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What science remains of the 1976 Friuli earthquake?

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ABSTRACT The main results obtained in the seismological field regarding the 1976 Friuli earthquake are summarized. They refer to the source identification of the main shock, to its dimension, and to the time and space evolution of the seismic sequence.

Key words: 1976 earthquake, Friuli, seismic source, space and time evolution, main shock location.

1. Introduction

A search on the expeditious scientific information available for the Belice earthquake of 1968 showed that very little is known of that earthquake (see e.g. Haas and Ayre, 1969; Monaco *et al.*, 1996), especially as regards the seismological aspect. Conversely, a few months after the 1976 Friuli earthquake (4 and 5 December) an international scientific conference was held in Udine, whose acts are collected in two volumes of the international journal “Bollettino di Geofisica Teorica ed Applicata” for a total of 1,410 pages of geology, seismology, geophysics and earthquake engineering. A year later (11-13 October 1977), the National Committee for Nuclear Energy (CNEN) organized a specialized conference in Rome on the earthquake in Friuli, also in relation to the design of nuclear installations, and the proceedings were collected in three volumes with a total of 882 pages.

Years later, other strong earthquakes occurred in Italy: Irpinia (1980, 2914 deaths), Umbria – Marche (1997, 11 deaths), Molise (2002, 30 deaths), L’Aquila (2009, 308 deaths), Emilia (2012, 27 deaths), Amatrice (2016, 298 deaths). They were studied in detail and a comprehensive literature documents the research performed.

Therefore, the Friuli earthquake can be considered the first event to be scientifically studied in Italy soon after its occurrence and, perhaps, also the starting point for the modern seismological investigation in Italy (Slejko *et al.*, 2018). What has been acquired in the seismological field is here summarized.

2. The seismological network at the time of the Friuli earthquake

In early 1976, 33 seismometric stations were operating in Italy: they were located at universities or geophysical institutions (Fig. 1). The stations located in north-eastern Italy were those of Trieste (TRI), Padua (PAD), Bolzano (BLZ), and Salò (SAL). Outside the country, the stations that were operational and, relatively, close to central Friuli (within 250 km) were those of Ljubljana (LJU), Cerknica (CEY), Labin (LABI), Puntijarka (PTJ), and Zagreb (ZAG), in former Yugoslavia, those of Kremsmunster (KMR), Mariazell (MZA), Molln (MOA), and Innsbruck (IBK) in Austria, and Bad Reichenhall (BHG), Fürstenfeldbruck (FUR), and Garmisch (GAP) in Germany (Fig. 2).

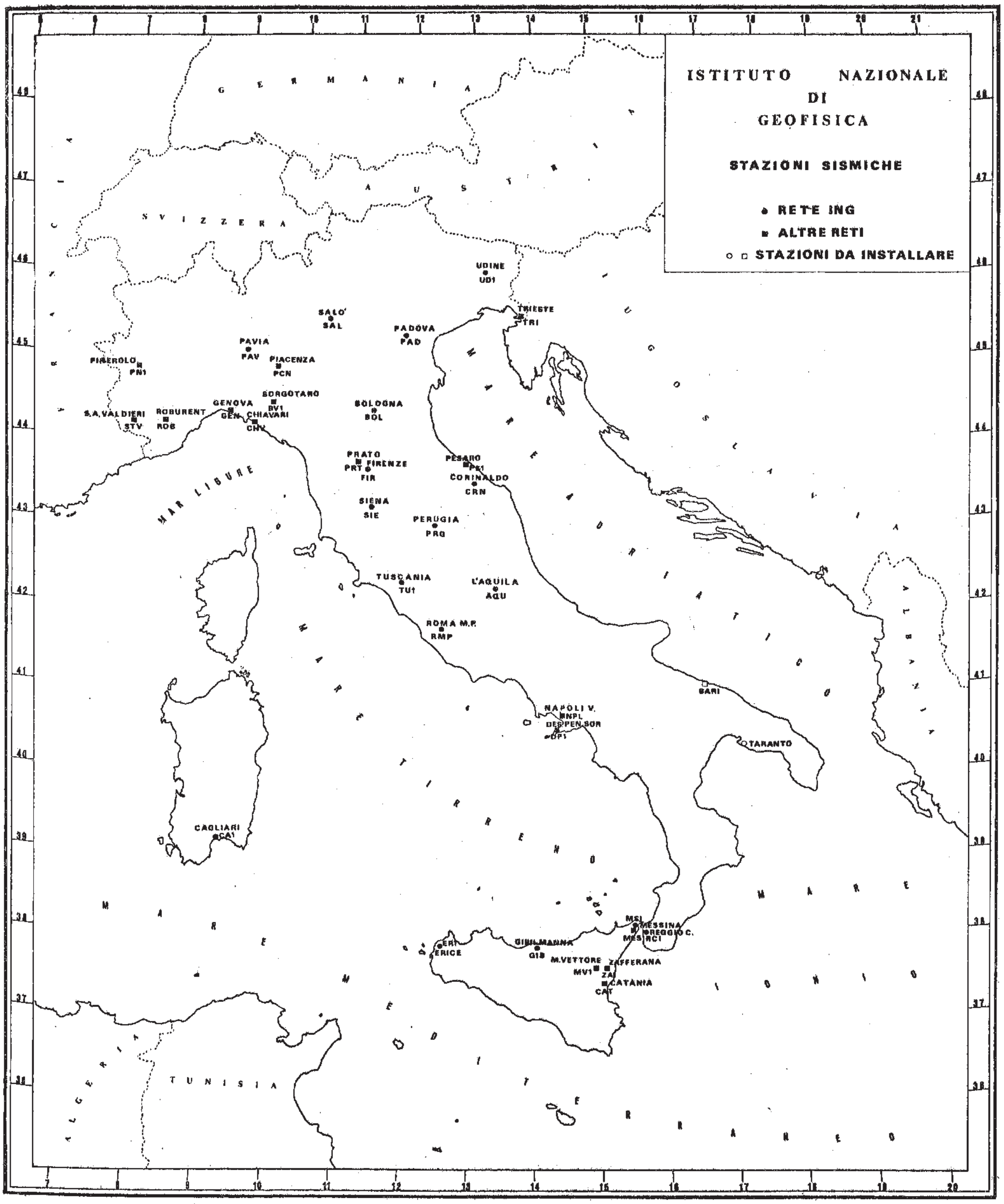

Fig. 1 - Map of the Italian permanent stations operating in 1976.

In June 1976, the University of Vienna deployed the stations of Klagenfurt (KFA) and Bad Blaiberg (BBA) in Carinthia (Aric *et al.*, 1992). Besides these, there were some seismometric stations for the specific control of some facilities (e.g. dams: AMBE, LAME, PIEE, MISE, VAJ). The Istituto Nazionale di Geofisica (ING) in Rome had the task of the Italian seismic monitoring and produced two bulletins: the first for the instrumental data, the second for the macroseismic ones. The data

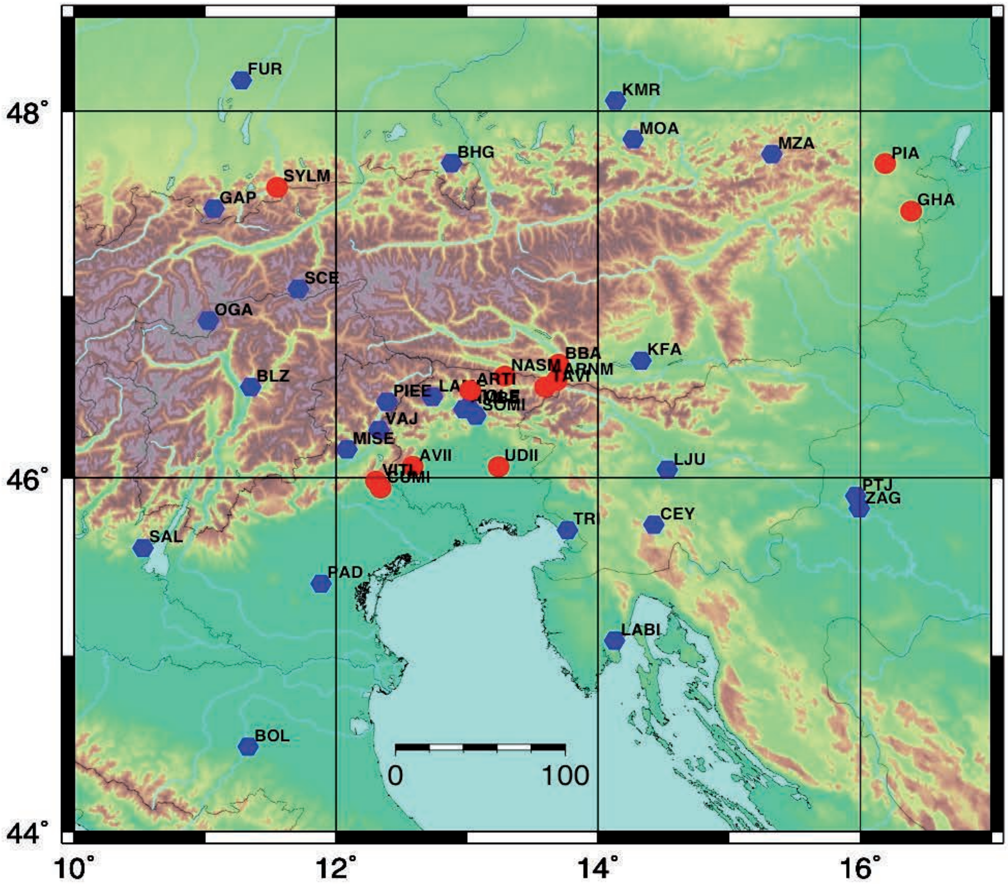

Fig. 2 - Map of the permanent stations operating in the eastern Alps at the beginning of May 1976 (blue hexagons) and temporary stations installed after the shock of 6 May (red circles). Temporary stations installed in the epicentral area after 6 May are not shown here but in Fig. 8.

processing time and that to compile the bulletins, were conditioned by the speed of data exchange, then based on mail and telephone. The seismological station of Trieste, managed by OGS the Osservatorio Geofisico Sperimentale (presently Istituto Nazionale di Oceanografia e di Geofisica Sperimentale) and whose instruments were (and still are) located at the bottom of the Karst cave called Grotta Gigante, was about 70 km far from the earthquake epicentre. At the time, the Trieste station was part of the World Wide Standardized Seismographic Network (WWSSN), installed in 1963 by the United States Geological Service with equipment capable of recording both near and far earthquakes. The installation also of a Wood Anderson seismometer at the Trieste station allowed the seismologists to accurately calculate the magnitude of all the local earthquakes (within 600 km from Trieste).

3. Seismicity in Friuli before 1976 in the tectonic framework

The Friuli area (north-eastern Italy) is the most seismically active sector of the Alpine chain: here the south-verging fold and thrust belt of the eastern Southern Alps joins up with the NW-SE trending dextral strike-slip fault systems of western Slovenia (Fig. 3). The presence in the northern portion

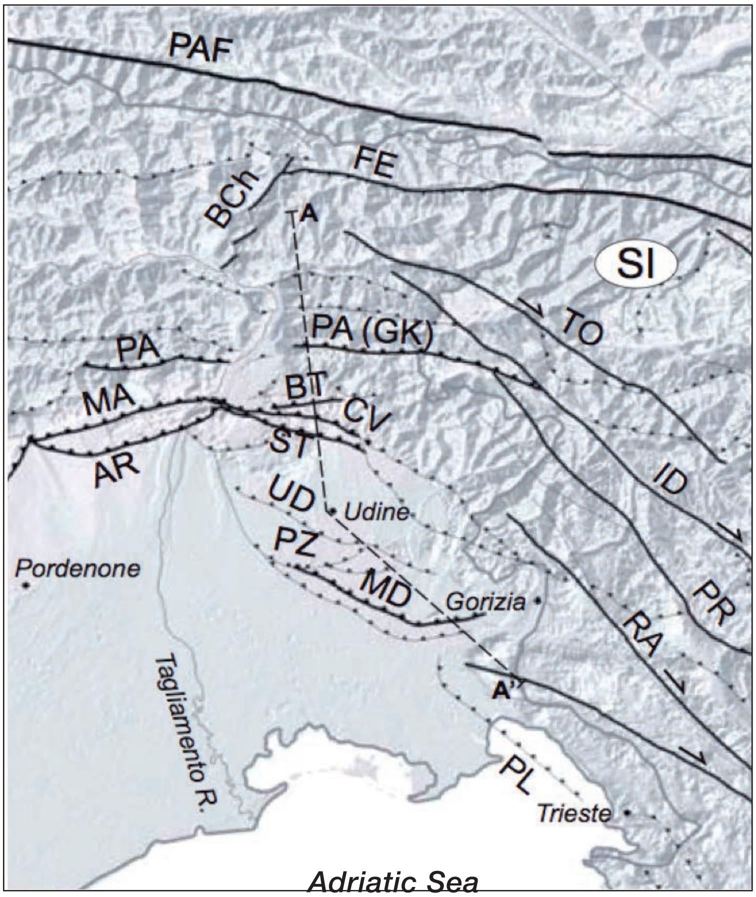

Fig. 3 - Regional tectonic sketch of north-eastern Italy and western Slovenia (modified from Burrato *et al.*, 2008). Black lines identify strike–slip faults, hachured lines show thrusts, solid lines represent active faults. Legend: AR = Arba–Ragogna thrust; BCh = But–Chiarsò fault system; BT = Buja–Tricesimo thrust; CV = Colle Villano thrust; FE = Fella thrust; ID = Idrija fault; MA = Maniago thrust; MD = Medea thrust; PA = Periadriatic thrust; PA (GK) = Periadriatic thrust Gemona–Kobarid segment; PAF = Periadriatic lineament; PL = Palmanova line; PR = Predjama fault; PZ = Pozzuolo thrust; RA = Raša fault; ST = Susans–Tricesimo thrust; TO = Tolminka or Ravne fault; UD = Udine–Buttrio thrust.

of the River Tagliamento valley of a few small N-S trending strike-slip faults is worthy of mention. Geological and seismological studies suggest that the region undergoes a main compressional, roughly NNW-SSE oriented, stress, linked to the indentation of the Adria microplate beneath the Eurasian Plate (e.g. Anderson and Jackson, 1987; Slejko *et al.*, 1989; Castellarin *et al.*, 2006).

The historical seismicity of Friuli and surrounding regions is quite well known for the presence, since the Roman times, of a number of settlements that later developed into major economic and commercial centres during the Middle Ages (Belluno, Cividale, Trieste). The latest catalogue of Italian earthquakes CPTI15 (Rovida *et al.*, 2016) and some studies on the regional seismicity (e.g, Slejko *et al.*, 1989) describe in a rather specific way the seismic areas in the eastern Alps.

Six earthquakes with a moment magnitude M_W greater than 6 (Rovida *et al.*, 2016) occurred between 1000 and 1975 (see Table 1): in 1348 the town of Villach, in Carinthia, suffered heavy damage and casualties (M_W 6.6); in 1511 Gemona, Venzone, and Osoppo, in Friuli, and Idrija with some castles in western Slovenia suffered severe destruction and casualties [M_W 6.3; see also Camassi *et al.*, 2011)]; in 1690 the town of Villach (Barbano *et al.*, 1994) was subsequently destroyed with a number of fatalities (M_W 6.2); in 1873 some villages in Alpago (eastern Veneto) suffered extensive destruction and there were 80 deaths (M_W 6.3); in 1928 Tolmezzo and several villages along the River Tagliamento suffered collapses and widespread damage and 11 fatalities (M_W 6.1); and, finally, in 1936 the settlements in the Cansiglio plateau (eastern Veneto) suffered total and partial collapses and 19 deaths (M_W 6.1).

Table 1 - List of earthquakes in Friuli and nearby areas with an M_W greater than 6 [data extracted from the catalogue CPTI15 (Rovida *et al.*, 2016)] I_O is espressed in the MCS scale.

Year	Mo	Da	Ho	Mi	Epicentral Area	Lat. N(°)	Lon. N(°)	I_O	M_w
1348	01	25			Julian Alps	46.504	46.504	IX	6.6
1511	03	26	15	30	Friuli-Slovenia	46.209	46.209	IX	6.3
1690	12	04	14		Carinthia, Villach	46.633	46.633	VIII-IX	6.2
1873	06	29	03	58	Alpago Cansiglio	46.159	46.159	IX-X	6.3
1928	03	27	08	32	Carnia	46.372	46.372	IX	6.0
1936	10	18	03	10	Alpago Cansiglio	46.089	46.089	IX	6.1
1976	05	06	20	00	Friuli	46.241	46.241	IX - X	6.4

Friuli-Venezia Giulia has a long history of collecting instrumental seismological data because a seismographic station was operational at the Astronomic and Maritime Observatory of Trieste already in early 1898 (Kozák and Piešinger, 2003). In 1949, the station became part of OGS and, in 1963, the seismographic station was moved from the centre of Trieste (Campo Marzio) to an environmentally sound site (Grotta Gigante) and equipped with the instruments of the WWSSN. Some stations located in areas near Friuli (e.g. Ljubljana, Pula, Padua, Venice, Treviso) have contributed to the data collection of earthquakes in the eastern Alps from the beginning of the 20th century.

Fig. 4 shows the epicentres of earthquakes with an M_W greater than, or equal to, 4.0 that occurred from 1000 to 5 May, 1976. It can be seen that the strong seismic activity is concentrated along the foothills, from Cividale to Belluno, with its highest in central Friuli.

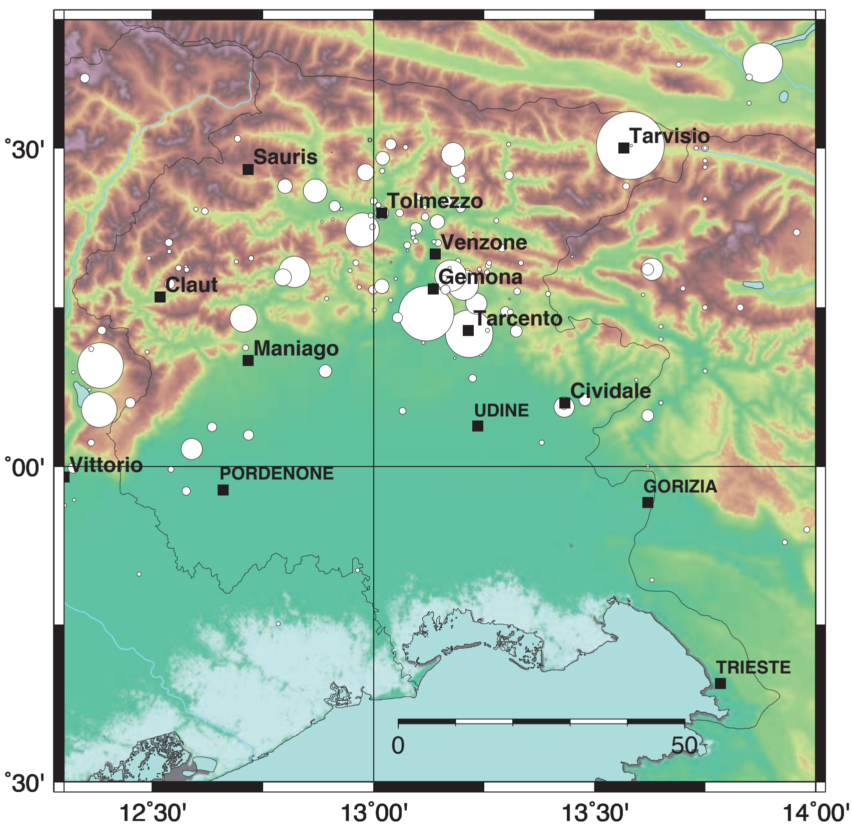

Fig. 4 - Epicentres of earthquakes from the year 1000 to 1975 in the eastern Alps [data extracted from the CPTI15 catalogue (Rovida *et al.*, 2016)]. The CPTI15 catalogue contains earthquakes with an M_W greater than, or equal to, 4.0.

The most seismically active area is located between Gemona, Tolmezzo and the border with Slovenia (Slejko *et al.*, 1989, 2011): in addition to the mentioned *M*>6 earthquakes (1511, 1928, and also the 1976 quake occurred here), it is worth remembering the earthquakes of 1389 and 1908 (epicentral area near Moggio Udinese) with intensity I_0 = VI-VII Mercalli-Carcani-Sieberg (MCS) and VII-VIII MCS, respectively. Another seismically active area is the Tramonti one: it was hit by destructive earthquakes in 1776 (I_0 = VIII-IX MCS) and 1794 (I_0 = VIII-IX MCS). An earthquake struck the nearby village of Maniago in 1812 (I_0 = VII-VIII MCS). The Cividale area, on the contrary, was affected only by the 1403 (I_0 = VIII MCS) and 1898 (I_0 = VII MCS) earthquakes and a few low magnitude events. The earthquake Raveo in 1700 (I_0 = VIII-IX MCS) merits noting since its effects were heavy, albeit only in a very limited area (about 70 km^2).

Some other zones, outside of the current Italian borders, are important for the seismic hazard of Friuli (Carulli *et al.*, 1990; Del Ben *et al.*, 1991; Slejko *et al.*, 2011). These include the aforementioned Carinthia, whose city of Villach and many villages along the Gail River valley were affected by the great earthquake of 1348 [whose epicentre is located by recent studies in the border area between Italy and Austria (OGS, 2005)] and by that of 1690: both earthquakes were clearly felt across the whole of Friuli. A minor seismicity has affected western Slovenia, in particular the area of the Sneznik Mountain, located SE of the city of Trieste. Further eastwards (Carulli *et al.*, 1990; Del Ben *et al.*, 1991), a few large earthquakes struck the city of Ljubljana (I_0 = VIII-IX MCS) in 1895 and the Croatian coastal area around the city of Rijeka in 1323 (I_0 = IX MCS), 1574 (I_0 = VIII-IX MCS), and 1721 (I_0 = X MCS).

4. The 1976 earthquake

The earthquake on 6 May 1976 hit an area of 5,700 km^2 in central-eastern Friuli, destroying several settlements (Ambraseys, 1976; Carulli and Slejko, 2005; Slejko, 2016, 2017) and causing 977 deaths (one victim was verified only as late as forty years after the earthquake) and 4.5 trillion Italian lira in damages [at the 1976 value (Cavallin *et al.*, 1990)]. The local magnitude (M_L) was 6.4 on the Richter scale, and the main shock was preceded a minute before by an M_L 4.5 event (Finetti *et al.*, 1979). The maximum intensity of the X degree (Gasparini, 1976; Giorgetti, 1976), on the Medvedev Sponheuer Karnik (MSK) scale, was observed in Gemona, Venzone, Trasaghis, Bordano, Forgaria, Maiano and Osoppo (Fig. 5), but the earthquake was felt over a very large area, to the north as far as to the Baltic Sea (Karnik *et al.*, 1978; Tertulliani *et al.*, 2018). Fortunately, it did not strike any big town: in fact, the same town of Udine, located just 30 km from the epicentre, had only marginal damage due to the strong ground motion attenuation towards the south (VII degree MSK, see Fig. 5).

After the strong M_L 5.3 aftershock of 9 May, the seismic sequence subsided in the summer. However, two quakes on 11 September, with an M_L of 5.1 and 5.6, and another two on 15 September, with an M_L 5.8 and 6.1 (Fig. 6), produced further collapses and another 13 victims, in addition to the 977 deaths of May, and weakened the spirit of Friulians, who had already begun the work of reconstruction. Another quake of M_L 5.2 occurred a year later, on 16 September, 1977: it was followed by an aftershock series that lasted more than one month (Siro and Slejko, 1981; Suhadolc, 1981, 1982).

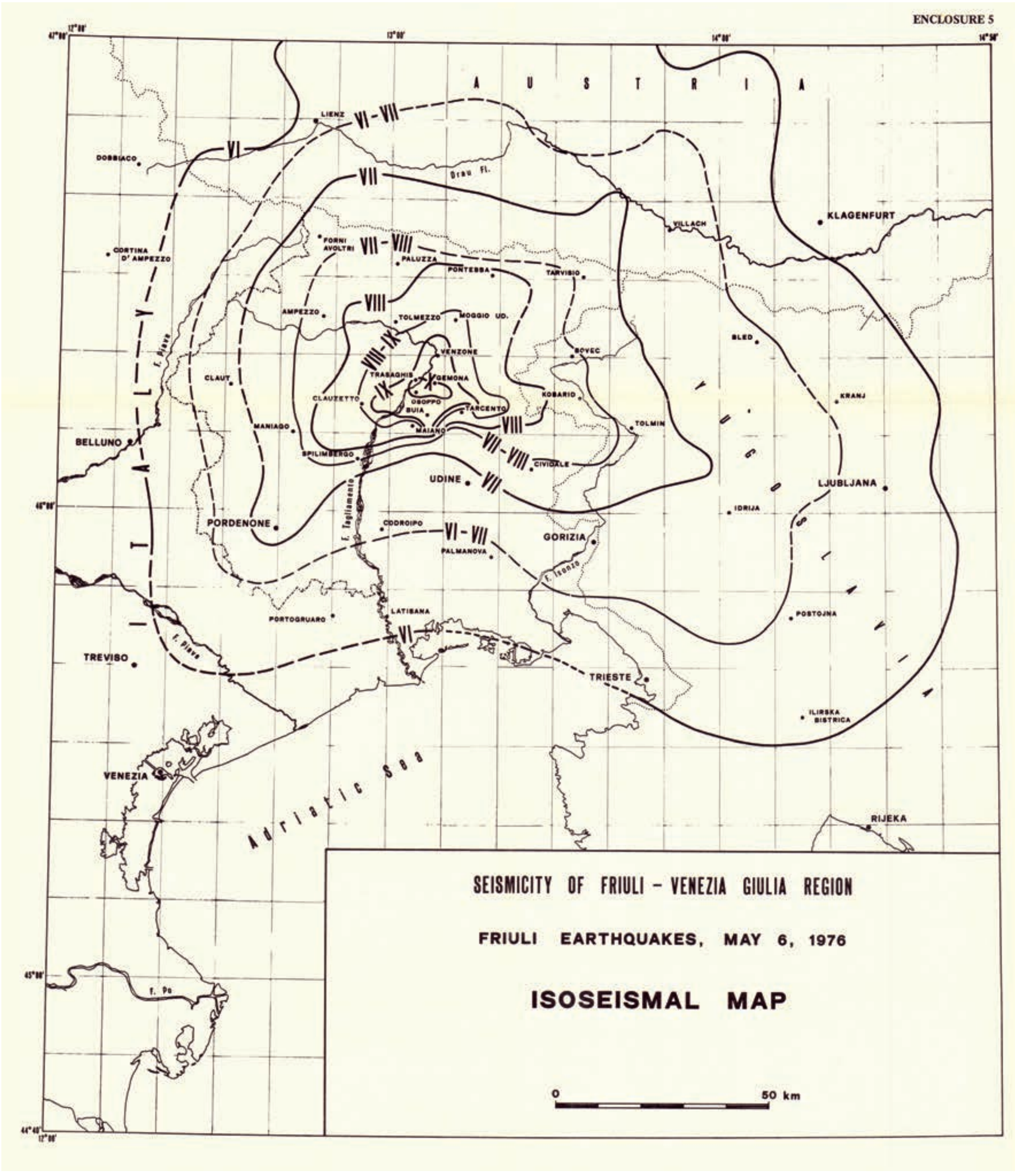

Fig. 5 - Isoseismals of the 1976 Friuli earthquake expressed in the MSK scale (Giorgetti, 1976). The strong southward attenuation of the shaking can be seen, a feature that saved the city of Udine from more extensive damage.

Caputo (1976) calculated the parameters of the main shock: a stress drop of 10 to 13 bar, a seismic moment of $10^{25.9}$ to $10^{26.1}$ dyne×cm, a fault area of 800 km^2, and a dislocation of 32 to 54 cm. These parameters were subsequently roughly confirmed by Cipar (1980, 1981), who calculated also those of some aftershocks.

The maximum deformation of 25 cm was discovered by geodetic data (Talamo *et al.*, 1978) between Venzone (+18 cm) to Carnia (-7 cm), on the basis of the levelling measurements done in

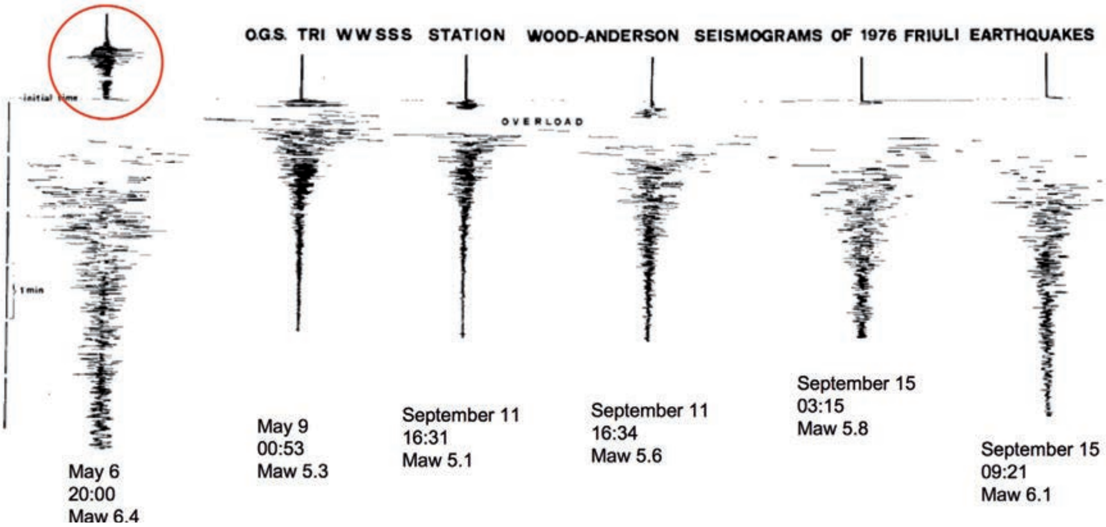

Fig. 6 - Seismograms recorded by the Wood-Anderson seismograph of the Trieste station related to the 6 major shocks of the 1976 sequence. The red circle indicates the M_L 4.5 foreshock. To these, the shock of the 16 September 1977 should be added.

1952 and 1977. Steinhauser and Lenhardt (1986) proposed that this crustal movement was mainly due to the Friuli earthquake sequence, as the general Alpine uplift rate is one order of magnitude lower. The inversion of such data (Arca *et al.*, 1985; Briole *et al.*, 1986) suggested a reverse fault plane in agreement with that obtained from seismic data, with ruptures both east and west of the River Tagliamento, these last also characterized by a transcurrent component.

Twelve stations of the accelerometric network of the national electricity company (ENEL) recorded the main shock of 6 May (Basili *et al.*, 1976; Commissione CNEN-ENEL, 1976) and a peak horizontal acceleration of 0.37 g was registered by the Tolmezzo station, very close (about 35 km) to the epicentre of the earthquake. The very next day, 8 other temporary stations were set up by the CNEN - ENEL Commission and 203 accelerograms, referring to 32 events that took place until 15 June, were recorded (Basili *et al.*, 1978). The CNEN-ENEL Commission then gathered all the accelerometric data and disseminated them in a series of five volumes (Commissione CNEN-ENEL, 1976-1979). These data were also used for the determination of focal and spectral parameters of the events (De Natale *et al.*, 1987) and for the soil characterization of the sites affected by a strong shaking (Chiaruttini *et al.*, 1979). The maximum acceleration (0.52 g) in former Yugoslavia was recorded by the temporary station of Breginj (located on soft soil) during the aftershock of 15 September at 3:15 (Mihailov, 1976).

Regarding aspects of structural engineering, a general overview of the damage suffered by the buildings in the epicentral area was presented with specific examples by Glauser *et al.* (1976) and as a comprehensive summary, documented by explicative photographs, of the damage reported by the different typologies of buildings old masonry buildings, recent masonry buildings, low-rise reinforced concrete (r.c.) buildings, tall r.c. buildings, with a particular detail for the settlements of Maiano and Gemona, by Commissione CNEN-ENEL (1976). The infrastructure in Friuli (bridges, roads, electric system) was inspected to identify possible deficiencies (Briseghella, 1976; Faoro and Ferrazza, 1976). A wide selection of damage suffered by monumental and common buildings in the epicentral area is reported in Briseghella *et al.* (1976): this substantial documentation provides a synthesis of the phenomena that determined the different behaviour of buildings under the earthquake shakings. Specific studies pointed out at the behaviour of selected typologies of buildings, i.e. old masonry and recently constructed masonry buildings (Cartapati and Cherubini, 1976; Pistone and Roccati, 1976), and to an r.c. structure still under construction (Bayulke, 1976). The damage suffered by some important buildings (e.g. the Tolmezzo hospital, some r.c. buildings in Maiano) was analysed in details (Giuffrè *et al.*, 1976; Petrini *et al.*, 1976; Berardi and Sanò, 1978; Scelfo *et al.*, 1978), as well as the behaviour of damaged buildings during renewed earthquakes (Heimgartner, 1976; Heimgartner and Glauser, 1978). After the 6 May earthquake, the buildings in the shaken area were investigated and 84,780 forms were filled, where the descriptions of the damage were georeferenced to compile a huge database (Di Cecca and Grimaz, 2009), which is available on line upon request and is suitable for in-depth studies and analyses.

5. The hypocentral location of the main shock

The main shock of 6 May and the seismic sequence which followed in the very next days were studied by OGS, initially only with the data recorded by the Trieste (Colautti *et al.*, 1976) station because the elaboration of data coming from different stations was impossible due to the difficulty in communication. Therefore, the epicentre was based on the estimate of the epicentral distance and the station-to-epicenter azimuth, with large uncertainties involved. The calculation of the focal depth was impossible: it was only possible to evaluate the surficial nature of the event. Further studies confirmed the superficial nature of all the shocks of the sequence, which were generally located in the first 10 km (Zonno and Kind, 1984). These limits in the earthquake location explain why the main shock location near Mount San Simeone communicated to the media immediately after the main shock was slightly modified by subsequent studies. In fact, numerous epicentre locations were produced for the main shock (Table 2). In summary, they can be related to two areas: the foothills of the Julian Alps east of Gemona and the Val Resia NE of Venzone (Fig. 7). Notably, the location computed by OGS, also using data from private stations (ENEL) operating in central Friuli, placed the epicentre in the Monteprato area, between the settlements of Taipana and Lusevera (Poli *et al.*, 2002).

To definitively fix the location of the main shock, a new elaboration has been performed considering all the available data. More precisely, all phase readings from original seismograms and bulletins of public and private, permanent and temporary stations within a 250-km epicentral distance, integrated with the data reported in the website of the International Seismological Centre (ISC), have been used. Several crustal models have been considered and, at the end, that of the European Mediterranean Seismological Centre Working Group on the Friuli Earthquakes (1976) has been selected because it produced the most reasonable depth estimation, according to the tectonic information available, as well as the smallest statistical errors on the location. This new location, reported in Fig. 7, confirms that of Poli *et al.* (2002) and is quite close to those of Cagnetti and Pasquale (1979), Barbano *et al.* (1985), and Aoudia *et al.* (2000). The epicentral area of the main shock is, then, in a sector of the pre-Alpine foothills where no major settlements are found: this fact justifies perhaps the different locations of both macroseismic epicentres here

Table 2 - Hypocentral locations of the main event of 6 May, 1976 according to different authors. h is the focal depth. Source: 1 = hypocentral determination by the Centre Seismologique Europeo-Mediterraneen (CSEM), 2 = http://earthquake.usgs.gov, 3 = www.isc.ac.uk, 4 = Cagnetti and Pasquale (1979), 5 = Cipar (1980), 6 = Barbano *et al.* (1985), 7 = Engdhal *et al.* (1998), 8 = Aoudia *et al.* (2000), 9 = Pondrelli *et al.* (2001), 10 = Engdahl and Villaseñor (2002), 11 = Poli *et al.* (2002), 12 = this work. In addition, also the macroseismic locations of Giorgetti (1976) (13) and the CPTI15 catalogue (Rovida *et al.*, 2016) are reported (14).

Hour	Minutes	Seconds	Lat. N (°)	Lon. E (°)	h (km)	Source
20	00	14.70	46.310	13.310	10.0	1
20	00	11.60	46.356	13.275	9.0	2
20	00	12.48	46.3517	13.2595	11.7	3
20	00	11.8	46.266	13.250	20.1	4
–	–	–	46.329	13.322	–	5
20	00	–	46.275	13.247	7	6
20	00	15.30	46.386	13.264	20.0	7
–	–	–	46.290	13.257	4-6	8
20	00	–	46.360	13.270	5-10	9
20	00	14.92	46.387	13.271	17.6	10
20	00	13.2	46.262	13.300	5.7	11
20	00	13.30	46.262	13.279	7.0	12
20	00	–	46.262	13.103	5	13
20	00	–	46.241	13.119	–	14

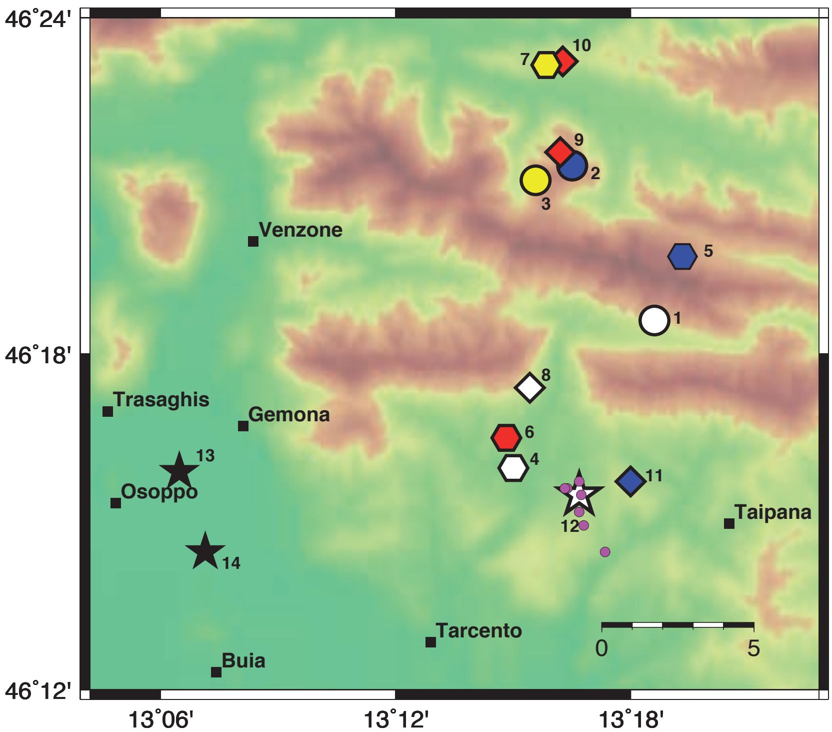

Fig. 7 - Epicentres of the main shock of 6 May 1976 according to different authors. Legend: 1 = hypocentral determination by the Centre Seismologique Europeo-Mediterraneen (CSEM), 2 = http://earthquake.usgs.gov, 3 = www.isc.ac. uk, 4 = Cagnetti and Pasquale (1979), 5 = Cipar (1980), 6 = Barbano *et al.* (1985), 7 = Engdhal *et al.* (1998), 8 = Aoudia *et al.* (2000), 9 = Pondrelli *et al.* (2001), 10 = Engdahl and Villaseñor (2002), 11 = Poli *et al.* (2002), 12 = this work. The solid magenta dots show alternative solutions of the location presented in this study obtained with different crustal models and parameters. The two black stars indicate macroseismic epicentres: 13 = Giorgetti (1976), 14 = Rovida *et al.* (2016). Two areas remain broadly identified: the foothills of the Julian Alps east of Gemona (nos. 4, 6, 8, 11, 12) and the Val Resia NE of Venzone (nos. 2, 3, 7, 9, 10). Only two locations (nos. 1 and 5) placed the epicentre in the Musi Mountains area.

considered (Giorgetti, 1976; Rovida *et al*., 2016) that remain westwards of the instrumental one, in an area populated by the three towns of Gemona, Trasaghis, and Osoppo. The southern position of the instrumental location here proposed with respect to all others, especially those of Pondrelli *et al.* (2001) and Enghdal and Villaseñor (2002), is motivated by the data of local stations, which before the present elaboration, were only in part evaluated by Poli *et al.* (2002). These new data, in fact, move the location of the events of the sequence to the south.

6. The space and time evolution of the seismic sequence

The considerable amount of data collected by the Trieste station allowed the localization of 695 shocks occurring until October 1976: these data highlighted which areas were affected, respectively, by the shocks of May and those of September and indicated a NW-ward migration of the seismicity (Colautti *et al.*, 1976).

Various national and international scientific institutions [ING, CNEN, Catania University, Munchen University, Institut de Physique du Globe of Strasbourg (IPG)] took part in the data collection of the seismic sequence with the installation of temporary stations in Friuli and Carinthia (Figs. 2 and 8). These data, although some stations operated only during two short periods respectively in May-June and September-October, enabled the localization of the events even at depth and brought to light the superficial nature (within 20 km) of the earthquakes (Finetti *et al.*, 1976). The analysis of about 4,000 events of the seismic sequence with M_L between 1.5 and 5.0 recorded by a temporary network installed by IPG after the strong earthquakes of May and September, pointed out that the seismicity of May was concentrated in eastern Friuli and propagated NW-wards during the month of September (Finetti *et al.*, 1976; Cagnetti and Console, 1977; Wittlinger *et al.*, 1978). The construction of some geological cross-sections brought to light that the hypocentres were superficial, with a depth between 1 and 7 km, even in the case of earthquakes of magnitude greater than 4.0. Further studies (Zonno and Kind, 1984) subsequently confirmed the superficial nature of all the shocks of the sequence, generally located within the first 10 km.

A first seismotectonic interpretation of the earthquake was also proposed with the association of the main shock to the Buja – Tricesimo overthrust and the of 11 and 15 September aftershocks to the Periadriatic thrust-belt, north of the first source (Amato *et al.*, 1976).

The estimate of the changes in the Coulomb stress proposed by Perniola *et al.* (2004) showed a positive correlation between the areas affected by increased stress following the main shock and the spatial distribution of the seismicity of the sequence, suggesting that the main shock favoured the rupture of neighbouring faults by the following major earthquakes.

The review of seismological data for 1256 events of the Friuli sequence from 6 May 1976 to 6 May 1977 [Renner, personal communication, see also Poli *et al.* (2002)] made it possible to describe the space and time evolution of the seismic phenomenon, characterized by the activation of gently north-dipping thrusts as well as of minor steeply south-dipping faults (Poli *et al.*, 2002).

A complete relocation of all earthquakes of the sequence from 6 May 1976 to 31 December 1977 has recently been performed (Rebez *et al.*, 2018). A total of 2012 events which occurred in central Friuli (46.0° – 46.6° N and 12.6° – 13.8° E) have been located using all data of public and private, permanent and temporary stations within a 250-km epicentral distance, integrated with the data reported in the ISC bulletins. Also in this case, the crustal model of the European Mediterranean

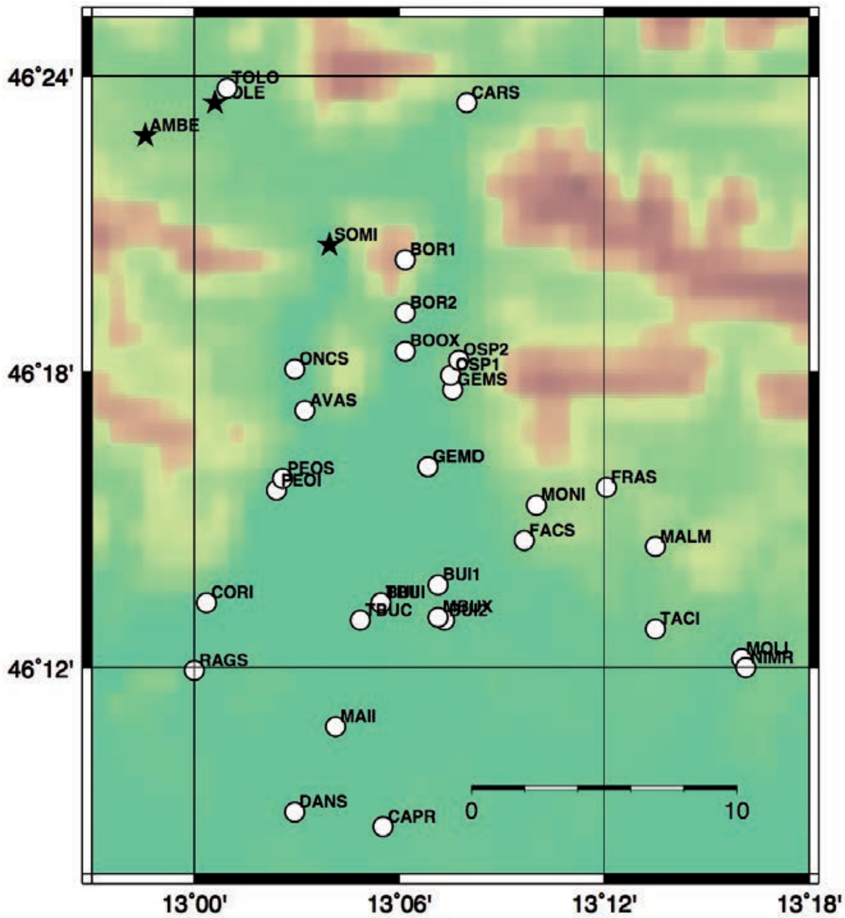

Fig. 8 - Map of private stations (black stars) operating in 1976 and temporary ones (white circles) installed after the earthquake of 6 May 1976 in the epicentral area.

Table 3 - Earthquakes of the seismic sequence of 1976-1977 with an M_L greater than, or equal to, 4.5. *h* is the focal depth (in km), No is the number of phases used in the elaboration, Gap is the maximum angle without stations, Dmin is the distance of the closest station (in km), Rms, Erh, and Erz are the standard errors on origin time (in s), epicentre (in km), and focal depth (in km), respectively.

N	Date	Origin Time	Lat. N (°)	Lon. E (°)	*h*	M_L	No	Gap	Dmin	RMS	ERH	ERZ
1	1976/05/06	19:59:05.69	46.275	13.313	9.4	4.5	35	75	28.4	0.47	1.0	1.5
2	1976/05/06	20:00:13.30	46.262	13.279	7.0	6.4	24	98	46.8	0.37	1.1	1.9
3	1976/05/07	00:23:49.44	46.250	13.291	8.5	4.5	33	81	48.3	0.50	1.2	1.6
4	1976/05/09	00:53:44.45	46.225	13.297	11.6	5.3	38	71	5.7	0.48	1.2	0.9
5	1976/05/11	22:44:00.64	46.260	13.058	12.1	4.8	43	47	1.2	0.32	0.7	0.6
6	1976/09/11	16:31:11.40	46.281	13.197	8.9	5.1	36	44	3.7	0.32	0.8	0.9
7	1976/09/11	16:35:02.35	46.259	13.232	4.8	5.4	31	70	5.1	0.51	1.1	2.2
8	1976/09/15	03:15:19.74	46.295	13.191	7.0	5.8	38	42	4.8	0.42	0.9	1.2
9	1976/09/15	04:38:53.50	46.279	13.198	14.1	4.7	34	44	3.6	0.38	0.8	1.0
10	1976/09/15	09:21:18.83	46.305	13.157	12.1	6.1	35	43	5.6	0.30	0.6	1.0
11	1976/09/15	11:11:11.25	46.280	13.158	6.2	4.5	34	49	2.9	0.42	1.0	1.3
12	1977/04/03	03:18:14.07	46.306	13.151	12.2	4.5	39	56	1.7	0.38	0.9	1.0
13	1977/09/16	23:48:07.45	46.303	12.997	11.0	5.2	31	68	8.1	0.44	1.0	1.5

Seismological Centre Working Group on the Friuli Earthquakes (1976) has been used. Although only stations within a 250-km distance have been considered for the best coherence with the crustal model, all locations are characterized by satisfactory solutions. Table 3 collects the hypocentral solutions obtained for the strongest events (M_L larger than, or equal to, 4.5) of the sequence: it can be seen that the number of data used in the elaboration is quite large, the azimuthal gap and standard errors are quite small. The focal depth for these strong quakes is between 4.8 and 14.1, confirming the surficial character of the events. The epicentres of the main events of the sequence are reported in Fig. 9.

These new accurate locations have been used to investigate the time and space distribution of the seismicity during the sequence. Fig. 10 illustrates the release of magnitude (Fig. 10a), cumulative number of events and cumulative energy (Fig. 10b) in time. The plot of magnitude vs. time (Fig. 10a) shows the reduction of seismic activity in July and August and then, starting from January 1977 with the exceptions of the two sequences of April (M_L 4.5) and September

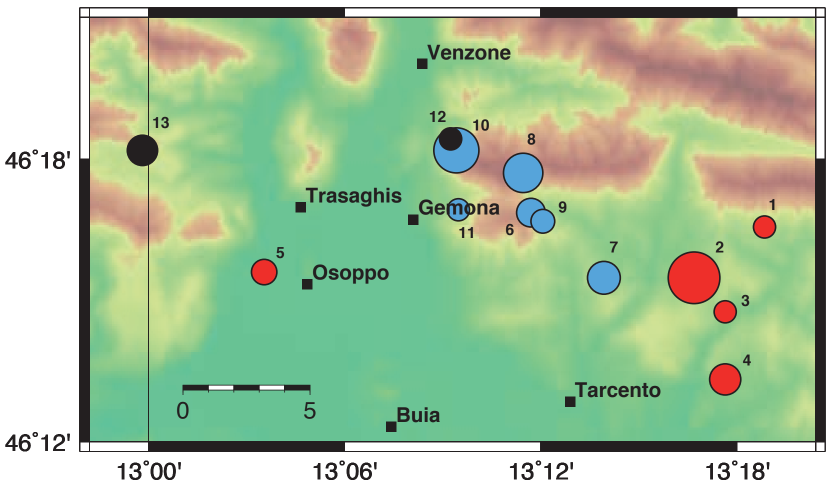

Fig. 9 - Epicentres of the main events of the Friuli sequence: red circles = 6 May 1976 – 31 August 1976; blue circles = 1 September 1976 – 31 December 1976; black circles = 1 January 1977 – 31 December 1977. The numbers refer to Table 3.

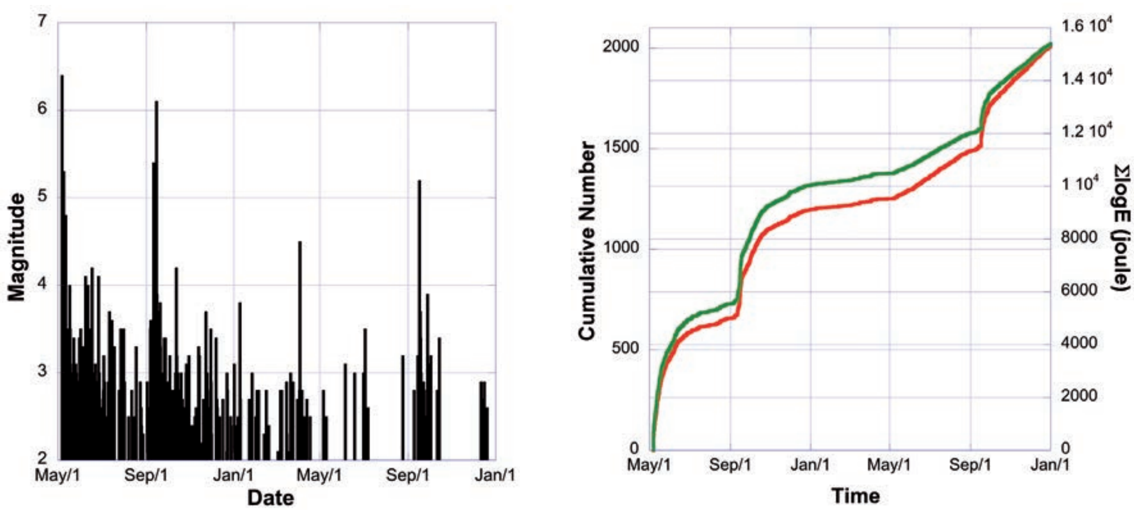

Fig. 10 - Evolution of seismicity over time during the seismic sequence (May 1976 - December 1977): a) magnitude vs. time; b) cumulative number of earthquakes (red line) and cumulative energy release (green line) vs. time. It can seen that, after the high activity of May and June 1976, the sequence diminished in July and August to then resume its force in September, and, in practice, the whole energy was released by the main shocks of May and September.

(M_L 5.2). The two graphs of the cumulative number of events and cumulative energy release are very similar: the three episodes of May and September 1976 and September 1977 are well highlighted by both plots and it can be seen that almost the entirety of the energy was released during the cited three episodes (Fig. 10b). The spatial distribution of events (Fig. 11) illustrates, as already shown by the studies mentioned above, the NW-ward migration of the seismicity from May (Fig. 11a) to September (Fig. 11b), although the crustal volume affected by the seismicity seems much broader than just that referring to the epicentral area of the main events. During 1977 (Fig. 11c), the seismicity moved further westwards but, again, a large region was affected by quakes.

7. The seismic sources

The focal mechanisms of the main events in the sequence were calculated both from the first arrivals of seismic waves (Console, 1976; Ebblin, 1976; Ritsema, 1976; Rouland and Peterschmitt, 1976; Mueller, 1977) and from the inversion of surface waves (Cipar, 1980, 1981). While all interpretations of the main shock refer to a reverse focal mechanism, possibly with a small strike-slip component, different mechanisms were initially proposed for some aftershocks: reverse or strike-slip. A general preference was given to reverse mechanisms, related to thrust faults ENE-WSW oriented and gently dipping to the north, except in the case of a few strike-slip events that occurred to the west of the River Tagliamento (Wittlinger *et al.*, 1978). Subsequent elaborations (Slejko *et al.*, 1999; Aoudia *et al.*, 2000; Pondrelli *et al.*, 2001) confirmed the compressional Alpine character of all the principal events of the sequence with a small strike-slip component; only the Cipar (1980) interpretation for the 15 September event at 03:15 identified an almost E-W compressional motion with an evident strike-slip component.

Studying the tectonic stress derived from focal mechanisms, Ebblin (1980) identified a possible inversion of the stress regime from reverse to normal at certain times and at particular focal depths.

Similar mechanisms for most of the events in the sequence were proposed by Slejko *et al.* (1999): they are of the reverse type with a low angle plane dipping towards N-NW, similar, therefore, to the main shock mechanism. The reconstruction of the stress field, obtained by the inversion of the same focal mechanisms indicates that it was not constant in time. After a first phase, which lasted until mid-September 1976, during which the stress field remained homogeneous and coherent with the regional tectonics, there was a mixed scenario after middle September, probably caused by the overlapping of local causes to the regional field.

The interpretation of the focal mechanisms of the seismic sequence of Friuli remains, then, well inserted in the geodynamic context of the Adriatic microplate movement, that occurs in this region mainly with the reverse mechanism of the Alpine faults along medium to low-angle north-dipping planes and, to a lesser extent, with the transcurrent activity of some Dinaric faults.

Already the first interpretation of the sequence (Amato *et al.*, 1976) set the hypocentres in the regional seismotectonic context and, considering that almost all earthquakes presented a focal mechanism associable to the activity of the Alpine low angle thrust faults, the events of May were associated with Buja - Tricesimo line, fault located in the Friuli foothills, while those of September to the Barcis - Starasella line (Periadriatic overthrust), located north of the Buja - Tricesimo line. The strong quakes of September were interpreted as due to the dynamic rebalancing after the decompression of the western rock blocks caused by the main shock. The surface cracks

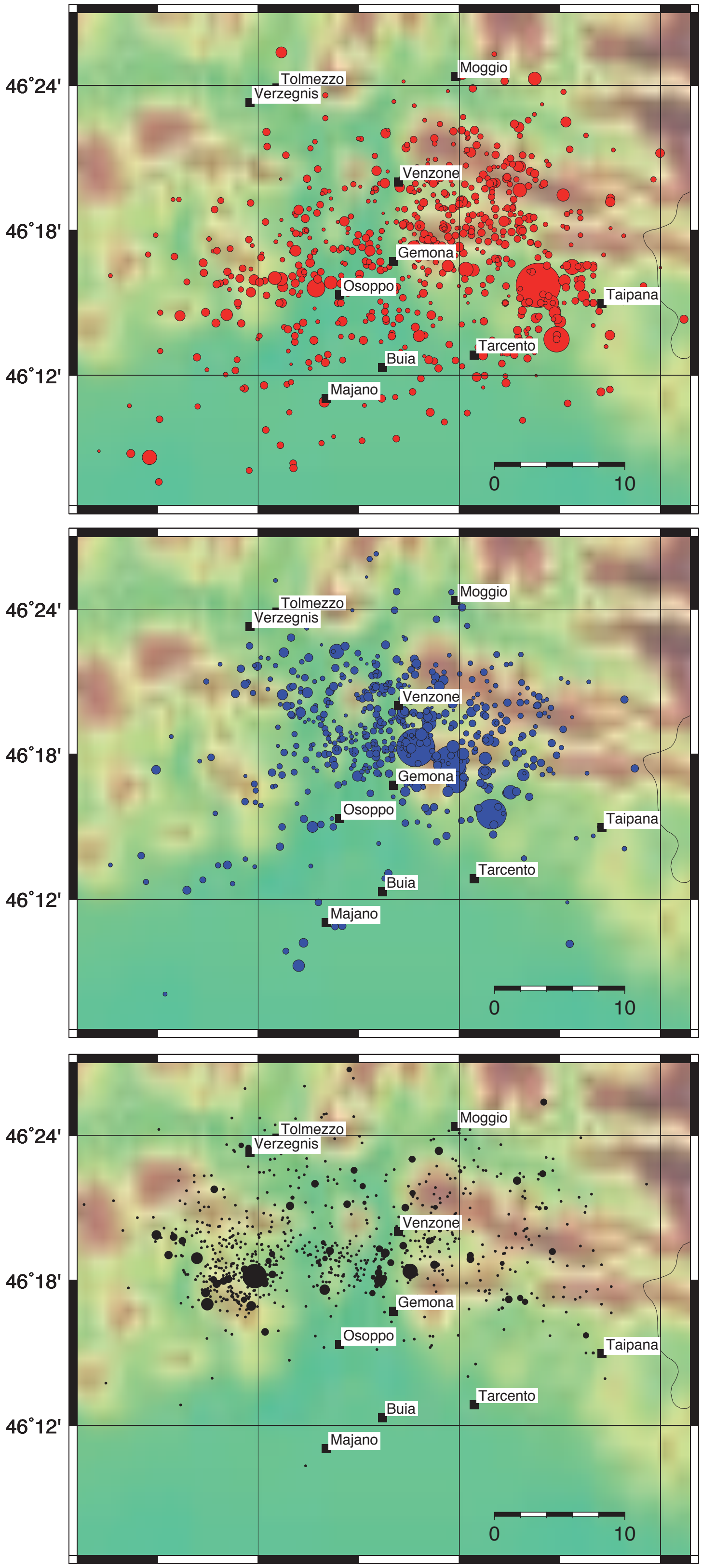

Fig. 11 - Space evolution of the Friuli seismic sequence: a) 6 May 1976 – 31 August 1976; b) 1 September 1976 – 31 December 1976; c) 1 January 1977 – 31 December 1977. Note the NW-ward migration of the seismicity (at least for major events), even though the shocks have always affected a very wide region.

highlighted by geological surveys (Ambraseys, 1976, Bosi *et al.*, 1976; Panizza, 1977), were not linked, however, to any seismogenic fault because of the complex tectonic framework of the epicentral area (Zanferrari *et al.*, 2013).

An interpretation of the seismic sequence of Friuli, inserted in the context of the Adria microplate geodynamics was given by Rogers and Cluff (1979), who confirmed the initial interpretation of Finetti *et al.* (1976), namely the Alpine character of earthquakes showing the fault plane dipping to the north with low-angle and reverse mechanism. Weber and Courtot (1978), considering all the information available (structural and geophysical data, satellite images, neotectonic activity, historical seismicity, macroseismic observations, spatial distribution of the aftershocks, focal mechanisms), reached the conclusion that the earthquake was caused by the NW-SE compression that activated existing both reverse and transcurrent faults.

Barbano *et al.* (1985) computed the focal parameters of major earthquakes of the sequence and identified the Tricesimo - Cividale fault as one of the sources of the major events of the sequence, without resolving, however, the question of the Alpine or Dinaric character of the sequence.

Considering the surficial character of the foci, confirmed also by the spectral analysis of some strong events of the sequence (Stoll, 1980), and since a connection between earthquakes and surface faulting is very difficult even in the light of the most recent studies (e.g. Pondrelli *et al.*, 2001; Carulli and Slejko, 2005), a complex geometry, in depth, of the faults involved in the sequence has also been proposed, with their merging at the contact with the crystalline basement causing the generation of a detaching surface at the depth of about 10 km (Slejko *et al.*, 1989). The same feature was already suggested by Siro and Slejko (1982), who studied the seismicity in Friuli in the years following the 1976 earthquake and found that the major seismicity was still associated to a deep thrust fault under the Tricesimo - Cividale fault, to the Tricesimo - Cividale line itself, and to the Periadriatic overthrust.

Amato and Malagnini (1990), through the tomographic inversion of local earthquakes from 1984 to 1986, identified a high density south-verging body at the depth of 5 to 10 km, which was interpreted as a wedge of the Paleocarnic Chain [this feature was already suggested by Castellarin (1979)]. This wedge overthrusts on the crystalline basement and may have been the main source of seismicity in Friuli and, consequently, of the 1976 earthquake.

From a comparative analysis of hypocentre relocations, long period surface wave inversion, field geology, and strong motion modelling, Aoudia *et al.* (2000) have concluded that the Friuli earthquake rupture was originated by a 19-km long fault-related folding developing from blind, under the Bernadia and Buja structures, to semi-blind, under the Susans structure, ending in the vicinity of the Ragogna fold. This model was shared by the interpretation (Cheloni *et al.*, 2012) of the geodetic measurements available for the observed deformation, which are compatible with the blind fault of Buja as the seismic source of all major earthquakes of the sequence (main shock of 6 May and two aftershocks of 15 September).

The statistical analysis of the time distribution of the events revealed a secondary sequence of aftershocks in September (Pasquale, 1985).

Also the studies conducted by Pondrelli *et al.* (2001) referred to the earthquake source. The authors, on the basis of locations and focal mechanisms processed by surface wave inversion, deduced that the majority of the events of the sequence were associated with the Periadriatic overthrust, while only two aftershocks in May 1976 affected/involved Dinaric structures.

New geological data and the review of the seismic ones relative to the sequence of 1976

(479 hypocentre locations and 123 focal mechanisms) have allowed the construction of a 2D structural model for the Southalpine Chain (Poli *et al.*, 2002), whose vertical cross-sections show a south-verging thrust system with a backthrust characterized by a concentration of fractures in the carbonate rocks at 5-8 km depth at the latitude of Gemona. The stress redistribution caused by the sequence of 1976 produced a transfer of the deformation towards the western sector. Therefore, the main event of 6 May 1976 is believed to be associated with the Susans - Tricesimo fault, while the strong aftershock of 15 September is considered connected to the buried Trasaghis fault, a lateral ramp of the Pozzuolo line (Galadini *et al.*, 2005). Other pieces of evidence, such as the considerable Quaternary deformations both on the surface and in the seismic profiles, the capacity of this fault to generate very large earthquakes (M_W around 6.5), and the damage distribution (Rovida *et al.*, 2016), mostly located in the hangingwall of the Susans - Tricesimo thrust, contribute to confirm this interpretation (Poli and Zanferrari, 2018).

The catalogue of active faults in Italy (Burrato *et al.*, 2008) highlights the sources of the main seismic episodes of the Friuli sequence. These sources are: Gemona South, for the 6 May main event; Tarcento, for the magnitude 5.6 11 September quake; Montenars, for the magnitude 5.9 15 September shock; and Gemona East, for the magnitude 6.0 15 September event (Fig. 12).

A recent interpretation of the Friuli sequence is owed to Cheloni *et al.* (2012) who, on the basis of geodetic measurements available for the observed deformation, identified the blind fault of Buja as the seismic source of all major earthquakes of the sequence (main shock of May 6 and the two strong aftershocks of 15 September). Assuming that all the deformation accumulated in the convergence process between Adria and Eurasia is released in a single earthquake, the same authors calculated a 500-700-year recurrence interval for an earthquake of magnitude comparable to that of the 1976 event.

An interesting picture of the sequence was proposed by Moratto *et al.* (2012), who modelled the seismic sources of the four strong earthquakes of September 1976 as finite faults by computing finite-fault synthetic seismograms for several possible proposed fault models and nucleation locations. Their four best-fit models were mainly based on the focal mechanisms of Slejko *et al.* (1999) and seem to be well related to the Periadriatic overthrust, with a progressive east-to-west migration in time of the seismicity.

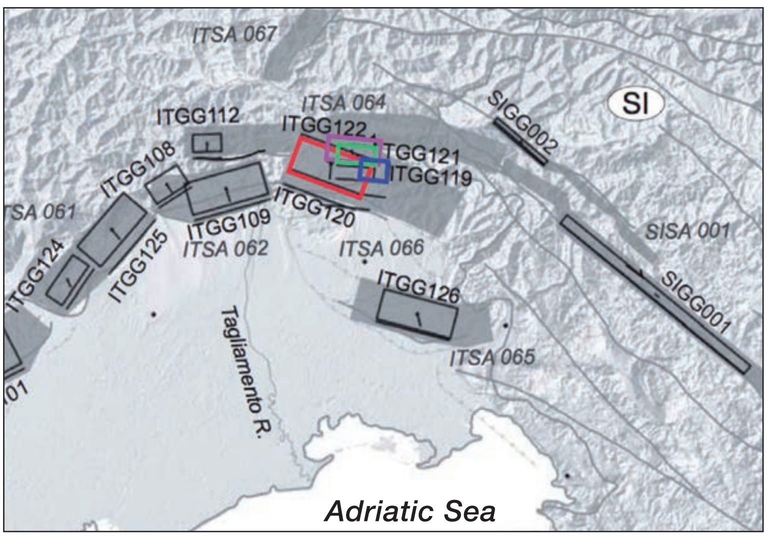

Fig. 12 - Seismic sources in the southern Alps (modified from Burrato *et al.*, 2008). The sources of the major earthquakes of the 1976 sequence are highlighted: 6 May (red rectangle), 11 September (blue rectangle), 15 September 03:15 (green rectangle), and 15 September 09:21 (violet rectangle).

Recently, on the bases of new geological mapping (Zanferrari *et al.*, 2008, 2013) and new interpretation of the seismic lines of the Friuli foothills (gently supplied by ENI), a new structural model of the Friuli region has been proposed by Zanferrari *et al.* (2013). There, a close relationship is suggested between the right lateral strike-slip system Idrija–Ampezzo (extending from the Isonzo valley in western Slovenia to the high Tagliamento valley in Carnia) and the south-verging thrusts that characterize the Julian foothills and the high piedmont Friuli plain (Gemona–Kobarid thrust, Susans-Tricesimo thrust, Buja thrust, Pozzuolo thrust, Udine thrust). This model could represent a new key to better understand the development of the Friuli sequence, even now not entirely clarified.

8. Forecasts of the Friuli earthquake

Two particular possible forecasts are reported in the literature related to the Friuli earthquake (Rebez *et al.*, 2018): the occurrence in the Latisana area (southernmost sector of the Friuli plain facing the Adriatic Sea) of some shocks of low magnitude in the winter preceding the earthquake and the recording by the Marussi pendulums, located in the Grotta Gigante on the Trieste Karst, of some low frequency disturbances, never registered before or thereafter.

Between November 1975 and February 1976, four earthquakes of magnitude between 2.5 and 3.5 were clearly felt by the population in the area of Latisana, considered until then practically aseismic and not characterized by the presence of known faults. Finetti *et al.* (1979) hypothesized that the Latisana earthquakes could have been a precursory phenomenon of the 6 May earthquake, caused by microfractures developed during an over-stress phase on a gentle undulation identified in the area by seismic exploration surveys, which should be indicative of the active geodynamic compression.

On 26 January 1973, an evident jump was recorded on both components of the Marussi pendulums (Chiaruttini and Zadro, 1976) and some anomalous disturbances, in the following hours. This type of perturbation was repeated more and more frequently later, and stopped abruptly with the shock of 6 May; they appear again, albeit weakly, before the September aftershocks. Since then, that kind of perturbation has not been recorded anymore (Braitenberg, personal communication). Chiaruttini and Zadro (1976) suggested that those perturbations were connected to phenomena either of creep or pre-seismic dilatance. Conversely, the occurrence of silent earthquakes, a sort of slow sliding below the focal zone of the 6 May event, was suggested by further studies as the source of the observed oscillations (Bonafede *et al.*, 1982, 1983).

Both the shocks of Latisana and the disturbances on the pendulum of the Grotta Gigante were, therefore, interpreted as possible precursory phenomena of the Friuli earthquake (Finetti *et al.*, 1979; Bonafede *et al.*, 1982, 1983), even if both phenomena have not yet found a robust scientific interpretation.

Indications on the possible occurrence of events with an M_L greater than 4.0 during the Friuli sequence were also detected, *a posteriori*, by Wittlinger *et al.* (1978) from the analysis of the V_P/V_S ratio. In the following years, some recordings of the stations of the clino-extensimetric network operating in Friuli since 1977 (Dal Moro and Zadro, 1999; Dal Moro *et al.*, 2000) showed strong anomalies in concomitance to two main (M_L 4.1 and 3.9) earthquakes which occurred close to some stations, suggesting, therefore, that precursory signals of seismic events can be detected only at distances comparable to that of the seismic source. A similar possible precursory signal of the 6 May earthquake was also identified, *a posteriori*, by Biagi *et al.* (1976) in the pre-seismic crustal variations evidenced by the clinometric records at the Ambiesta dam (SW of Tolmezzo); it is worth noting that a similar signal was also recorded in the case of the earthquake of 11 October 1954 with epicenter around Gemona.

9. Conclusions

The earthquake on 6 May 1976 in Friuli was the first strong Italian earthquake studied with data and scientifically advanced methods. It probably represents the maximum potential earthquake that the Southalpine structures can express, although larger earthquakes cannot be totally excluded (Benvegnù *et al*., 1978; Cheloni *et al.*, 2014).

As described before, the tectonic complexity of the region has made the association of hypocentres of the Friuli sequence to faults extremely difficult. Also for this reason, the autonomous Region of Friuli Venezia Giulia funded, as part of action for the reconstruction of the earthquake-stricken areas, the realization of a regional seismomentric network that was inaugurated on 6 May 1977 with the first three stations, located in the epicentral area (see Santulin *et al.*, 2018). In the following years, the number of stations increased, reaching its present configuration with 21 stations, which are complemented by those of the Veneto Region and the autonomous provinces of Trento and Bolzano to form the North-East Italy Seismic Network. The improvement of the hypocentre locations, obtained through the better distribution of the stations of the regional seismic network today, allows a good definition of the seismically active volumes. Consequently, also the connection with the faults is facilitated, even if the association of an earthquake to the generating fault remains affected by large uncertainties.

At the present state of knowledge, it can be stated that the seismic sequence begun on 6 May 1976 represents the evolution of a complex phenomenon that affected many reverse Alpine tectonic structures, often blind, even if activity also on Dinaric faults [e.g. strong quakes of 7 and 9 May (Pondrelli *et al.*, 2001)] cannot be ruled out. A general agreement can be found in the literature for the source of the 6 May main shock, even taking into account the slightly different opinions that geologists have on the deep geometry of the faults in the epicentral area. In fact, the main shock is associated with the Susans-Tricesimo fault (Galadini *et al.*, 2005; Burrato *et al.*, 2008; Poli and Zanferrari, 2018), a new interpretation (Poli *et al.*, 2002) of the Buja-Tricesimo line of Finetti *et al.* (1976). Cheloni *et al.* (2012) share this interpretation, as do Aoudia *et al.* (2000), who also suggest distinct segments for this event. Other studies (Barbano *et al.*, 1985) relate the main shock to the Tricesimo-Cividale overthrust (Colle Villano Thrust in Fig. 3) and to the Periadriatic overthrust (Pondrelli *et al.*, 2001). Different interpretations were also proposed for the events of September 1976: they were associated either to the Periadriatic overthrust (Amato *et al.*, 1976; Pondrelli *et al.*, 2001; Moratto *et al.*, 2012) or to the Trasaghis fault, a lateral ramp of the Pozzuolo line (Poli *et al.*, 2002; Galadini *et al.*, 2005; Burrato *et al.*, 2008) or to the Buja blind thrust as the unique source for the whole 1976 sequence (Cheloni *et al.*, 2012). Finally, the September 1977 event (M_L 5.4) occurred west of the Tagliamento River and it was associated with the western part of the Periadriatic overthrust (Suhadolc, 1981, 1982).

The question of whether the faults responsible for the earthquakes of the 1976 - 1977 Friuli sequence activated or not the crystalline basement remains open, although the majority of the proposed interpretations (e.g. Siro and Slejko, 1982; Slejko *et al.*, 1989; Moratto *et al.*, 2012) share the opinion that they did not.

A detailed interpretation of the activated structures in the sequence (Burrato *et al.*, 2008) identified four faults specifically responsible for the stronger shocks: in practice, those faults released the whole elastic energy of the sequence. The tectonic complexity of the affected region, with its numerous especially reverse fault systems, and the intermittent release of elastic energy with three major episodes (6 May, 11 and 15 September 1976), without also considering the strong earthquake of 16 September 1977 which occurred again in the epicentral area, probably characterize the earthquake of 1976 as the maximum event that the seismic sources of the central Friuli can generate .

For the above reasons, it is important to glean as much as possible from the data of the sequence starting on 6 May 1976, and from those recorded in the following years in order to accurately identify the active seismic sources in north-eastern Italy and to define their characteristics (maximum magnitude and recurrence interval).

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