	325/62	080/098
33	19760511	232251.8	46-16.26	13-02.93	9.1	3.4	63	33	2	0.5	0.9	0.7	270/42	064/51	166/05	275/76	023/024
34	19760511	233643.1	46-16.53	13-03.35	4.4	3.7	65	43	8	0.6	0.9	1.0	270/28	100/62	187/17	001/72	030/032
35	19760512	030116.6	46-20.20	13-07.02	10.8	3.6	55	45	12	0.5	0.9	0.8	270/30	066/62	164/16	317/70	025/026
36	19760512	090407.4	46-18.17	13-05.13	11.6	3.6	49	63	10	0.5	0.9	0.9	266/46	060/47	163/01	255/76	021/022
37	19760512	180652.7	46-16.08	13-17.81	5.9	3.5	49	46	8	0.5	0.8	1.0	260/50	114/43	001/04	108/77	022/024
38	19760513	130450.0	46-13.68	13-00.45	6.5	3.7	57	41	17	0.6	1.1	1.1	272/20	084/70	176/25	349/65	027/037
39	19760515	042614.5	46-16.12	13-19.60	3.9	3.7	60	58	17	0.5	0.7	0.9	260/30	124/67	199/20	066/62	025/027
40	19760515	084017.0	46-14.55	13-01.63	7.9	3.4	57	50	15	0.5	0.8	0.8	290/40	082/53	184/07	300/74	017/021
41	19760515	160559.0	46-14.18	13-18.11	9.8	3.5	53	60	14	0.8	1.3	1.3	270/40	110/52	191/06	070/78	020/022
42	19760515	165048.7	46-18.62	13-13.86	9.7	3.0	39	103	11	0.5	1.1	1.2	016/70	108/85	330/17	244/10	019/019
43	19760515	183707.0	46-16.51	13-14.98	5.2	3.0	36	84	7	0.4	0.8	1.2	270/56	120/38	013/09	134/72	017/018
44	19760517	161316.3	46-15.67	13-02.32	9.8	4.2	79	39	14	0.8	1.1	1.0	270/30	090/60	180/15	360/75	045/053
45	19760517	173556.9	46-16.19	13-03.92	10.7	3.2	57	61	14	0.5	0.7	0.8	266/48	102/43	004/02	111/82	021/022
46	19760518	013008.8	46-16.04	12-59.50	6.4	3.7	65	40	12	0.7	1.2	1.3	270/15	066/76	161/31	328/59	039/045
47	19760518	023940.4	46-16.06	12-59.85	5.7	3.3	65	46	13	0.7	1.0	1.2	266/46	096/44	001/01	100/85	023/025
48	19760518	143222.3	46-14.13	12-58.68	7.0	3.1	46	62	9	0.6	1.0	1.2	270/46	098/44	184/04	048/84	020/021
49	19760523	005109.4	46-12.77	13-13.69	5.5	3.6	61	40	11	0.6	0.9	1.2	286/40	116/50	201/05	065/83	020/020
50	19760530	211310.8	46-20.21	13-08.52	10.2	3.6	62	38	12	0.5	0.8	0.9	282/40	096/50	189/05	338/84	023/023
51	19760601	172108.1	46-14.17	12-55.94	5.3	3.7	57	49	16	0.5	0.9	1.1	254/20	086/70	173/25	003/65	028/038
52	19760604	074915.7	46-14.99	12-59.21	16.1	3.3	62	48	9	0.6	1.0	0.9	264/44	094/46	179/01	075/85	026/026
53	19760608	121437.6	46-18.94	13-15.61	9.4	4.3	68	39	23	0.9	1.3	1.3	256/22	100/70	183/25	024/64	047/054
54	19760609	184815.3	46-14.22	12-58.03	9.3	4.0	79	42	16	0.8	1.0	1.0	260/20	084/70	173/25	356/65	034/047

Table 1 - continued.

N	Date	Time	Lat	Long	Dept	Mag	No	Gap	Dmin	Rms	Erh	Erz	Plane A	Plane B	P axis	T axis	Score
55	19760611	171640.3	46-14.76	13-00.03	9.9	4.2	80	38	15	0.9	1.2	1.2	260/30	088/60	175/15	009/75	052/062
56	19760615	054632.8	46-20.49	13-15.90	9.2	3.7	42	54	23	0.7	1.5	1.6	258/24	104/68	186/22	032/66	021/026
57	19760616	032032.5	46-18.03	13-06.93	11.2	3.7	67	30	9	0.5	0.8	0.9	304/30	108/61	204/16	359/73	028/029
58	19760617	142848.6	46-9.02	12-53.48	9.5	4.4	74	49	7	0.8	1.2	1.2	238/22	060/68	149/23	331/67	037/050
59	19760617	164208.9	46-17.25	13-11.88	8.3	3.5	51	39	10	0.4	0.7	0.8	320/40	130/50	225/05	001/83	021/022
60	19760626	111347.5	46-16.86	13-09.30	7.2	4.3	65	37	8	0.7	1.1	1.2	194/46	086/72	146/16	039/45	050/055
61	19760710	041123.5	46-18.40	13-12.73	3.5	4.2	50	38	13	0.7	1.2	1.7	208/44	026/46	117/01	249/89	024/031
62	19760712	080450.2	46-20.00	13-11.03	8.4	3.9	42	50	14	0.6	1.2	1.2	266/19	102/72	188/27	020/63	019/020
63	19760714	053934.2	46-19.21	13-15.67	9.2	4.2	70	33	10	0.9	1.3	1.3	248/20	104/74	185/28	030/59	039/057
64	19760715	125849.6	46-17.40	13-11.43	4.8	3.8	52	39	11	0.7	1.2	1.6	268/10	082/80	173/35	351/55	026/027
65	19760718	133918.1	46-18.85	13-07.26	15.6	3.5	50	69	11	0.6	1.2	1.2	244/52	086/40	343/06	102/77	025/025
66	19760730	073244.1	46-18.91	13-02.14	7.8	3.5	56	39	8	0.7	1.2	1.2	244/21	080/70	166/25	359/65	018/024
67	19760731	144653.8	46-17.34	13-14.86	4.9	3.7	42	34	14	0.5	1.0	1.3	224/18	100/80	178/33	027/53	021/023
68	19760818	055850.6	46-20.24	13-12.63	12.9	3.8	54	31	10	0.7	1.3	1.4	306/20	072/78	175/31	322/54	021/023
69	19760906	192814.6	46-16.95	13-05.70	7.0	3.7	69	36	5	0.7	1.0	1.1	250/46	076/44	343/01	095/87	027/028
70	19760907	110817.1	46-14.73	13-02.98	11.1	3.8	66	33	2	0.7	1.1	1.0	256/26	118/70	195/23	054/61	039/042
71	19760911	163111.5	46-16.49	13-11.87	9.8	5.1	76	28	3	0.5	0.8	0.6	258/30	086/60	173/15	007/75	083/105
72	19760911	163502.4	46-15.36	13-14.00	4.3	5.4	55	46	5	0.8	1.3	1.5	260/30	078/60	169/15	345/75	050/066
73	19760911	164855.6	46-16.35	13-13.62	2.5	4.3	50	55	23	0.7	1.2	1.6	248/10	080/80	168/35	353/55	029/036
74	19760911	210547.6	46-16.51	13-10.88	8.8	3.7	67	38	2	0.7	1.0	1.1	220/44	060/48	140/02	040/80	029/029
75	19760912	011958.8	46-16.37	13-16.16	7.1	4.0	67	40	8	0.6	1.0	1.1	272/20	104/70	191/25	021/65	031/040
76	19760912	080831.3	46-15.59	13-16.04	9.1	3.5	53	41	12	0.5	0.8	1.0	304/30	084/66	188/19	323/64	026/028
77	19760912	081449.6	46-16.46	13-08.93	2.1	3.6	52	42	7	0.7	1.1	1.5	246/46	076/44	341/01	079/85	022/024
78	19760912	195328.5	46-17.51	13-13.52	7.2	4.1	65	37	6	0.5	0.8	0.8	256/40	080/50	168/05	010/85	041/051
79	19760913	070353.3	46- 9.85	13-02.79	3.6	3.4	59	44	6	0.6	1.0	1.3	312/46	120/45	036/01	300/84	022/024
80	19760913	185446.5	46-16.64	13-12.58	8.2	4.3	71	37	4	0.7	1.1	1.0	248/40	074/50	161/05	012/85	039/048
81	19760913	194214.1	46- 8.43	13-01.97	6.5	4.1	49	64	9	0.7	1.5	1.7	300/21	102/70	197/25	002/65	028/038
82	19760914	082519.9	46-16.01	13-09.76	6.3	4.0	45	38	1	0.8	1.6	1.8	266/23	116/70	197/24	044/63	026/031
83	19760915	031519.8	46-17.07	13-12.20	6.8	5.8	66	30	4	0.5	0.9	0.8	236/34	058/56	147/11	332/79	043/055
84	19760915	033922.1	46-17.36	13-09.10	2.0	3.5	37	38	8	0.6	1.3	1.8	268/42	108/50	189/04	077/79	020/021
85	19760915	043853.9	46-17.65	13-11.97	12.7	4.7	69	32	5	0.8	1.2	1.1	262/25	062/66	158/21	316/68	051/066
86	19760915	045843.1	46-19.38	13-11.44	8.1	4.3	66	31	8	0.8	1.2	1.1	270/21	050/74	150/62	302/59	040/052
87	19760915	092119.0	46-18.01	13-10.44	11.3	6.1	65	30	5	0.5	0.8	0.8	270/39	050/58	157/10	272/67	111/138
88	19760915	094556.3	46-18.31	13-15.39	11.8	4.3	50	39	9	1.0	1.9	2.0	252/38	094/54	175/08	048/77	036/048
89	19760915	111111.3	46-16.68	13-09.79	9.1	4.5	66	30	3	0.7	1.1	0.9	246/37	094/56	172/10	048/73	048/068
90	19760915	111744.6	46-19.23	13-09.65	8.3	3.7	44	36	7	0.6	1.3	1.4	270/44	052/53	160/05	262/70	018/019
91	19760915	144235.7	46-19.44	13-01.21	7.7	3.7	54	38	13	0.8	1.5	1.7	270/20	078/70	171/25	341/65	021/028
92	19760915	151953.9	46-20.00	13-01.88	13.4	3.7	49	41	14	0.7	1.4	1.5	252/26	076/64	165/19	350/71	028/041
93	19760915	152424.4	46-22.99	13-00.37	1.4	3.5	37	42	6	0.5	1.1	1.6	248/58	136/59	192/01	102/42	019/022
94	19760915	172604.6	46-20.44	13-08.33	4.3	3.7	55	41	6	0.6	1.1	1.4	306/48	106/44	026/02	285/80	021/022
95	19760915	193111.2	46-17.63	13-12.41	4.3	4.1	71	30	5	0.8	1.2	1.4	286/31	090/60	186/15	339/74	034/044
96	19760915	202409.5	46-18.25	13-08.69	7.9	4.1	59	36	6	0.7	1.3	1.4	266/28	078/62	171/17	339/73	027/040
97	19760915	203454.2	46-19.80	13-10.89	4.7	3.7	53	37	8	0.6	1.0	1.4	290/44	068/54	178/06	281/67	021/022
98	19760916	013043.8	46-19.93	13-10.22	10.0	3.7	55	38	8	0.6	1.1	1.2	280/24	072/69	170/23	324/65	023/024
99	19760917	041406.5	46-18.08	13-13.36	5.3	3.9	53	38	7	0.8	1.4	1.7	254/20	074/70	164/25	344/65	022/025
100	19760918	003939.6	46-17.93	13-04.90	9.9	3.6	62	35	8	0.5	0.9	0.9	290/40	054/65	167/14	280/57	023/024
101	19760919	102652.0	46-16.24	13-11.30	8.2	3.7	57	38	2	0.5	0.9	0.9	278/40	104/50	191/05	042/84	024/025
102	19760920	090958.8	46-18.60	13-14.31	6.5	4.4	55	31	8	0.8	1.3	1.5	256/22	086/68	173/23	003/67	023/036
103	19760920	233420.7	46-20.00	13-12.76	11.5	3.5	49	37	19	1.0	1.7	1.7	246/22	092/70	175/24	017/64	021/025
104	19760926	015150.2	46-17.85	13-08.24	7.1	3.6	59	36	5	0.9	1.4	1.5	278/15	118/76	204/31	035/59	023/028
105	19760926	145220.2	46-14.67	13-07.84	5.2	3.6	52	34	3	0.8	1.4	1.5	286/15	090/76	184/31	355/59	023/026
106	19760927	143729.2	46-17.84	13-15.58	4.8	3.6	61	39	9	0.6	0.9	1.2	262/40	060/52	160/06	279/77	026/027
107	19761001	181447.9	46-21.62	13-04.59	9.6	3.2	54	53	5	0.3	0.6	0.6	266/46	122/50	195/02	098/71	025/026
108	19761009	034110.0	46-17.73	13-17.20	3.7	3.0	51	42	8	0.4	0.6	1.5	254/52	106/43	359/05	105/73	025/027

Table 1 - continued.

N	Date	Time	Lat	Long	Dept	Mag	No	Gap	Dmin	Rms	Erh	Erz	Plane A	Plane B	P axis	T axis	Score
109	19761011	165716.1	46-18.41	13-10.43	4.7	3.2	48	46	3	0.3	0.6	0.8	273/50	055/47	344/02	250/70	023/025
110	19761013	024839.3	46-22.01	13-05.42	10.7	4.4	74	30	9	0.7	1.0	1.0	244/39	050/52	146/07	280/80	040/056
111	19761015	022833.7	46-19.97	13-01.98	4.4	3.2	35	80	5	0.3	0.9	1.2	269/40	056/55	160/08	275/72	025/026
112	19761026	060248.7	46-18.18	13-11.08	7.0	3.2	54	42	4	0.4	0.7	0.8	252/40	074/50	163/05	354/85	023/027
113	19761027	042542.6	46-19.79	13-08.76	4.5	3.3	43	43	3	0.3	0.5	1.0	252/50	116/49	004/00	095/66	023/025
114	19761113	011333.7	46-19.65	13-01.06	8.6	3.5	67	33	26	0.7	1.0	1.2	278/46	146/55	214/05	114/63	025/027
115	19761120	000135.6	46-17.50	13-16.46	5.7	2.9	42	48	7	0.2	0.4	0.9	242/50	112/53	177/01	085/62	023/024
116	19761123	073025.9	46-18.13	13-09.89	14.4	3.9	52	37	27	0.7	1.2	1.2	292/35	146/60	223/13	095/69	021/027
117	19761125	014626.2	46-18.67	13-09.18	4.0	3.2	45	53	2	0.3	0.5	0.8	264/50	104/42	003/04	116/69	023/025
118	19761207	033700.9	46-18.16	13-08.94	7.0	3.6	62	36	1	0.4	0.7	0.6	246/54	116/49	360/03	096/62	027/028
119	19761222	110253.8	46-23.03	13-05.55	7.0	3.2	40	46	3	0.3	0.7	0.8	258/50	090/41	354/05	122/82	023/025
120	19761223	022445.6	46-20.95	13-04.84	8.3	3.0	44	43	4	0.3	0.7	0.7	246/38	103/58	178/11	059/69	021/024
121	19770109	142627.5	46-17.24	13-08.16	5.8	4.0	59	37	16	0.7	1.1	1.3	244/42	086/50	166/04	056/79	035/046
122	19770315	154728.6	46-17.90	13-00.58	7.0	3.1	42	02	3	0.3	0.6	0.7	266/50	070/41	349/04	230/81	020/024
123	19770403	031814.1	46-17.68	13-09.58	7.3	4.5	69	33	17	0.6	1.0	1.1	242/17	116/80	195/34	042/53	049/063
124	19770703	114455.8	46-16.55	13-3.91	13.7	3.7	43	51	6	0.6	1.2	0.9	100/60	242/36	175/13	052/68	022/034
125	19770824	120010.3	46-18.01	13-7.62	5.5	3.4	39	51	3	0.7	1.1	1.2	175/88	266/64	224/17	127/20	024/025
126	19770916	234807.6	46-16.99	13-01.12	10.8	5.2	31	83	7	0.7	1.0	0.9	080/44	268/46	354/01	248/86	108/123
127	19770917	231651.4	46-18.26	12-56.94	13.2	3.9	41	76	12	0.5	0.8	0.7	080/52	234/41	158/06	045/76	029/031
128	19770928	014314.1	46-16.90	12-58.05	9.3	4.2	33	77	5	0.6	1.0	0.8	090/68	282/22	183/23	352/67	025/033
129	19770928	015637.6	46-16.56	12-57.70	7.3	3.4	55	53	4	0.7	1.2	1.1	058/70	236/20	147/25	329/65	021/027
130	19771014	201155.4	46-16.47	12-59.97	9.1	3.6	38	67	4	0.7	1.0	0.9	088/57	246/35	169/11	033/75	022/030
131	19771207	192105.5	46-18.61	13-15.98	8.7	3.4	39	44	8	0.4	0.7	0.9	092/38	254/53	351/08	123/78	019/024
132	19780109	214954.7	46-21.87	13-01.56	8.2	3.4	40	48	4	0.5	0.8	1.0	102/49	243/48	173/00	081/69	016/026
133	19780220	121333.9	46-27.52	13-15.92	5.7	4.0	23	70	20	0.7	1.0	1.3	102/60	001/72	318/35	054/08	034/045
134	19780402	182321.4	46-21.32	13-17.20	7.7	3.5	42	54	14	0.5	0.8	1.2	113/67	220/55	169/07	072/43	020/024
135	19780403	104945.9	46-18.71	13-10.32	7.8	4.2	37	71	6	0.7	0.9	1.0	100/52	252/42	177/05	067/75	031/045
136	19780403	143458.5	46-18.57	13-10.64	6.9	3.8	37	58	6	0.8	1.3	1.4	094/74	266/16	182/29	007/61	021/027
137	19780612	222404.7	46-19.40	13-4.28	7.5	3.4	31	61	2	0.5	0.8	0.8	078/73	200/30	149/24	020/55	021/032
138	19781202	040534.3	46-19.50	13-15.38	6.8	3.5	38	53	22	0.7	1.1	1.3	118/70	246/31	190/22	061/58	022/028
139	19790306	134606.3	46-24.98	13-2.65	5.6	3.5	34	56	7	0.6	0.9	1.4	001/50	264/82	319/21	214/34	016/028
140	19790418	151919.3	46-20.58	13-17.42	9.3	4.8	30	88	12	0.7	0.9	0.9	056/50	296/59	357/05	260/55	059/080
141	19790619	100314.6	46-17.62	13-9.74	10.4	3.7	39	72	6	0.5	0.7	0.6	112/40	250/58	358/10	111/66	026/034
142	19790814	185857.5	46-19.27	13-2.37	8.3	3.5	31	69	5	0.6	0.9	0.8	100/56	244/40	174/08	060/70	026/031
143	19791224	153756.3	45-28.38	13-13.20	22.0	2.8	15	257	50	0.2	1.9	2.8	194/74	302/36	194/50	302/24	011/014
144	19810830	233028.7	46-19.26	13-16.50	10.7	4.0	23	48	10	0.6	1.6	1.6	156/46	290/54	042/04	141/65	020/021
145	19821130	160907.6	45-43.26	13-04.92	27.1	2.5	15	193	40	0.3	1.5	2.2	136/50	272/50	110/66	022/02	013/013
146	19830210	223034.3	46-15.04	13-23.27	10.6	4.4	53	60	11	0.9	1.2	1.2	132/50	284/44	209/03	106/75	033/042
147	19880201	142137.8	46-21.67	13- 5.41	7.4	4.1	48	41	4	0.3	0.5	1.2	260/40	098/51	182/05	054/81	040/045
148	19880204	193736.2	46-21.70	13- 6.01	4.1	3.8	44	41	4	0.4	0.8	2.6	262/44	116/51	190/04	088/72	027/032
149	19890527	173439.5	46-21.30	12-55.20	14.7	2.6	55	47	14	0.7	0.8	1.1	262/40	130/61	200/11	087/63	011/013
150	19891008	193423.4	46-10.07	13-23.94	9.1	2.6	25	72	4	0.6	1.1	1.1	140/60	340/32	024/73	238/14	015/020
151	19910611	080553.5	46-15.24	12-54.90	16.7	3.8	73	24	6	0.8	0.9	0.9	174/42	016/50	094/08	225/82	044/050
152	19911005	051458.5	46-15.22	13-21.03	10.8	4.0	51	29	9	0.7	0.9	0.8	066/56	296/46	179/05	279/62	030/035
153	19911005	053137.0	46-16.83	13-19.25	1.8	2.6	27	69	8	0.5	0.7	2.2	290/40	200/90	142/34	260/34	017/017
154	19911005	060206.2	46-15.71	13-19.10	11.1	2.6	16	77	7	0.4	1.0	1.5	136/30	316/60	046/14	226/76	012/012
155	19911005	145629.2	46-16.07	13-18.82	6.0	3.1	43	66	7	0.6	0.8	1.1	118/50	250/51	004/01	095/64	018/023
156	19911108	215032.2	46-18.54	13-16.08	8.0	2.8	24	43	8	0.4	0.8	1.3	178/80	276/52	233/18	130/34	013/016
157	19920912	202617.6	46-21.78	12-54.48	6.0	2.5	15	74	15	0.3	0.5	1.9	280/26	010/89	124/39	256/40	013/014
158	19921225	054602.4	46-19.98	13-15.99	12.9	2.6	15	73	11	0.3	0.7	1.5	063/54	274/40	167/07	280/73	013/013
159	19930722	103242.4	46-06.45	13-15.26	11.6	3.3	30	51	8	0.4	0.6	0.7	078/02	258/88	168/47	348/43	018/018
160	19930723	193408.6	46-05.92	13-14.63	10.0	3.6	44	32	7	0.8	1.0	1.0	258/89	350/27	193/41	324/38	018/021
161	19980528	093219.1	46-17.75	13-3.93	11.3	4.1	61	48	4	0.4	0.6	0.8	260/10	085/80	174/35	356/55	033/034
162	19990321	040741.8	46-25.86	13-20.28	7.0	3.5	79	35	10	0.5	0.5	0.7	290/50	066/49	358/00	267/66	034/040

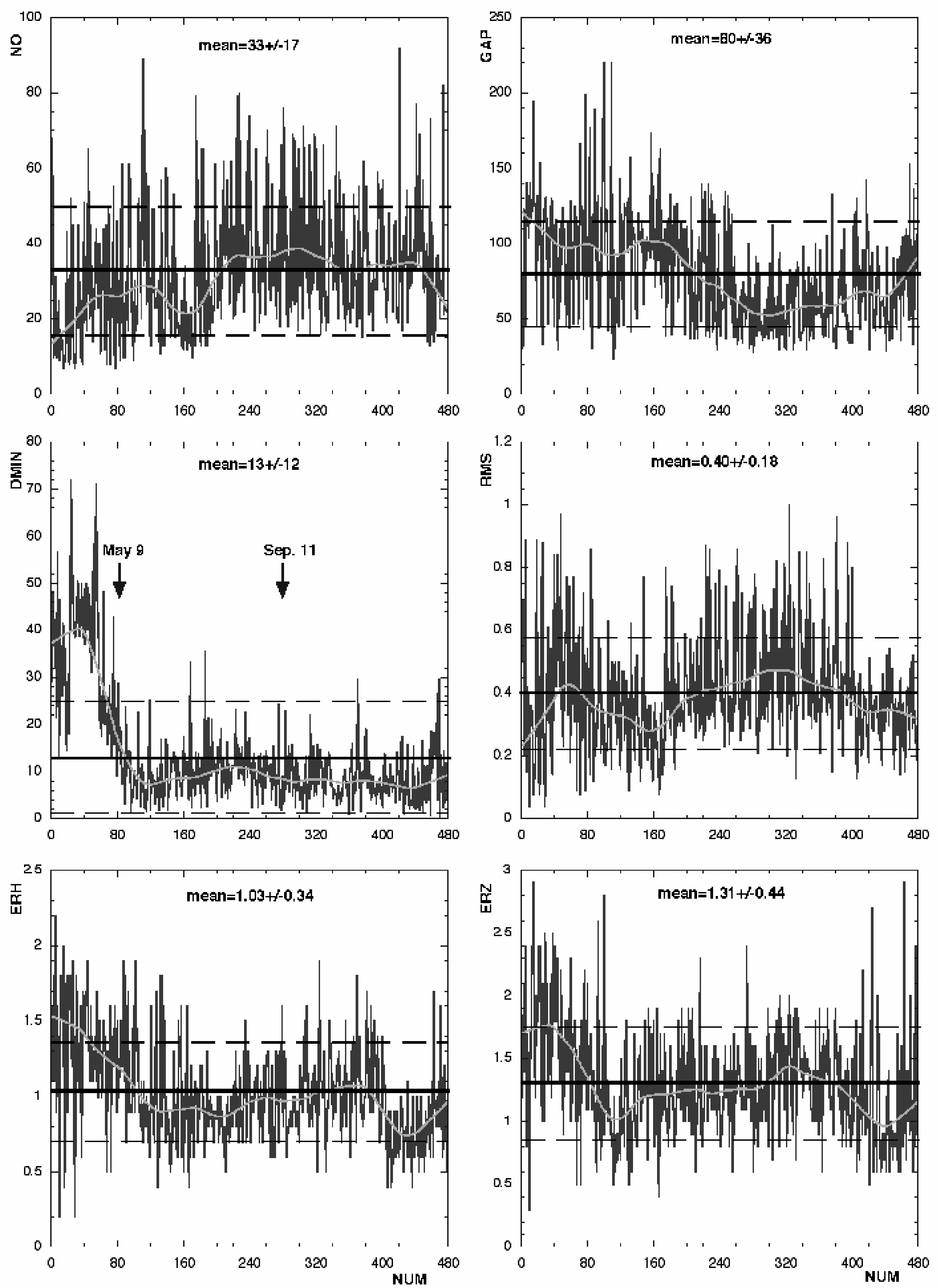

Fig. 3 - Statistics on the hypocentral locations of the 1976 sequence. On the x-axis the progressive earthquake number is reported; no = number of stations used in the location; gap = maximum angle without recording stations; dmin = epicentral distance of the closest recording station; rms = root mean square error on time residuals; erh = horizontal standard error; erz = vertical standard error. The solid straight line represents the mean value, the dashed straight lines represent the mean value respectively plus and minus one standard deviation; the grey solid curve represents the 10% locally weighted least squared fit.

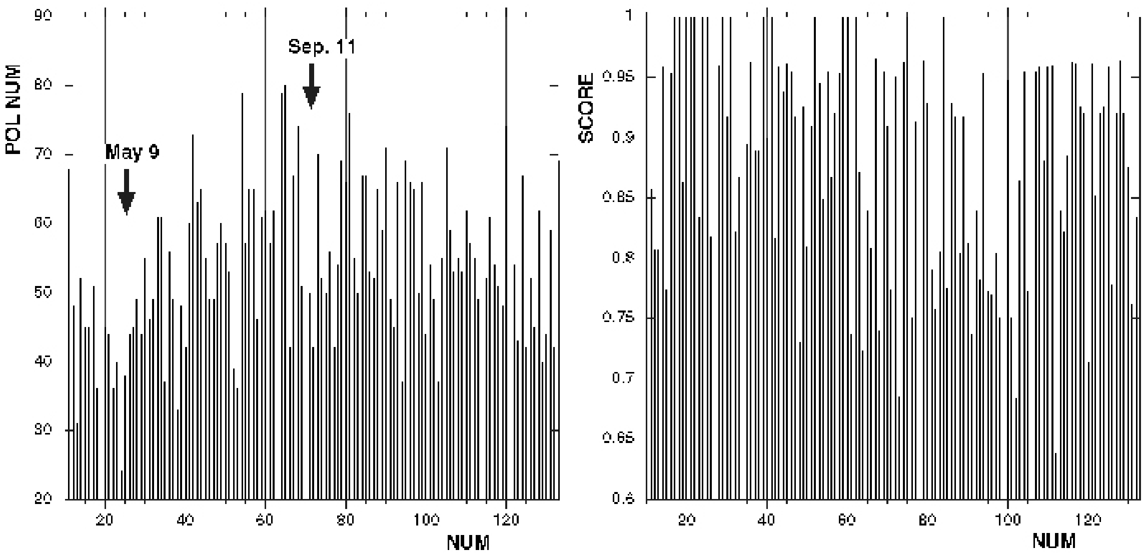

Fig. 4 - Statistics on the fault-plane solutions of the 1976 sequence. The progressive earthquake number (see Table 1) is reported on the x-axis; pol num = number of polarities used in the fault-plane computation; score = ratio between number of polarities in agreement with the proposed solution and total polarity number.

the zones characterised by high brittle deformation. A detailed comparison with classical cross-sections, which use symbols proportional to magnitude, and sections representing HP weighted with earthquake magnitude can be found in Peruzza et al. (1991) and is out of the scope of the present paper.

Seven sections are N-S oriented (Figs. 6a to 6g) and are evenly spaced between 13.00° E and 13.30° E. Four are W-E oriented (Figs. 6h to 6k): they are evenly spaced between 46.20° N and 46.35° N. All sections are 3 km thick and the mesh used for the calculation is 1 km: HP is, then, the probability that one hypocentre occurred in the investigated parallelogram with a 1x1x3 km^3 volume.

The best evidence of HP maxima can be seen in the central sections of the series N-S oriented: an elongated lobe, steeply dipping southwards (Figs. 6d and 6e) can be observed. Moreover, a gently north-dipping trend (the bulk of HP seems to become slightly deeper from Figs. 6i to 6k) can be suggested especially by the lowest HP level (see also Fig. 6e). The W-E sections show scattered spots of high HP: the main evidence can be seen in Fig. 6j. The wide fuzzy character of the HP volumes supports the fact that the investigated structure strikes about E-W. Furthermore, the high HP spot in the central area (Fig. 6j), i.e. the absence of a continuous HP belt which could be associated to a well-defined fault system, supports the hypothesis of a complex tectonic activity during the sequence, involving more than one structure.

Fig. 6 suggests also the following considerations.

1) The crustal volume interested by the 1976 - 1977 earthquakes is well defined between a 5 and 10 km depth. Its bottom is located at the depth of 11-12 km and dips gently to the north; below this depth the seismicity vanishes abruptly.

2) In this general framework an antithetic seismogenic system seems to have been active

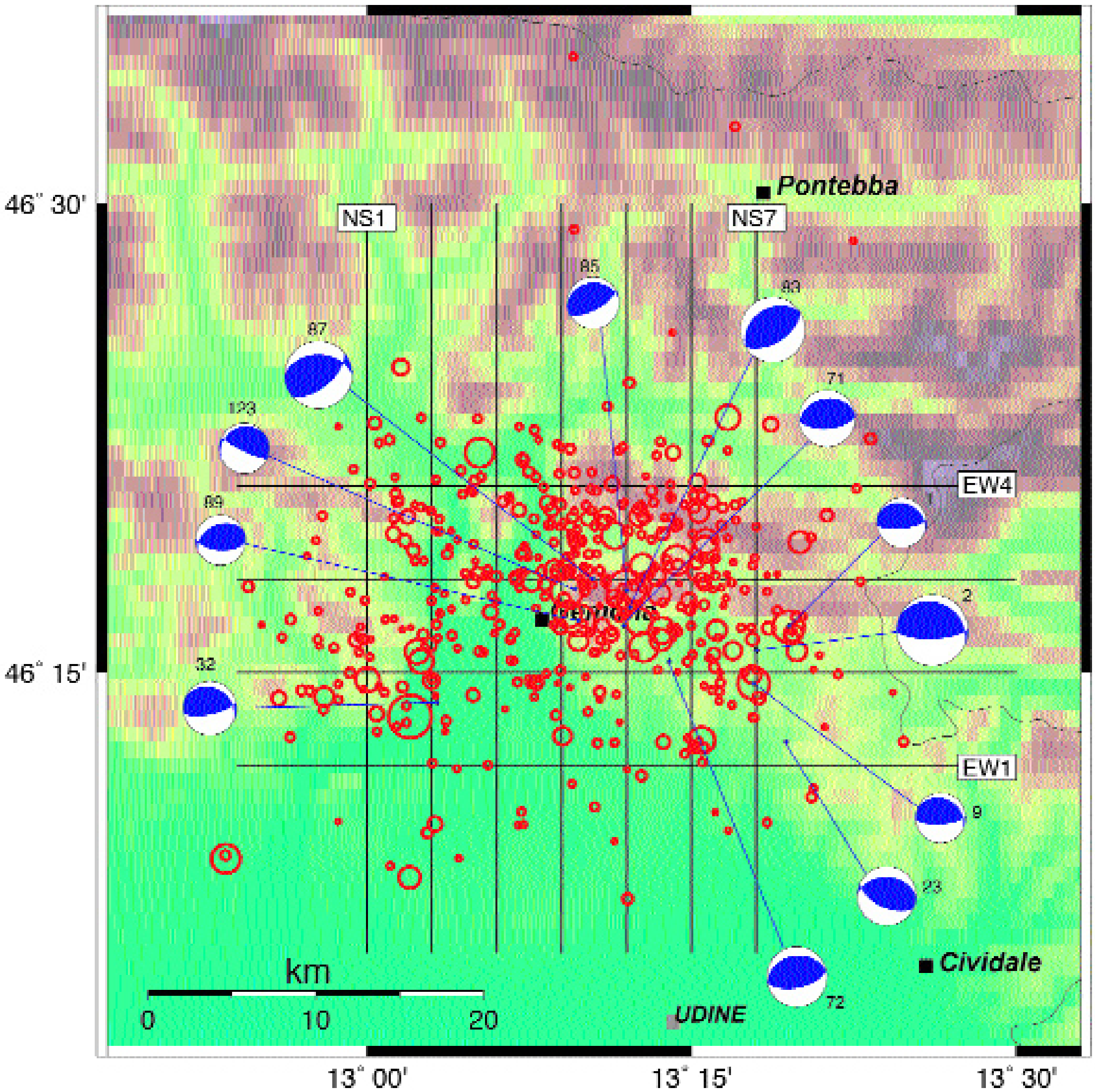

Fig. 5 - Epicentral distribution of the seismicity between May 6, 1976 and May 6, 1977, fault-plane solutions of the events with MAW ≥ 4.5, and traces of the cross-sections presented in Fig. 6. The number of the fault-plane solution refers to Table 1.

during the seismic sequence. This steeply south-dipping (about 60°) seismogenic system seems to be limited in width (5-6 km, according to Figs. 6d and 6e) and in thickness (5 km).

To summarise all the geological and seismological information available, an additional N-S-oriented 3-km thick HP section has been studied (45.92° N, 13.17° E – 46.64° N, 13.17° E): it correspands to the geological section of Fig. 2. The fault-plane solutions of the quakes in a 6 km-wide strip have been projected after an adequate rotation in the section plane (Fig. 7a). Both nodal planes (equivalent, for seismological studies) are in agreement with the elongations of the two HP lobes and they better support the steep south-dipping fault-planes at the Gemona latitude and the gently north-dipping system at a greater depth.

The suggestion of a high angle, south-dipping fault system has been recently proposed

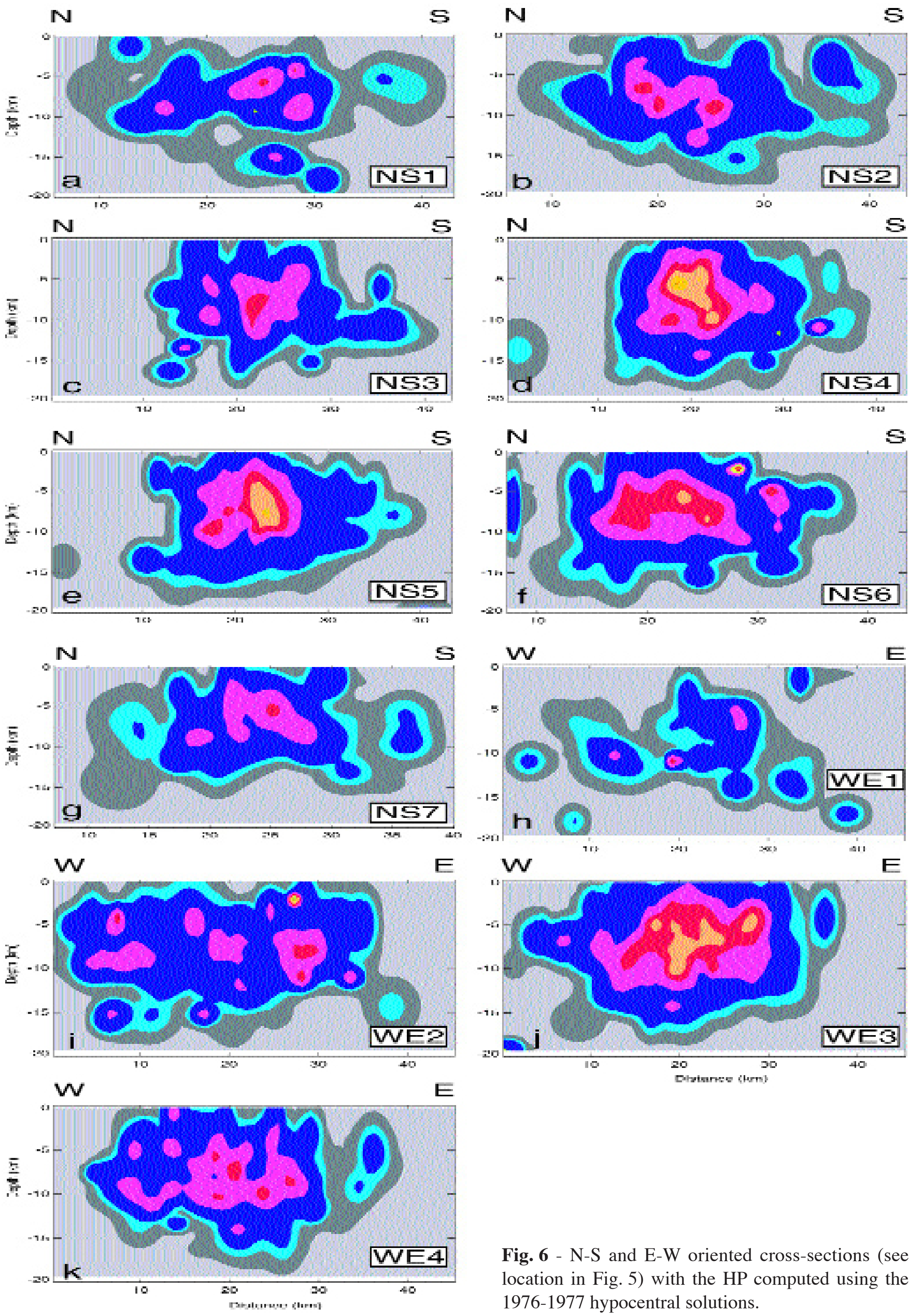

Fig. 6 - N-S and E-W oriented cross-sections (see location in Fig. 5) with the HP computed using the 1976-1977 hypocentral solutions.

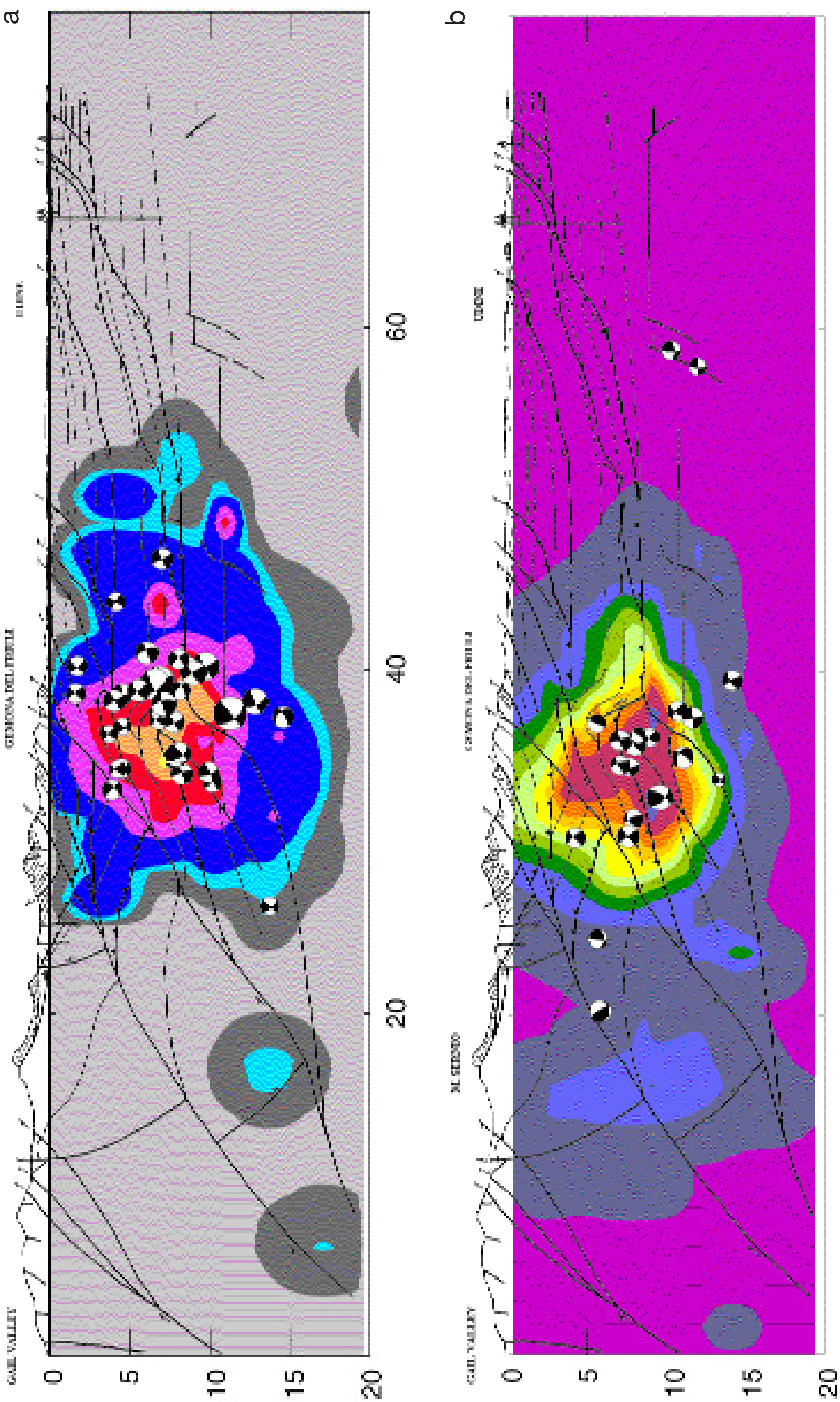

Fig. 7 - Geological - geophysical cross-section (see its location in Fig. 1): a) the HP in a 3 km-wide strip of the 1976-1977 seismicity is reported together with the fault-plane solutions of the main earthquakes in a 6 km-wide strip; b) the HP in a 3 km-wide strip of the recent (post May 6, 1977) seismicity is reported together with the fault-plane solutions of the main earthquakes in a 20 km-wide strip.

for the Friuli earthquakes (Peruzza et al., 2002a): it differs with the previous structural and seismogenic models proposed for the Friuli sequence, where only the activity of low-angle south-vergent overthrusts was pointed out (Amato et al., 1976; Slejko et al., 1989; Carulli and Ponton, 1992; Aoudia et al., 2000). It must be stated, anyway, that this antithetic lobe could be given by the superimposition of the activity along several short segments of low-angle north-dipping systems. In Fig. 7a, a notable crustal thickening of the Mesozoic limestones and dolomites develops where the Pozzuolo thrust cuts the magnetic basement and forms a frontal ramp. There, part of the shortening is accommodated by the activation of a back-thrust structure. The 5-8 km deep tectonic wedge could represent the seismogenic source for several earthquakes of the 1976 - 1977 Friuli sequence.

4. The recent seismicity in Friuli

Since May 1977, as said before, a regional seismometric network has been operating, initially in the 1976 quake epicentral area, later covering the whole Friuli - Venezia Giulia region. The number of stations increased with time and are 15 now, in addition to the historical Trieste station. Up to the end of 1999, 13,298 earthquakes were recorded and located (Lee and Lahr, 1975), 468 of which with a magnitude Md larger than, or equal to, 3.0 (see the data in OGS, 1977-1981, 1982-1990, 1991-1999). The major part of this seismicity (9,728 events) remains located in the area studied here (46.05° N, 12.8° E - 46.6° N, 13.55° E).

Figs. 8 and 9 show the statistics of the data set considered in the present study. Also in this case the solutions are of good quality with an average number of phases used in the location of 10, and a gap that, after the first period, remains lower than 200° (Fig. 8). The root mean square error of time residuals is good (0.15 s) and the standard errors in the location are good as well: 1 km in the horizontal plane, and 2 km in depth. The improvement of the location quality in time is not important, with the worst period being from 1983 to 1992 (considering the error in the origin time). The number of fault-plane solutions available for these 23 years is rather low, 39 events only but characterised by quite a large number of first polarities most of which agree with the proposed solution (see Table 1 and Fig. 9).

Fig. 10 shows the epicentral distribution of the seismicity and the focal mechanisms of the main quakes (see Table 1). It can be seen that an E-W trending strip remains defined, it becomes diffuse at the border with Slovenia and bends south-eastwards. Minor concentrations of epicentres are found to the north, around Pontebba, and to the east, in the Cividale area. Almost all fault-plane solutions refer to a thrust mechanism with a few exceptions located at the northern and eastern border of the Friuli area. A few small extensional earthquakes occurred also near Udine.

The same statistical treatment considered for the first year of the seismic sequence has also been applied to the recent seismicity. More precisely, the HP has been computed along the same vertical cross-sections (see their location in Fig. 10) with the same previous features. Because of the huge amount of earthquake data in these sections, the HP values are remarkably higher than in the 1976-1977 ones. Consequently, a different colour scale was selected, although only a

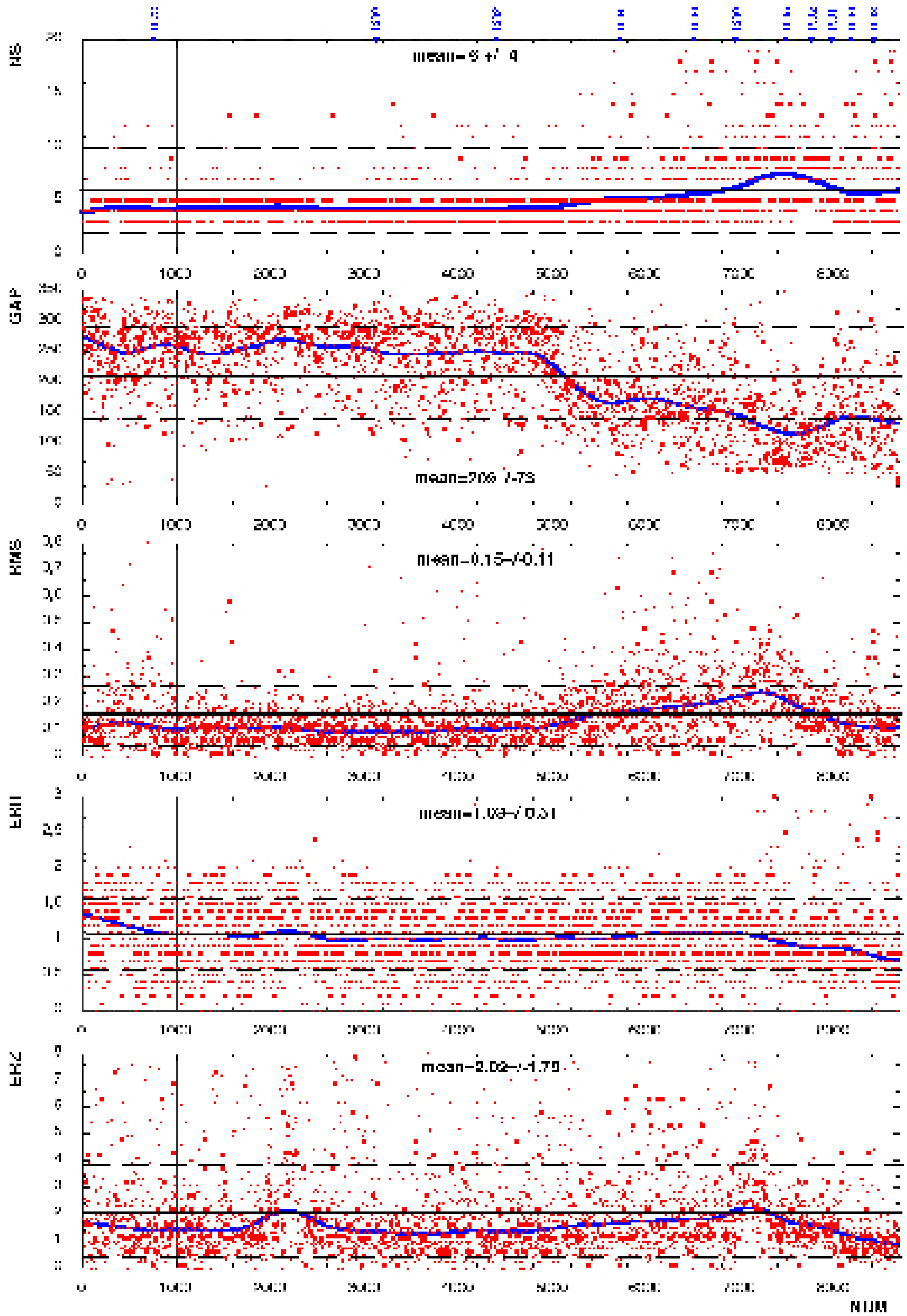

Fig. 8 - Statistics on the hypocentral locations in the study area from May 7, 1977 to December 31, 1999. The progressive earthquake number is reported on the x-axis; ns = number of stations used in the location; gap = maximum angle without recording stations; rms = root mean square error on time residuals; erh = horizontal standard error; erz = vertical standard error. The solid straight line represents the mean value, the dashed straight lines represent the mean value respectively plus and minus one standard deviation; the blue solid curve represents the 10% locally weighted least squared fit.

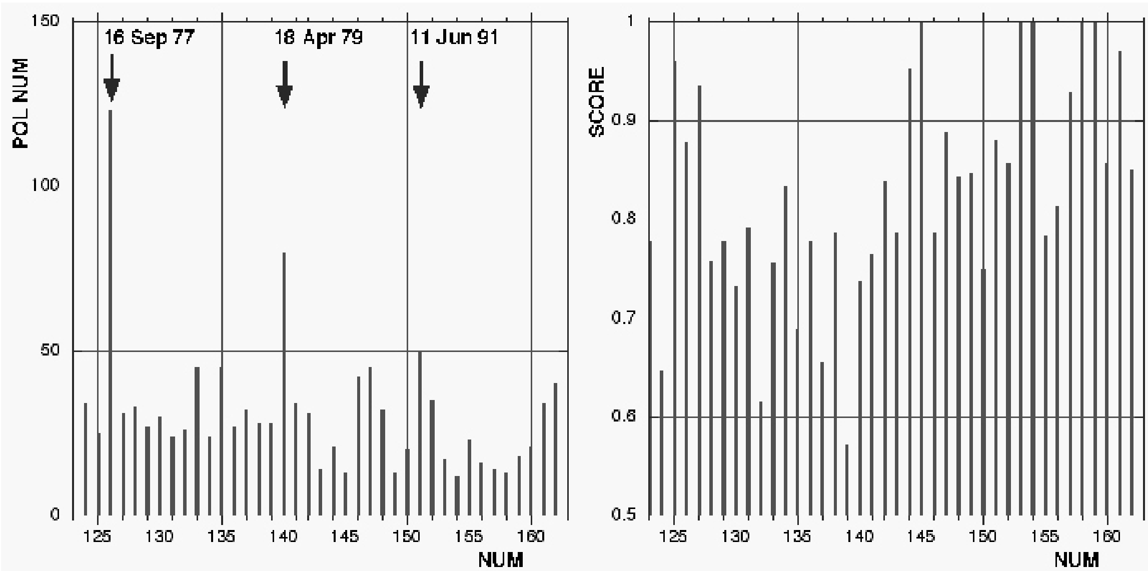

Fig. 9 - Statistics on the fault-plane solutions in the study area from May 7, 1977 to December 31, 1999. The progressive earthquake number (see Table 1) is reported on the x-axis; pol num = number of polarities used in the fault-plane computation; score = ratio between number of polarities in agreement with the proposed solution and total polarity number.

qualitative analysis of the HP sections is proposed.

Some features pinpointed on the sections referring to the 1976-1977 period (Fig. 6) can be seen again now (Fig. 11), and a general westward shift of the seismicity bulk is evident (compare Figs. 6b to 6d with Figs. 11b to 11d and Figs. 6j and 6k with Figs. 11j and 11k). Moreover, a reappraisal of activity can be observed in the easternmost section (Fig. 11g): this sector manifested seismicity, although not high, throughout the past years and a seismic sequence occurred in October 1991. All the sections of Fig. 11 point out that the seismicity vanishes abruptly under the 12 km depth, suggesting the presence of a seismogenic limit for the ESC.

The analysis of the N-S oriented HP sections again suggests the presence of a gently north-dipping plane (Fig. 11d). Furthermore, the high-angle south-dipping lobe of Figs. 6d and 6e can be seen again, although less clearly (Fig. 11b).

The W-E oriented sections show a more diffuse seismicity which can be associated to E-W oriented structures, similarly to what has been suggested for the seismicity of the 1976-1977 earthquake sequence. In this case, two seismogenic sources seem to be active at present: the first is about 5 km wide, 3 km thick and is located at the 5-8 km depth; the second is 10 km wide, 2-3 km thick, is located at the 9-11 km depth and is probably limited at its bottom by the seismological boundary. This arrangement can be observed in the N-S sections also (Figs 11b, 11c and 11d).

The same summary figure proposed for the 1976-1977 seismic sequence (Fig. 7a) is proposed also for the seismicity of the following years (Fig. 7b). The same gridding for the computation of HP chosen for Fig. 7a (1x1x3 km^3) was used in this case. Similar features of

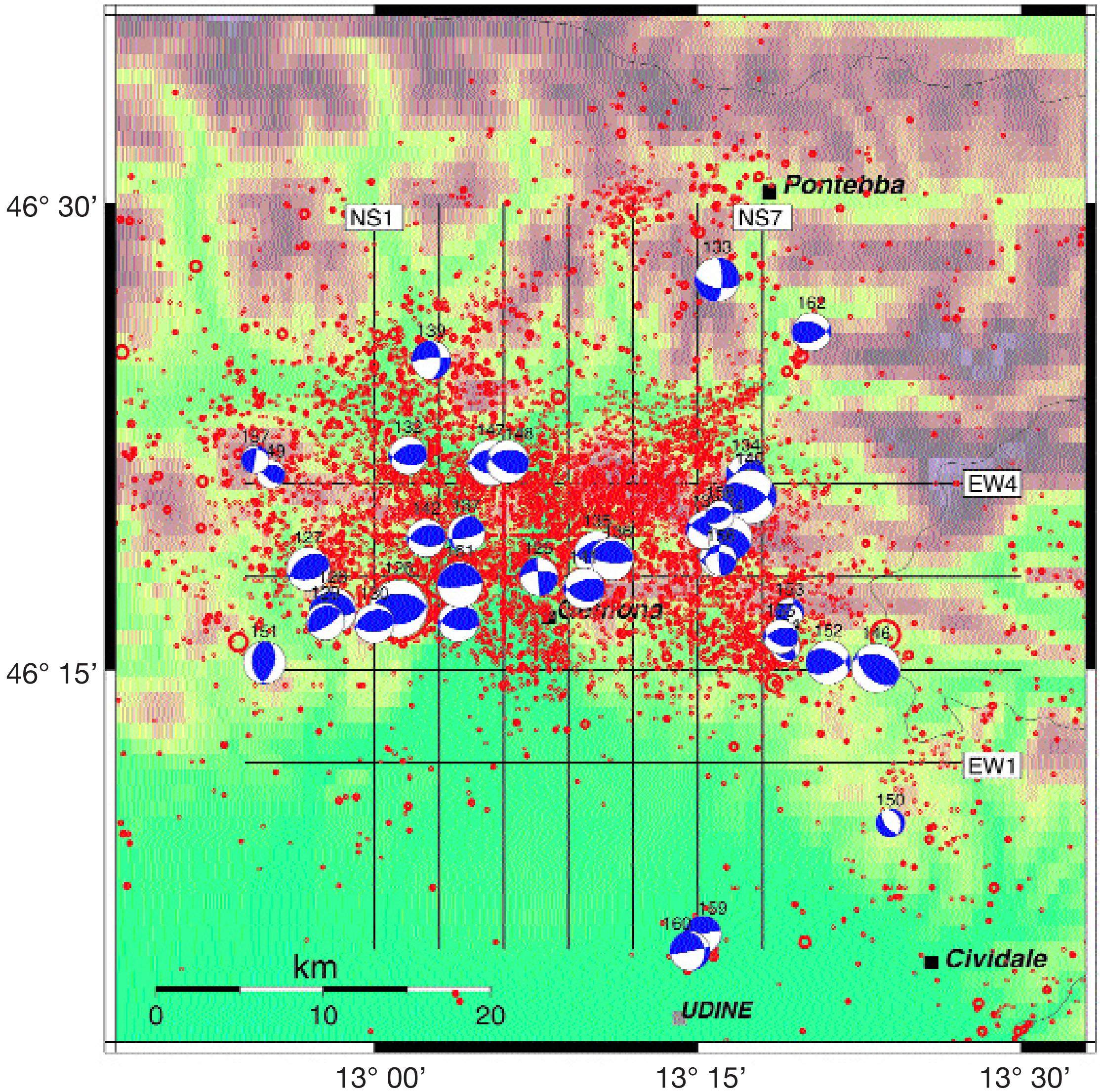

Fig. 10 - Epicentral distribution of the seismicity between May 7, 1977 and December 31, 1999, fault-plane solutions, and traces of the cross-sections presented in Fig. 11. The number of the fault-plane solution refers to Table 1.

those highlighted by Fig. 7a can be now seen with the bulk of seismicity almost in the same place (perhaps shifted a little to the north). The two planes are now much better defined and some lobes at lower depths could mean small active segments of north-dipping thrusts. In the northern part of the section, a sub-vertical lobe with middle HP can be observed, probably connected to a steeply south-dipping fault.

The few fault-plane solutions available in a 20 km-wide strip are located at the southern edge of the area with high HP and their planes are in agreement both with the gently north-dipping plane as well as with the steeper south-dipping one.

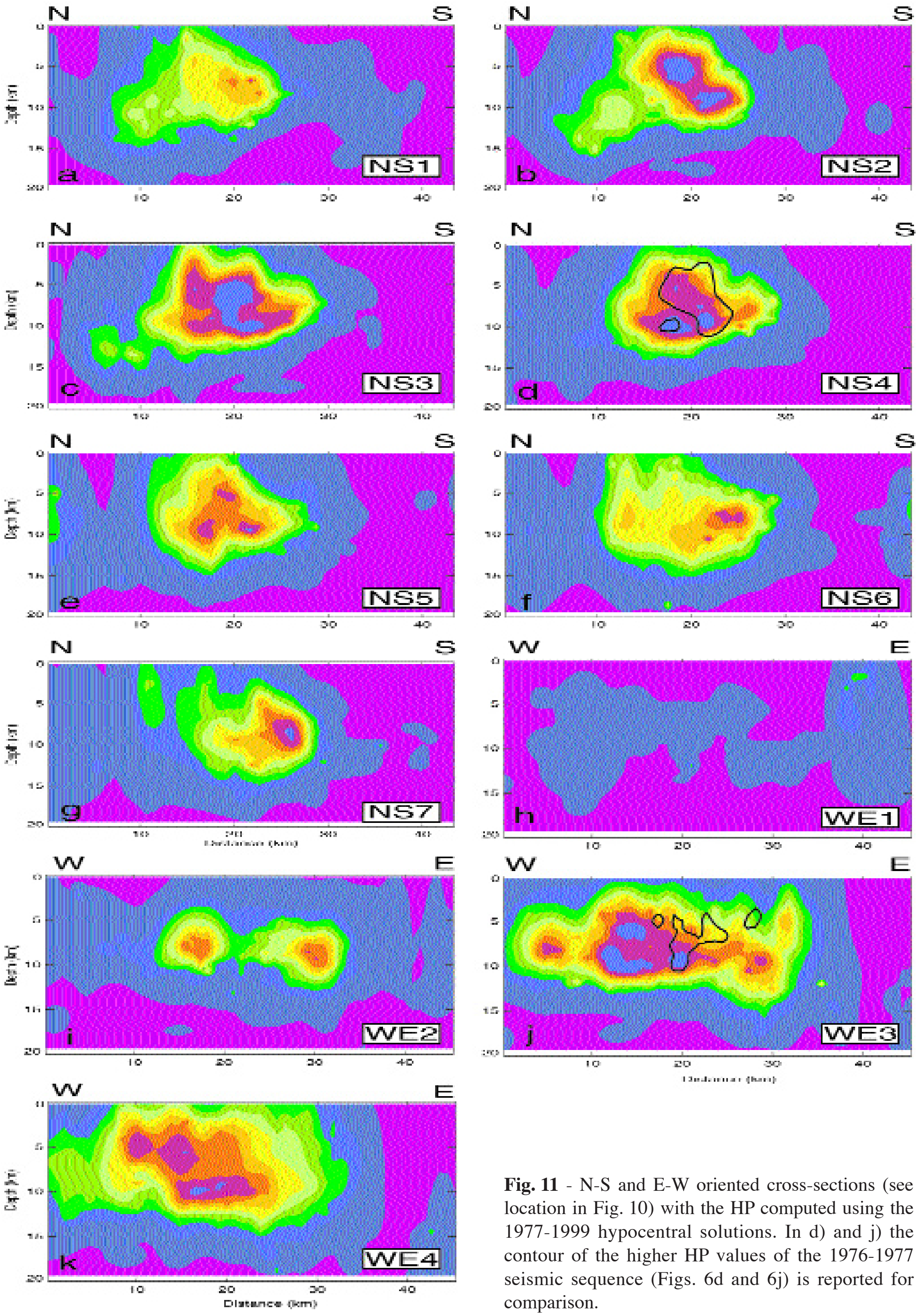

Fig. 11 - N-S and E-W oriented cross-sections (see location in Fig. 10) with the HP computed using the 1977-1999 hypocentral solutions. In d) and j) the contour of the higher HP values of the 1976-1977 seismic sequence (Figs. 6d and 6j) is reported for comparison.

5. Seismotectonic interpretation of the seismicity in Friuli

Comparing the HP sections of the 1976-1977 Friuli sequence (Fig. 6) with the HP sections of recent seismicity (Fig. 11), the following pieces of evidence can be noted.

1. The seismicity monitored in the last two decades confirms that most of the earthquakes lay in a crustal volume between 5 and 12 km deep, with a northernmost limit coinciding with the Fella-Sava fault, whose activity is confirmed by a seismic crisis in February 2002, and a southernmost limit that reaches the northern portion of the Friuli plain, near the relief boundary. Moreover, in the Friuli plain a few extensional fault-plane solutions could indicate a reactivation of inherited Permo-Triassic normal faults (Cati et al., 1987) connected with the northward underthrusting and buckling of the buried ESC foreland. The recent seismicity is shifted westwards with respect to the 1976-1977 seismic sequence (see Fig. 11j) while the possible northward shift appears very slight (see Fig. 11d).

2. Two seismogenic zones are active inside this crustal volume. The first, about 3 km thick and about 10 km wide, gently dips to the north; its bottom is located at the 11-12 km depth: below this depth the seismicity vanishes abruptly. The second is located between a 5 and 8 km depth. The two seismogenic zones seem to be separated by a low seismicity sector. As a working hypothesis, the first seismogenic volume can be referred to the hangingwall of the Pozzuolo thrust, while the second to the Susans-Tricesimo and Buia thrust system. It is worth noting that, during the investigated period, no evidence of seismogenic activity can be observed in correspondence to the Periadriatic thrust. This seismotectonic framework confirms that the Eastern Southern Alps is a south-verging foreland thrust system.

3. On the other hand, the analysis of the 1976-1977 Friuli sequence, confirmed also by the recent seismicity, indicates the presence of a third seismogenic zone with peculiar geometrical characteristics. It deals with a high-angle south-dipping lobe, about 5 km thick and about 5 km wide. According to Peruzza et al. (2002a) this seismogenic volume could be referred to minor contractional structures, such as backthrusts, developing within the south-verging thrust system of the ESC. Such backthrusts accommodate part of the shortening along the frontal ramp of the Pozzuolo thrust, where notable crustal thickening of Mesozoic limestones and dolomites develops. Therefore, the 5-8 km-deep tectonic wedge (Fig. 2) could represent the seismogenic source for several earthquakes of the 1976 Friuli sequence as well as of minor recent events.

Summing up, the seismic sequence of 1976-1977 in Friuli has been interpreted till now on the basis of the regional deformation pattern (i.e. south-verging thrust-belt) and on the focal mechanisms of the main shocks (low-angle reverse fault mechanisms): the re-interpretation of several cross-sections in terms of HP gives more emphasis to the complex pattern of brittle deformation, suggesting also the presence of high-angle, south-dipping faults.

The most striking considerations, when the features of the seismic crisis are compared with those of the following years, concern the level of activity and the present location of the seismicity bulk. Concerning the first point, it must be underlined that the higher HP values in the 1977-1999 sections are driven by the long time span considered, while the sequence which started in May 1976 probably ended before the end of that year (the conditional is motivated by the 5.2 earthquake of September 1977). Regarding the second point, it may be stressed that the recent seismicity appears distributed in a larger crustal volume, with an evident westward shift of the maximum seismic activity, i.e. of the maximum brittle strain. The relatively low level of the HP in the 1976 source zone is interpreted as a temporary and partial equilibrium in the regional framework of tectonic stress reached by this crustal volume. The stress rearrangement caused by the 1976 sequence possibly transferred the deformation in the western sector.

It is clear that the systematic gathering and analysis of the existing seismometric data, even if characterised by a lower quality level than that of the present recordings, can improve the understanding of the faulting mechanism in regions of complex tectonics, such as the Friuli region.

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